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Radio-frequency heating of heterogeneous food – Meat lasagna

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ABSTRACT

This research studied feasibility of using radio-frequency (RF) energy to thermally process highly heterogeneous foods in large containers as shelf-stable products. Meat lasagna was selected as the food for the study. Dielectric properties of beef, mozzarella cheese, noodles, and sauce were determined between 1 and 1800 MHz and from 20 to 121 °C. A 6-kW 27-MHz RF system was used to sterilize packaged meat lasagna in large polymeric containers (295 × 253 × 42 mm) during which the temperature of different components were monitored. Computer simulations were also conducted to evaluate the influence of the dielectric properties of each food component on the electric field distribution and heating pattern during RF heating. The measurements indicated small temperature differences in beef meatballs, mozzarella cheese and sauce when they were properly distributed between layers of noodles. Simulation results suggested that in spite of large differences in electric field intensities in different food components, adequate heat transfer reduced differential heating. Thus, RF heating can be used to process pre-packaged heterogeneous foods and retain product quality.

1. Introduction

Conventional thermal processes for solid and semi-solid foods in large containers, such as size 10 cans (159 mm diameter, 178 mm height) for food services or 6 lb capacity (295 mm length, 254 mm width and 42 mm depth) trays for US military group meal rations, often lead to severe overheating at the periphery of the foods by the time the package interior reaches the desired sterility for heat resistant food pathogens. Dielectric heating by microwave or radio-frequency (RF) energy shortens thermal processes because heat is generated by direct interaction between electromagnetic energy and the foods within food packages. The free-space wavelength in the RF range (e.g., 13.56, 27.12 and 40.68 MHz) is 20–360 times longer than that of commonly used microwave frequencies (e.g., 915 and 2450 MHz), allowing RF energy to penetrate foods more deeply than microwave energy. Thermal processing with RF heating is, therefore, suitable for large food trays (Wang et al., 2003c). Indeed, our previous inoculated pack studies (Luechapattanaporn et al., 2004, 2005) demonstrated that RF energy has adequate penetrations to inactivate heat resistant bacteria spores in food prepackaged in 6-lb capacity polymeric trays. We have also demonstrated with a pilot-scale RF sterilization unit that the total time for RF processing of foods in 6-lb capacity trays was reduced to one-third the time required in conventional canning processes to achieve approximately the same level of thermal sterility for bacterial spores (Wang et al., 2003c; Luechapattanaporn et al., 2005). Thus, RF thermal processes have the potential to reduce thermal quality degradation, in terms of color, texture, and flavor, in sterilized food (Luechapattanaporn et al., 2005). Further research is required to show the possibilities for a broad range of products.

Computer simulation is an effective tool for studying influence of various parameters on heating uniformity in RF heating of products. But, accurate computer simulation needs information on the dielectric properties of foods as functions of temperature and electromagnetic (EM) wave frequencies (Zhao et al., 2000; Chan et al., 2004; Wang et al., 2008a).

When the electric field intensity and frequency are fixed, differences in loss factors among the components of a heterogeneous food may result in nonuniform heating in an RF system. Preferential heating has been considered beneficial in certain applications such as post-harvest pest control and lumber drying (Zhao et al., 2000; Wang et al., 2003a; Luechapattanaporn et al., 2005), but in sterilization of pre-packaged foods, nonuniform heating should be avoided because it tends to compromise food safety and quality. Most previous experiments on RF sterilization have been conducted on homogeneous foods, such as mashed potatoes (Luechapattanaporn et al., 2004) and scrambled eggs (Luechapattanaporn et al., 2005). Macaroni and cheese is one of few heterogeneous foods reported in the literature related to RF sterilization research

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(Wang et al., 2003c), even though heterogeneous foods are more common in the food market.

The overall goal of this research was to study the feasibility of using RF heating to process a selected heterogeneous food, meat lasagna. Specific objectives were to: (1) determine the dielectric constants and loss factors of different components in meat lasagna; and to (2) investigate, via pilot-scale experimentation and computer simulation, how the different dielectric properties of the various components in meat lasagna influence its overall heating pattern.

2. Materials and methods

2.1. Materials

Dielectric properties were determined in four different main components of thawed frozen meat lasagna (Chefs Circle™, Supervalu Inc., Eden Prairie, MN, USA). These components were meatballs (about 39% total weight), grated mozzarella cheese (7%), noodles (38%) and sauce (14%). Proximate compositions of each component are presented in Table 1. The samples were kept frozen in a freezer at −18 °C and thawed at room temperature (∼20 °C) for at least 24 h before each measurement.

2.2. Dielectric properties measuring equipment and procedures

The open-ended coaxial probe method is an effective broadband measuring technique that does not require sample in a particular shape (Sheen and Woodhead, 1999). It is commonly used in the food research community for measuring the dielectric properties of liquid or semi-solid foods (Seaman and Seals, 1991; Herve et al., 1998). This method was chosen in this study to measure the dielectric properties of food samples.

The open-ended coaxial dielectric property measurement system consisted of an Agilent 4291B impedance analyzer (Agilent Technologies, Palo Alto, CA), a custom designed test cell, a VWR Model 1157 programmable temperature control circulation system (VWR Science Products, West Chester, PA), a high-temperature coaxial cable, and a dielectric probe included in the Hewlett

Table 1
Approximate composition of each ingredient in the RF-heated meat lasagna.

Ingredient	% (wb)				
	Carbohydrate	Fat	Protein	Moisture	Ash
Beef meatballs	1.3	12.7	18.0	66.9	1.0
Noodles	30.6	1.0	7.2	60.7	0.5
Cheese	6.4	15.7	15.8	59.1	3.1
Sauce	5.4	0.0	1.2	92.0	1.4

Packard 85070B dielectric probe kit. Wang et al. (2003b) provides a detailed description of the dielectric property measurement system.

A 30-min warm-up and calibration on the impedance analyzer were performed prior to each test. The sample was kept in close contact with the dielectric probe and sealed in the test cell. Each measurement was conducted at 10 °C increment from 20 to 121 °C. Type-T thermocouples for sample temperature measurement were pre-calibrated to an accuracy of ±0.5 °C. An interval of 12 min was allowed for the temperature of the sample to reach the desired 10 °C increase before every measurement. Dielectric property values were reported at 27, 40, 915 MHz which are allocated by the US Federal Communications Commission (FCC) for industrial, scientific, and medical ISM applications (Rowley, 2001). The data at 1800 MHz, the upper limit of the impedance analyzer, were also reported.

Preliminary results of the dielectric properties of mozzarella cheese showed non-reproducible data at temperatures greater than 90 °C when the samples were placed in the test cell at 20 °C and incrementally heated to the set temperature as described above. This was due to a separation of cheese serum (Metzger et al., 2000), which might have resulted in a loss of good contact between the probe and the food sample (Herve et al., 1998). A different filling method was used by preheating the test cell with a temperature-controlled liquid at 90 °C before filling with the cheese sample. Dielectric properties at 90 °C were measured right after filling, before cooling the test cell to 20 °C. Approximately, the same values (±3%) were obtained after elevating the sample temperature to 90 °C for the second time.

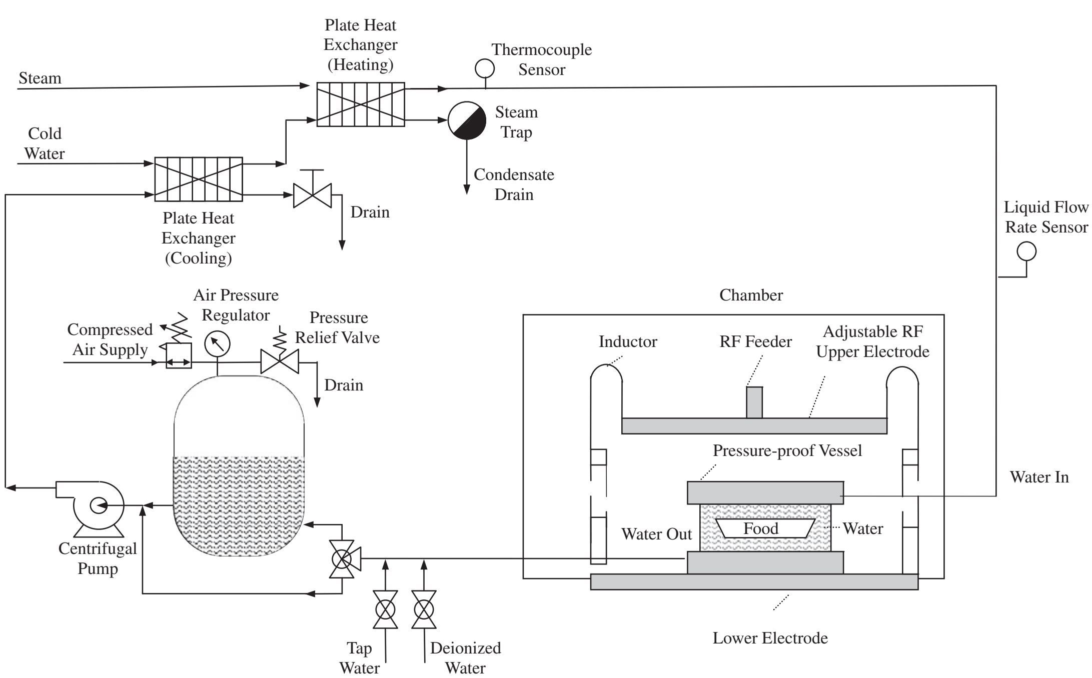

Fig. 1. Simplified schematic diagram of the RF sterilization unit with a water circulating system (Luechapattanaporn et al., 2004).

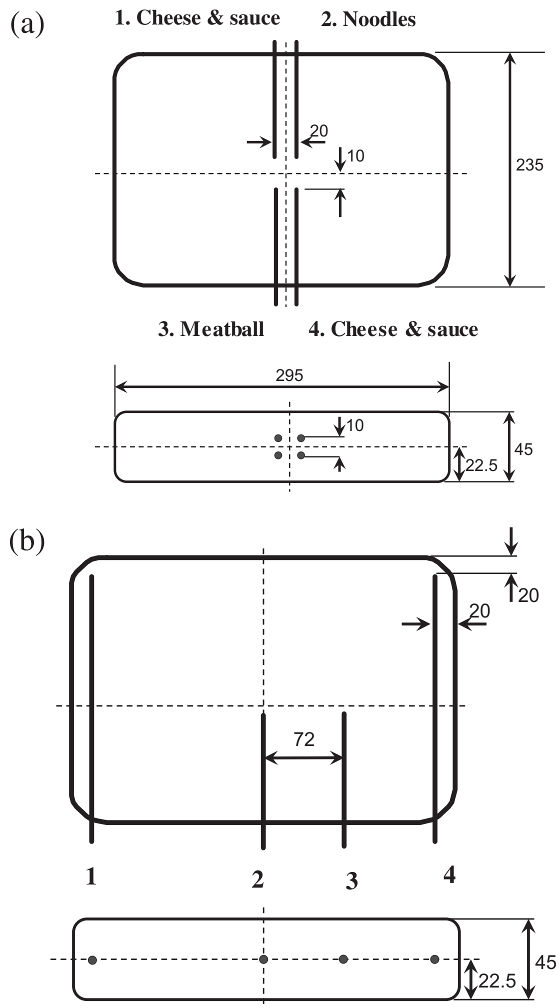

Fig. 2. Positions of fiber optic temperature probes inside polymeric trays inserted in: (a) different lasagna components: beef meatballs, noodles, mixture of cheese and sauce within close proximity; and (b) beef meatballs at different locations. Unit indicated for dimensions in the horizontal plane cross section view (above) and vertical cross section view (below) diagram is in mm (not to scale).

Power penetration depth, at which the incident power is reduced by $1/e$, or approximately 37% of its initial value, is used as an indicator to select appropriate food thickness to ensure a vertically uniform dielectric heating (Wang et al., 2003b). Power penetration depth d_p (m) can be calculated by (Buffler, 1993):

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

where c is the speed of light in a vacuum (2.998×10^8 m/s), f is frequency (Hz), ε_r' and ε_r'' are relative dielectric constant and loss factor, respectively.

2.3. RF heating of lasagna

A pilot-scale 6 kW 27 MHz RF sterilization system developed at Washington State University was used to perform the experiments. Detailed information about the RF sterilization system is described in Luechapattanaporn et al. (2004) and Wang et al. (2008a). In brief, the RF sterilization system consisted of an RF feeder, two parallel plate electrodes, four balanced inductors connected to the upper electrode, and a pressure-proof vessel in which the food package was heated (Fig. 1). The height of the top electrode was adjustable to allow appropriate coupling of RF energy into the food. The pressure vessel walls were made of polyetherimide (commonly referred to as Ultem), while the top and bottom plates of the vessel were made of aluminum with internal channels to allow water to enter and leave the pressurized chamber. Detailed design of this pressure vessel is provided in Wang et al. (2008a).

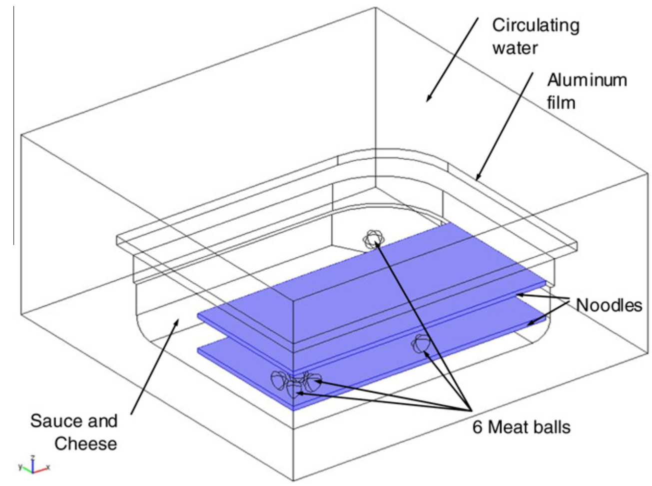

Fig. 3. Detailed geometry used in the computer simulation model for a quarter of the packaged lasagna and circulating water.

The water conditioning system consisted of a pump, a tank connected to compressed air, and two plate heat exchangers, one for heating circulation water with steam and the other for cooling with tap water. The circulation water temperature was controlled by the conditioning system to match the temperature of the heated food during RF process. The main purpose of the immersion water was to reduce the fringe effects at the interface between the food package and the air in the RF applicators (Wang et al., 2003a,b,c). Based on preliminary results, the electric conductivity of the circulation water was adjusted to 337×10^{-4} S/m at 65 °C by mixing tap water with de-ionized water.

Frozen lasagna noodles were taken from the freezer and conditioned at room temperature for 24 h to thaw before being placed in layers in 6-lb capacity polymeric combat group ration trays ($295 \times 235 \times 45$ mm). Beef meatballs (9.4 mm in diameter), grated mozzarella cheese and sauce were well mixed and then evenly distributed between each of two layers of noodles ($107.9 \times 254 \times 1.5$ mm). Trays containing about 2600 g of meat lasagna were vacuum-sealed with a 0.15 mm thick laminated PET/Nylon/Aluminum/PP film (Jefferson Smurfit, Dublin, Ireland) in a

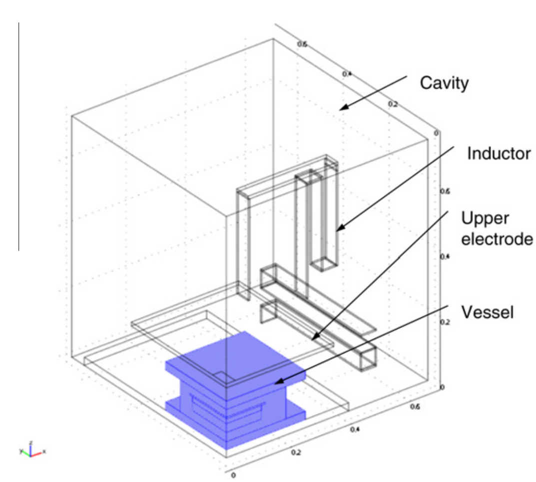

Fig. 4. Detailed geometry used in the model of a quarter of the RF heating cavity.

laboratory vacuum tray sealer (Reynolds Metals Company, Richmond, VA, USA).

The filled tray was placed in the pressure-proof vessel resting on the bottom electrode in the RF heating system. The food sample in the tray was preheated by circulation water until the core reached 65 °C. The circulation water was maintained at 65 °C for 2 h to ensure a uniform food temperature prior to RF heating in order to simulate industrial hot fill. The food was then processed with RF heating. Unlike microwave heating which does not penetrate through metal material, the laminated aluminum film as the lid for the polymeric tray severed as a floating electrode. Along with the parallel aluminum plate that formed the bottom of the pressure vessel, it supported a relatively uniform RF field inside the food (Wang et al., 2003c). Several probe ports with pressure fitting permitted the insertion of fiber optic temperature sensors directly into the food package through sealed thermal wells.

During RF processing, the gauge over-pressure in the circulation water flowing through the pressurized vessel was adjusted gradually from 34 kPa (5 psig) to 138 kPa (20 psig) to prevent bursting of packages. The flow rate of the circulation water was controlled at approximately 10 L/min. The inlet water temperature was controlled by the computer through the external heat exchanger to increase linearly with time from 65 to 120 °C. Pre-calibrated fiber optic temperature sensors (FISO technologies, Inc., Que., Canada) inserted at four different locations within the lasagna monitored temperature changes. Temperature of those four locations were recorded every second during the thermal processes.

Two different sets of experiments were conducted in which temperature was measured in: (1) different food components, namely beef meatballs, noodles, mixture of cheese and sauce, within 2 cm of each other inside a tray (Figs. 2a, and 3) the same food component (beef meatballs) at different locations inside a tray (Fig. 2b). The experiments were conducted in duplicate. The recorded temperature data were used to calculate the sterilization value (F_0) (Stumbo, 1973):

$$F_0 = \int_0^t 10^{\left(\frac{T(t)-121.1}{z}\right)} dt \tag{2}$$

where $T(t)$ is product temperature (°C), t is processing time (min), and z is 10 °C for *Clostridium botulinum* spores, which are target microorganisms in commercial thermal processing of low acid foods (pH > 4.5).

Table 2
Dielectric properties of beef meatballs (mean ± standard deviation of triplicate samples).

T (°C)		27 MHz	40 MHz	915 MHz	1800 MHz
20	ε_r'	68.8 ± 3.6	56.6 ± 2.7	41.9 ± 0.5	40.1 ± 0.7
	ε_r''	474.4 ± 9.5	323.9 ± 6.0	20.5 ± 0.7	14.3 ± 0.3
30	ε_r'	70.6 ± 3.4	57.6 ± 1.9	40.9 ± 0.2	39.3 ± 0.5
	ε_r''	561.7 ± 40.6	382.9 ± 27.1	22.7 ± 1.1	14.9 ± 0.4
40	ε_r'	72.1 ± 5.0	64.0 ± 5.5	38.7 ± 2.9	36.3 ± 3.7
	ε_r''	639.5 ± 4.3	434.7 ± 4.8	24.5 ± 0.8	16.1 ± 0.0
50	ε_r'	76.6 ± 1.3	67.5 ± 2.9	39.8 ± 2.4	37.0 ± 3.5
	ε_r''	800.9 ± 11.2	544.1 ± 8.5	29.8 ± 0.9	18.5 ± 0.0
60	ε_r'	79.1 ± 0.7	69.1 ± 1.4	39.4 ± 1.6	36.4 ± 2.8
	ε_r''	922.0 ± 10.4	625.4 ± 5.8	33.6 ± 0.2	20.2 ± 0.3
70	ε_r'	83.9 ± 5.4	72.6 ± 2.6	39.9 ± 0.7	36.8 ± 0.6
	ε_r''	1096.6 ± 120.0	743.6 ± 79.9	39.2 ± 3.2	23.0 ± 2.2
80	ε_r'	88.8 ± 9.8	75.5 ± 5.4	39.9 ± 1.9	36.6 ± 0.6
	ε_r''	1269.4 ± 229.8	860.1 ± 153.5	44.5 ± 6.3	25.5 ± 3.6
90	ε_r'	91.5 ± 11.8	76.8 ± 6.4	39.2 ± 2.0	35.8 ± 0.7
	ε_r''	1394.8 ± 262.6	944.5 ± 175.2	48.4 ± 7.2	27.5 ± 4.1
100	ε_r'	95.8 ± 14.9	79.0 ± 7.8	39.1 ± 2.1	35.4 ± 0.8
	ε_r''	1557.5 ± 296.3	1054.1 ± 197.7	53.6 ± 7.9	30.3 ± 4.3
110	ε_r'	93.4 ± 8.3	76.8 ± 3.3	36.9 ± 0.7	33.1 ± 1.9
	ε_r''	1553.9 ± 82.0	1051.8 ± 53.7	53.7 ± 1.4	30.2 ± 1.0
121	ε_r'	92.9 ± 3.4	75.7 ± 0.8	35.3 ± 2.6	31.4 ± 3.7
	ε_r''	1604.5 ± 57.3	1086.2 ± 40.2	55.4 ± 2.7	31.0 ± 1.2

Table 3
Dielectric properties of mozzarella cheese (mean ± standard deviation of triplicate samples).

T (°C)		27 MHz	40 MHz	915 MHz	1800 MHz
20	ε_r'	55.6 ± 8.8	49.4 ± 9.0	28.2 ± 6.4	25.6 ± 5.4
	ε_r''	358.5 ± 56.9	245.5 ± 39.1	17.2 ± 3.0	11.9 ± 2.0
30	ε_r'	60.5 ± 8.2	53.0 ± 8.9	29.2 ± 6.2	26.5 ± 5.4
	ε_r''	482.8 ± 57.8	329.6 ± 39.7	21.2 ± 2.7	13.8 ± 1.8
40	ε_r'	66.2 ± 6.9	57.1 ± 7.9	29.1 ± 6.8	27.3 ± 4.9
	ε_r''	621.4 ± 35.2	423.3 ± 24.8	25.6 ± 1.9	16.0 ± 1.4
50	ε_r'	70.8 ± 6.9	60.3 ± 8.2	30.2 ± 5.4	27.4 ± 4.8
	ε_r''	740.5 ± 32.2	503.9 ± 22.7	29.4 ± 1.7	17.8 ± 1.2
60	ε_r'	74.6 ± 6.8	63.0 ± 8.6	30.3 ± 5.4	27.2 ± 4.7
	ε_r''	853.6 ± 25.5	579.9 ± 18.4	30.2 ± 5.3	22.1 ± 2.3
70	ε_r'	77.5 ± 6.8	64.5 ± 8.5	30.0 ± 4.9	27.0 ± 4.6
	ε_r''	956.4 ± 19.2	650.0 ± 14.4	36.4 ± 1.3	21.5 ± 1.3
80	ε_r'	78.7 ± 9.1	64.9 ± 10.2	29.6 ± 4.9	26.6 ± 4.6
	ε_r''	1050.6 ± 58.7	713.3 ± 40.9	39.2 ± 2.7	22.9 ± 2.0
90	ε_r'	81.2 ± 8.0	66.1 ± 9.7	29.4 ± 4.9	26.2 ± 4.5
	ε_r''	1168.8 ± 41.0	792.7 ± 29.0	42.8 ± 2.0	24.8 ± 1.8
100	ε_r'	82.2 ± 6.9	66.1 ± 9.0	29.1 ± 4.8	25.8 ± 4.3
	ε_r''	1266.9 ± 28.0	858.9 ± 20.2	45.6 ± 1.5	26.3 ± 1.6
110	ε_r'	83.1 ± 5.6	65.9 ± 8.2	28.8 ± 4.5	25.8 ± 4.1
	ε_r''	1368.9 ± 32.6	927.3 ± 23.0	48.5 ± 1.6	27.8 ± 1.5
121	ε_r'	84.2 ± 2.4	65.8 ± 5.8	28.6 ± 4.0.	25.3 ± 3.6
	ε_r''	1525.1 ± 25.2	1032.2 ± 15.7	53.0 ± 0.4	30.3 ± 0.5

Table 4
Dielectric properties of noodles (mean ± standard deviation of triplicate samples).

T (°C)		27 MHz	40 MHz	915 MHz	1800 MHz
20	ε_r'	92.5 ± 0.9	84.3 ± 0.8	54.7 ± 0.1	50.9 ± 0.1
	ε_r''	516.8 ± 15.3	353.3 ± 10.1	25.5 ± 0.1	19.6 ± 0.1
30	ε_r'	92.1 ± 1.3	83.9 ± 1.1	54.4 ± 0.3	50.8 ± 0.3
	ε_r''	617.2 ± 18.9	420.4 ± 12.5	27.8 ± 0.2	19.9 ± 0.4
40	ε_r'	87.8 ± 1.5	79.9 ± 1.2	53.9 ± 0.5	50.5 ± 0.5
	ε_r''	708.5 ± 20.7	480.6 ± 13.6	29.7 ± 0.3	20.5 ± 0.0
50	ε_r'	85.6 ± 1.8	77.3 ± 1.6	53.5 ± 0.3	50.3 ± 0.3
	ε_r''	812.5 ± 26.0	550.0 ± 17.2	31.9 ± 0.4	21.2 ± 0.1
60	ε_r'	85.2 ± 1.61	76.2 ± 1.7	52.7 ± 0.1	49.6 ± 0.2
	ε_r''	943.3 ± 39.3	637.7 ± 26.5	35.2 ± 0.8	22.5 ± 0.4
70	ε_r'	85.0 ± 1.5	74.9 ± 1.6	51.8 ± 0.0	48.8 ± 0.0
	ε_r''	1084.0 ± 53.2	732.4 ± 35.6	39.0 ± 1.2	24.1 ± 0.6
80	ε_r'	84.6 ± 1.6	73.7 ± 1.4	50.8 ± 0.2	47.9 ± 0.1
	ε_r''	1228.1 ± 68.3	828.9 ± 45.7	42.7 ± 1.7	25.7 ± 0.9
90	ε_r'	84.5 ± 0.7	72.3 ± 1.1	49.8 ± 0.3	46.9 ± 0.3
	ε_r''	1367.7 ± 91.8	922.6 ± 61.3	46.5 ± 2.4	27.4 ± 1.2
100	ε_r'	85.1 ± 0.1	71.7 ± 0.6	48.7 ± 0.5	45.9 ± 0.4
	ε_r''	1496.6 ± 108.9	1009.2 ± 72.5	49.8 ± 2.9	28.9 ± 1.4
110	ε_r'	85.5 ± 0.4	70.7 ± 0.4	47.7 ± 0.5	45.0 ± 0.4
	ε_r''	1638.5 ± 125.6	1104.3 ± 83.9	53.7 ± 3.3	30.8 ± 1.7
121	ε_r'	85.9 ± 0.8	69.7 ± 0.1	46.5 ± 0.6	43.9 ± 0.5
	ε_r''	1811.7 ± 138.6	1220.2 ± 92.6	58.4 ± 3.7	33.0 ± 1.8

Theoretic sterilization value (F_0) of 3 min is adequate in commercial processing of low acid foods to ensure inactivation of *C. botulinum* for consumer safety (Frazier and Westhoff, 1988). But most food companies use a sterilization value of at least 5.0 min in order to add safety margins or to reduce chances of spoilage caused by nonpathogenic bacterial spores that are more heat resistant than *C. botulinum* spores (Teixeira, 1992). The RF sterilization process for the 6-lb capacity trays with meat lasagna was designed based on the temperature history measured by fiber optic sensors at the cold spots (the least thermally processed part of the food within a package) to reach a sterilization value (F_0) of ∼5.0 min.

2.4. Numerical model

Computer simulation was conducted to investigate the influence of various dielectric properties associated with each food component on electric field distribution and heating pattern.

Table 5
Dielectric properties of sauce (mean ± standard deviation of triplicate samples).

T (°C)		27 MHz	40 MHz	915 MHz	1800 MHz
20	ε_r'	86.2 ± 2.5	82.0 ± 3.2	79.2 ± 5.2	76.4 ± 4.2
	ε_r''	1045.3 ± 6.8	703.2 ± 4.5	38.8 ± 6.6	27.6 ± 4.6
30	ε_r'	84.9 ± 2.7	79.5 ± 3.6	76.4 ± 4.9	74.1 ± 4.1
	ε_r''	1243.8 ± 10.4	836.4 ± 6.6	43.4 ± 6.7	29.0 ± 4.9
40	ε_r'	81.5 ± 0.7	75.3 ± 2.0	71.9 ± 2.4	69.7 ± 1.6
	ε_r''	1461.8 ± 53.9	965.7 ± 13.0	48.1 ± 6.1	30.4 ± 4.3
50	ε_r'	79.1 ± 0.6	71.9 ± 1.1	67.8 ± 0.7	66.2 ± 0.1
	ε_r''	1652.4 ± 56.9	1110.5 ± 38.7	53.3 ± 5.0	32.1 ± 3.2
60	ε_r'	77.7 ± 2.6	69.0 ± 0.2	64.4 ± 0.8	63.1 ± 1.2
	ε_r''	1862.1 ± 109.7	1250.8 ± 74.0	58.4 ± 3.3	34.4 ± 2.4
70	ε_r'	79.0 ± 2.3	68.6 ± 0.2	62.6 ± 1.2	61.7 ± 1.2
	ε_r''	2150.7 ± 156.0	1446.5 ± 108.5	65.7 ± 2.2	37.6 ± 1.4
80	ε_r'	81.7 ± 0.7	69.0 ± 3.2	61.4 ± 0.4	61.0 ± 0.9
	ε_r''	2448.6 ± 80.4	1649.0 ± 54.9	74.0 ± 4.5	41.5 ± 2.4
90	ε_r'	83.3 ± 3.3	68.7 ± 5.2	59.5 ± 1.2	59.5 ± 1.9
	ε_r''	2743.2 ± 45.0	1848.3 ± 31.6	82.1 ± 5.8	45.4 ± 3.1
100	ε_r'	85.6 ± 4.8	69.0 ± 7.4	58.3 ± 3.0	57.8 ± 2.8
	ε_r''	3043.7 ± 21.3	2051.2 ± 16.2	91.1 ± 7.7	50.4 ± 4.8
110	ε_r'	87.1 ± 5.8	68.4 ± 8.9	55.8 ± 2.8	56.3 ± 3.8
	ε_r''	3333.5 ± 2.9	2247.2 ± 3.7	98.9 ± 8.3	53.8 ± 4.4
121	ε_r'	88.3 ± 7.2	67.6 ± 9.6	52.2 ± 0.9	53.0 ± 2.2
	ε_r''	3599.9 ± 34.5	2428.1 ± 18.8	106.0 ± 8.6	56.6 ± 3.5

Table 6
Regression analysis of the dielectric properties of lasagna components based on the mean values in Table 2–5 (T is temperature °C).

Meatballs	ε_r'	$=62.6 + 0.29\ T$
	ε_r''	$=198.4 + 12.6\ T$
Noodles	ε_r'	$=98.9 - 0.34\ T + 2 \times 10^{-3}\ T^2$
	ε_r''	$=203.1 + 13.0\ T$
Cheese	ε_r'	$=54.6 + 0.28\ T$
	ε_r''	$=160.6 + 11.2\ T$
Sauce	ε_r'	$=101.8 - 0.932\ T + 1.16 \times 10^{-2}\ T^2 - 4 \times 10^{-5}\ T^3$
	ε_r''	$=418.3 + 25.9\ T$

Commercial software COMSOL Multiphysics (Burlington, MA, USA) was chosen in this study because of its ability to model the electric field patterns and heat transfer through solving partial differential equations. Although other software could be used for analyzing electric field distributions in RF cavities (Chan et al., 2004), COMSOL had been used successfully for modeling RF heating of packaged foods (Wang et al., 2008a).

2.5. Assumptions

In order to accomplish an acceptable accuracy on the computer available for this simulation (Dell Precision 870 workstation, 2 Dual-Core 2.80 GHz Intel® Xeon™ Processors and 12 GB memory), several assumptions were made to simplify the heating system. First, a quasi–static analysis was assumed. Second, the flow of circulating water inside the pressure vessel and the heat transfer between circulating water and food were neglected. Third, only six meatballs and two layers of noodles were included in the model computations as shown in Fig. 3. Four meatballs were arranged at the center of the tray to investigate the electric field distribution.

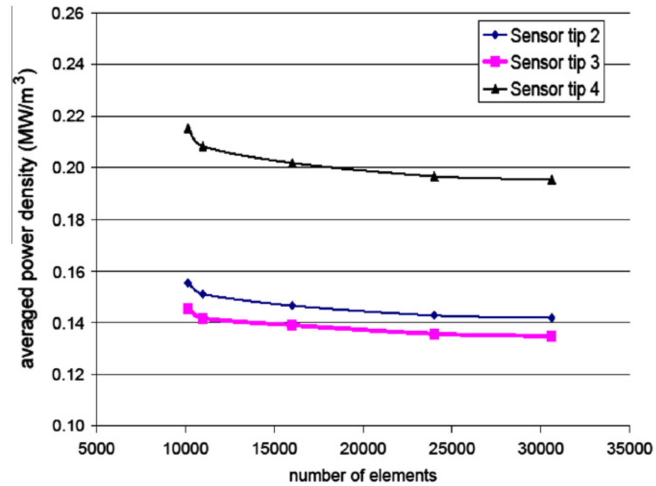

Fig. 5. Effects of the number of elements on the accuracy of the power density at sensor tips 2, 3, and 4 (Fig. 2b).

3. Governing equations

Dimensions of the food are much smaller than the wavelength in question, quasi–static analysis is appropriate. This assumption was made based on the results of Chan et al. (2004) in which no apparent heating patterns due to standing electromagnetic waves were observed in the horizontal planes (parallel to RF plate electrodes) within a model food when heated in 6-lb capacity polymeric trays in a 27.12 MHz RF cavity. In addition, in the vertical direction, the thicknesses of the layered food ingredients and the height of the tray used in the current study were much smaller than the wavelength of 27.12 MHz waves in food (∼800 mm, estimated from the free-space wave length divided by the square root of the dielectric constant of the food sample). The Laplace equation can then be deduced from Maxwell's equations as (Haus and Melcher, 1989):

$$\nabla^2 V = 0 \tag{3}$$

Calculation of the scalar electric potential, V (V) from above equation leads to the value of the corresponding electric field intensity by using:

$$E = -\nabla V \tag{4}$$

The time-averaged power density, P, was then determined by Eq. (2)

Since the time period for the electromagnetic wave at 27 MHz is less than 0.04 µSec, which is much smaller than the thermal changes, the power density can be used as a time varying quantity, $P(t)$, in the thermal problem. With time-averaged power density as the heat source in the heat transfer analysis, the electromagnetic field is coupled with the thermal field by:

$$\rho C_p \frac{\partial T}{\partial t} - \nabla(k \nabla T) = P(t) \tag{5}$$

Table 7
Summary of the thermal properties of lasagna components at 20 °C (mean ± standard deviation of triplicate samples).

	Meatballs	Noodles	Cheese	Sauce
Thermal conductivity (W/m K)	0.48 ± 0.03	0.52 ± 0.02	0.48 ± 0.01	0.51 ± 0.02
Heat capacity (kJ/kg K)	3.60 ± 0.19	3.69 ± 0.15	3.70 ± 0.05	3.73 ± 0.11
Density (kg/m^3)	1144.7 ± 26.5	977 ± 16.7	1013.2 ± 3.7	905.6 ± 10.1

Table 8
Summary of the meshing effects on the power density.

Meshing	Number of elements	Percentage (%) differences between number of elements*	Percentage (%) differences between power densities*		
			Position 2	Position 3	Position 4
1	10095				
2	10151	0.6	10.1	10.3	10.5
3	10985	8.2	2.8	2.7	3.3
4	16022	45.9	3.1	1.9	3.2
5	24019	49.9	2.6	2.5	2.6
6	30624	27.5	0.7	0.7	0.6

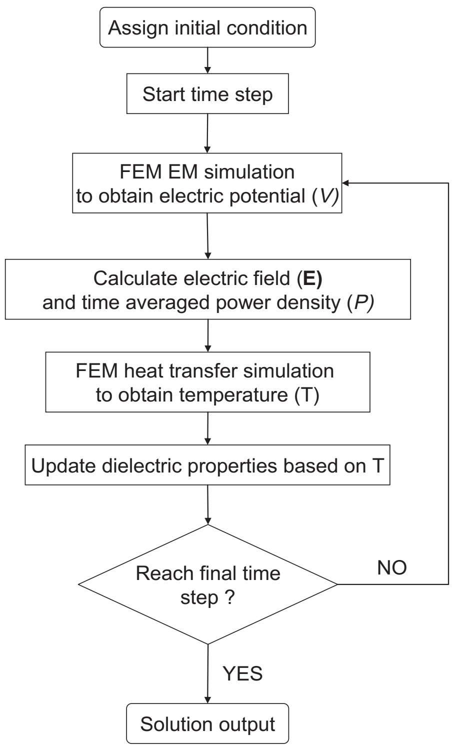

Fig. 6. Flow chart of the solution computation procedure.

where ρ is density (kg/m^3), C_p is heat (J/kg K), k is thermal conductivity (W/m K), $P(t)$ is time-averaged power density, and T is temperature (°C).

3.1. Geometry model

By using the finite element method (FEM), the COMSOL Multiphysics software modeled the quasi–static electric and heat transfer phenomena through predefined modeling templates (COMSOL, 2005). The geometry of the overall RF heating system is presented in Fig. 4.

3.2. Sub-domain and boundary condition setting

Regression analysis of mean values of the dielectric properties of the lasagna components (Tables 2–5) are summarized in Table 6. The electric conductivity value of the circulation water was set as a function of temperature according to the measured value by a model 53 conductivity analyzer (GLI International, Milwaukee, WI, USA) during a complete 30 min RF heating process expressed as:

$$\sigma = [8.797(T - 65) + 337.14] \times 10^{-4} (\mathrm{S/m}) \qquad (6)$$

Table 9
Power penetration depths of electromagnetic waves in different ingredients of lasagna.

Product	T (°C)	Power penetration depth (mm)			
		27 MHz	40 MHz	915 MHz	1800 MHz
Beef meatball	20	61.7	51.1	17.0	11.9
	30	56.1	46.5	15.2	11.3
	40	52.3	43.5	13.8	10.1
	50	46.3	38.5	11.7	9.0
	60	43.0	35.6	10.5	8.2
	70	39.2	32.5	9.2	7.3
	80	36.3	30.0	8.3	6.6
	90	34.6	28.6	7.7	6.1
	100	32.7	27.0	7.1	5.6
	110	32.7	27.0	6.9	5.5
	121.1	32.1	26.5	6.7	5.3
Cheese	20	71.3	59.5	16.8	11.6
	30	60.5	50.3	14.1	10.2
	40	52.9	43.8	11.9	9.0
	50	48.2	39.9	10.7	8.2
	60	44.7	37.0	10.4	6.7
	70	42.1	34.8	8.9	6.8
	80	40.0	33.0	8.3	6.4
	90	37.8	31.2	7.8	6.0
	100	36.3	29.9	7.4	5.6
	110	34.8	28.7	7.0	5.3
	121.1	32.9	27.1	6.5	5.0
Noodles	20	60.1	50.5	15.5	9.8
	30	54.2	45.4	14.2	9.7
	40	49.9	41.8	13.3	9.4
	50	46.2	38.6	12.4	9.0
	60	42.6	35.5	11.3	8.5
	70	39.5	32.8	10.2	7.9
	80	36.9	30.6	9.3	7.4
	90	34.8	28.9	8.6	6.9
	100	33.2	27.5	8.0	6.5
	110	31.7	26.2	7.5	6.1
	121.1	30.1	24.8	6.9	5.6
Sauce	20	40.3	33.7	12.3	8.5
	30	36.7	30.6	10.9	8.0
	40	33.6	28.2	9.6	7.4
	50	31.5	26.1	8.6	6.9
	60	29.6	24.5	7.8	6.3
	70	27.4	22.7	6.9	5.8
	80	25.7	21.2	6.3	5.2
	90	24.2	20.0	5.7	4.8
	100	23.0	18.9	5.2	4.3
	110	21.9	18.1	4.8	4.0
	121.1	21.1	17.4	4.5	3.8

where T is temperature from 65 to 120 °C. The electric potential of the aluminum cavity was set to 0, and a 5 kV electric potential (RMS at 27 MHz) was applied to the upper electrode.

In the heat transfer analysis, heat effects were only considered in the food sample domain to simplify the model. The thermal conductivity and specific heat of each of the four components of the meat lasagna at room temperature were measured with a KD2 pro thermal properties analyzer (Decagon Devices, Pullman, WA,

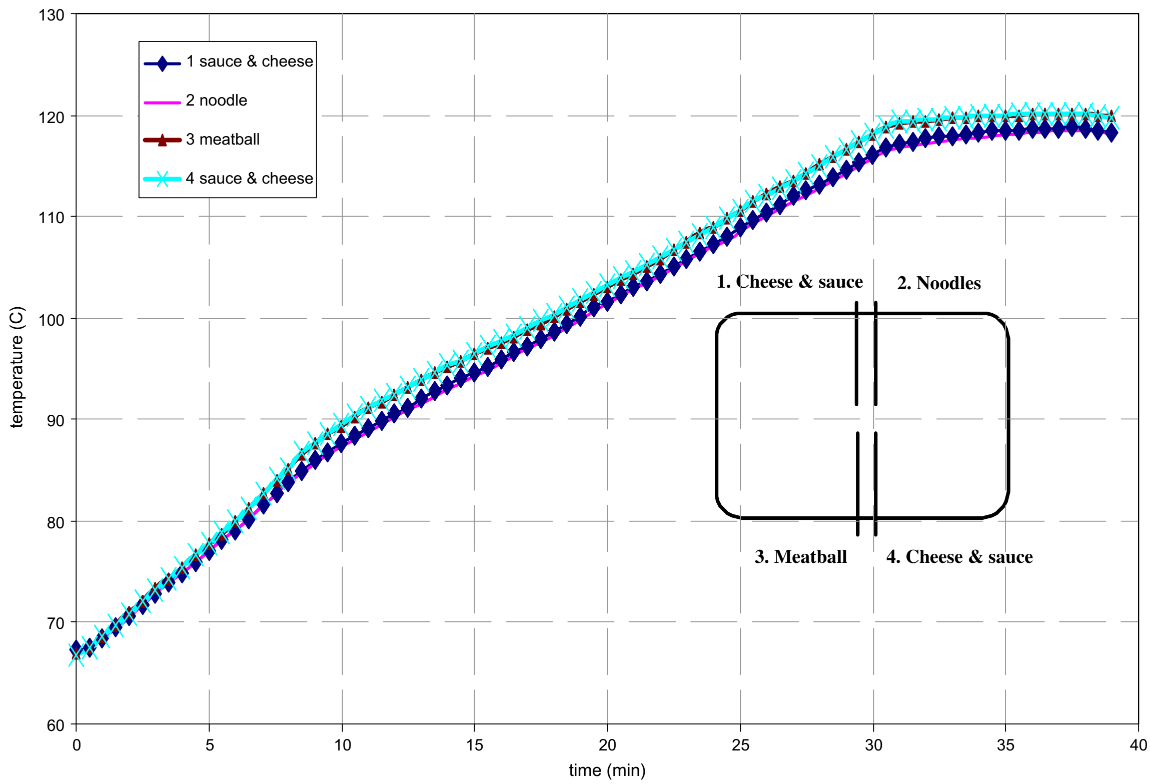

Fig. 7. Measured temperature of lasagna components inside a polymeric tray thermally processed in RF system (measurement locations shown in Fig. 2a).

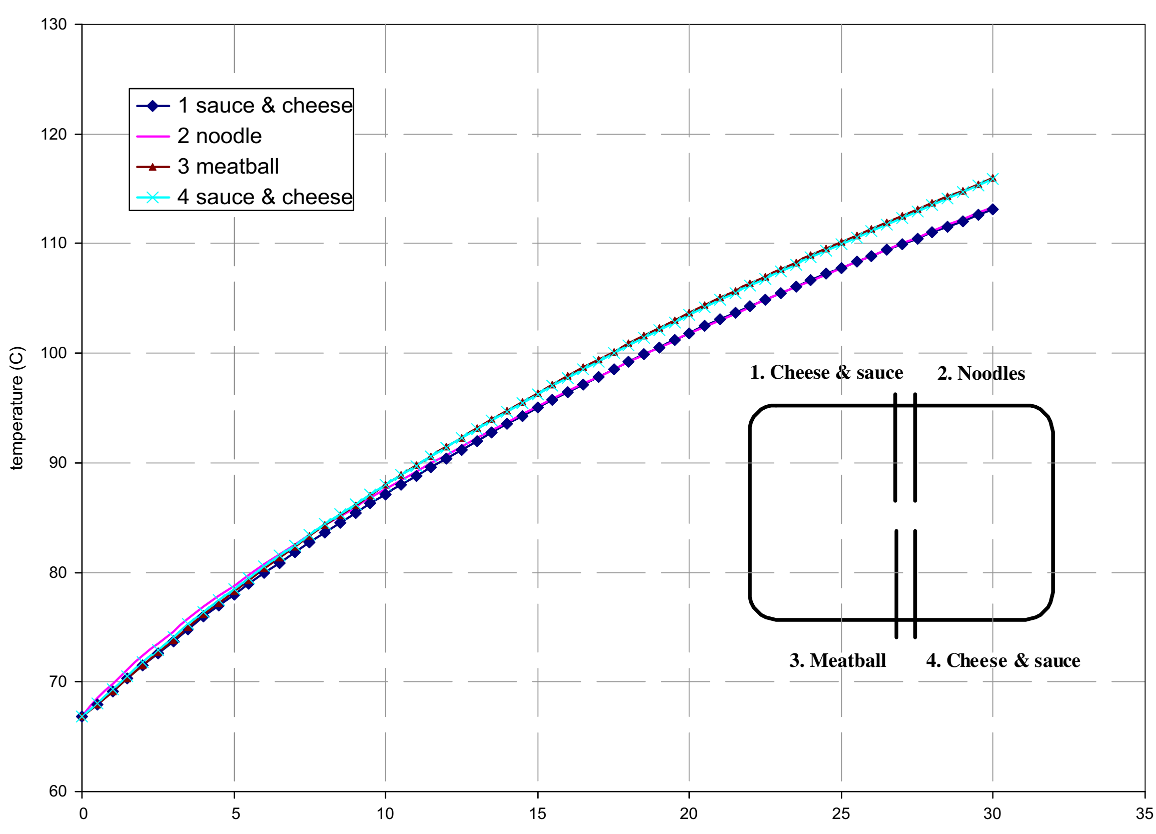

Fig. 8. Simulated temperature history for lasagna components in a polymeric tray thermally processed by RF (detailed locations shown in Fig. 2a).

USA), as shown in Table 7. The density of the components was measured by sinking the pre-weighted samples in pure Wesson canola oil (ConAgra Foods, Omaha, NE, USA) to determine the volume for calculation of the density. The measurements were conducted in triplicate and results are also presented in Table 7. To simplify the calculation, we assumed that package temperature was the same as that of the circulating water. The boundary conditions for the temperature at the surface of the sample trays were increased linearly with time from 65 to 120 °C in 30 min.

3.3. Convergence study for RF power density

Preliminary simulations were performed to obtain an appropriate meshing density and element number. The typical geometric shape of the elements is tetrahedral with various sizes, which are determined by software to maintain a balance between accuracy and computation efficiency. The power density at fiber optic sensor tips of 2, 3, and 4 (as shown in Fig. 2b) were used to test the convergence of the simulation. As presented in Fig. 5, with an increase in number of elements, the power density at the three sensor tips was stabilized. When the number of elements reached 30,624 (Table 8), there was not more than 0.7% difference in the power density for a 27.5% increase in number of the elements (from 24,019 to 30, 624), indicating that the 30,624 was a reasonable element number for simulation.

The time step of the simulation was automatically selected by the simulation software to optimize the simulation process while maintaining calculation accuracy. In our model, it took 4–5 h for one simulation run.

3.4. Solution computation

Procedures for obtaining the simulation solutions for complete RF heating processes are shown in Fig. 6. The same procedures were used by Wang et al. (2008a). The initial condition was assigned to the model at the start of the computation. The electric potential and electric field distribution were calculated which in turn led to a value of power density based on the properties of the materials. Then the heat generation and transfer were determined. The temperature-dependent dielectric property values were updated for elements of packaged lasagna and circulation water. The time-varied temperature and electric conductivity of circulation water were also renewed. The updated variables were applied to the model, and iterations continued until the final time step was reached.

4. Results and discussion

4.1. Dielectric properties

Dielectric properties of beef meatball, mozzarella cheese, noodles, and sauce are summarized in Tables 2–5, respectively.

Dielectric constant (ε_r') of beef meatballs (Table 2) increased steadily as the temperature increased at the two RF frequencies (27 and 40 MHz) until 100 °C, while it decreased with increasing temperature at the two microwave frequencies in particular 1800 MHz. Similar trends were observed in the dielectric properties of salmon fillets (Wang et al., 2008b). Protein denaturation at high temperature leads to a release of water and shrinkage, which is believed to cause significant changes in the dielectric properties of beef (Nelson and Datta, 2001). Three main types of proteins (actin, collagen and myosin) in beef denature at different temperatures. The denaturation is most likely accompanied by the release of water and other components. The dielectric constant for mozzarella cheese is summarized in Table 3. Values of ε_r' increased with temperature at the two RF frequencies but remained relatively stable at the two microwave frequencies. The decrease in ε_r' of mozzarella cheese with increasing frequency at a given temperature agrees with the results reported by Green (1997) for cheddar cheese and by Herve et al. (1998) for low fat (<2%) cottage cheese. Values of ε_r' of noodles (Table 4) slightly decreased at all frequencies between 40 and 121 °C. Values of ε_r' of sauce (Table 5) decreased with increasing temperature at 40, 915, and 1800 MHz. A slight increase of the values at 27 MHz was observed as temperature increased to greater than 60 °C.

Relative loss factors (ε_r'') of beef meatballs (Table 2), mozzarella cheese (Table 3), noodles (Table 4) and sauce (Table 5) increased 3–5-fold at 27 and 40 MHz as temperature increased from 20 to 121 °C, whereas the values of ε_r'' increased approximately 2–3-fold at 915 and 1800 MHz for the same temperature rise. The relative loss factor of sauce was about two times as much as the other food components for all frequencies. Based on Eq. (2), and assuming the same electric field intensity, one would then anticipate much higher temperature increases in sauce during the RF processing compared to the other food components, leading to possible localized thermal runaway.

The observed trends in the sharp increases in loss factors for the tested food components with increasing temperature at the two RF frequencies agree with the trends reported in the components of macaroni and cheese by Wang et al. (2003b). Within the RF and microwave range of interest in our study, two main elements contribute to the value of the loss factor (Mudgett, 1986):

$$\varepsilon'' = \varepsilon_d'' + \varepsilon_\sigma'' \quad (7)$$

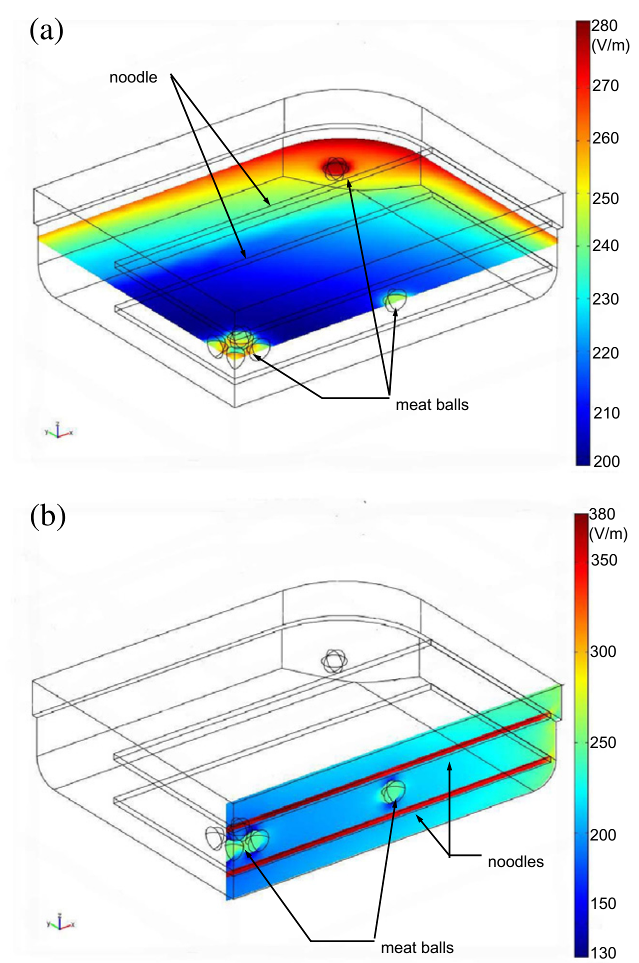

Fig. 9. Simulated Eelectric field distribution at (a) plane 1 and (b) plane 2.

where the dipole loss component (ε''_d) is influenced by dipole rotation mainly of water molecules. The ionic loss component, ε''_σ, results from electric conductivity of dissolved salt. The larger measured loss factors for sauce suggested higher ionic conductivity in this lasagna component as compared to noodles, cheese and meatballs.

The ionic loss component plays a significant role in dissipating electromagnetic fields at radio frequencies (Guan et al., 2004), and ionic conductivity increases sharply with increasing temperature (Barber, 1983; Decareau, 1985; Tang et al., 2002; Guan et al., 2004). As a result, the loss factors of beef meatball, mozzarella cheese, noodles, and sauce increased sharply as temperature increased at 27 and 40 MHz.

4.2. Power penetration depth and RF heating uniformity

Power penetration depths in beef meatball, mozzarella cheese, noodles, and sauce decreased by approximately 50% as temperature increased from 20 to 120 °C at all frequencies (Table 9). At each temperature, the penetration depth at RF frequencies (27 and 40 MHz) was much greater than that of microwave frequencies (915 MHz). For a given frequency, the larger the loss factor, the smaller the penetration depth. For example, power penetration depth at 27 MHz in beef meatball, mozzarella cheese, and noodles were 30–33 mm at 121 °C. The value for sauce was 21 mm at 121 °C. This is half the depth of the 6-lb polymeric trays.

4.3. RF heating experimental and computer simulation results

Measured temperature data in four different food components in close proximity (Fig. 2a) within a tray during RF heating is shown in Fig. 7. The greatest temperature difference among the beef meatballs, mozzarella cheese, noodles, and sauce within 2 cm of each other was not more than 2 °C over 30 min RF heating. The anticipated thermal runway, namely, increasingly higher heating rate caused by higher loss factor at elevated temperatures, did not occur in sauce. Computer simulation results for the same heating conditions as used in the experiment are shown in Fig. 8 with a 4 °C difference between sauce/cheese and the meatball at the end of the 30 min RF heating. Both experimental and simulation results indicate that differential heating in food components with vastly different loss factors, in particular at elevated temperatures, did not occur when they were in close proximity.

The computer simulation model was used to provide an insight into why there was no apparent overheating for the food components with high loss factors in a heterogeneous food. The simulation was checked at two planes. The results revealed that electric field intensity was relatively low in the sauce (between two layers of noodles) and high in the noodles (Fig. 9). Dielectrically, the only main difference between the two components was the much higher relative loss factor of sauce (Tables 4 and 5). Wang et al. (2008a) also demonstrated experimentally and using computer simulation that the electric field intensity in mashed potato with 1.3% salt is

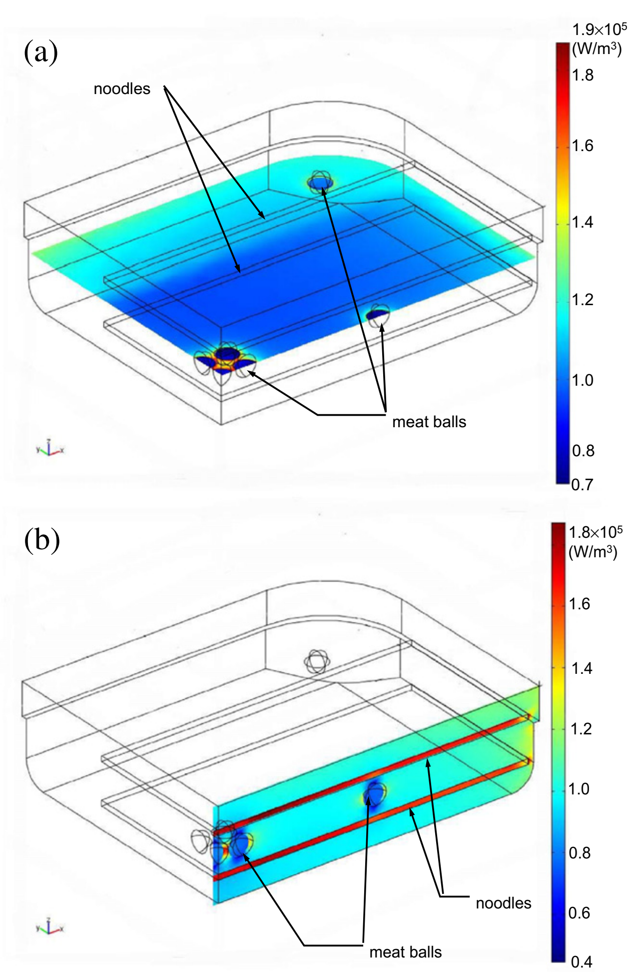

Fig. 10. Simulated Power density distribution at (a) plane 1 and (b) plane 2.

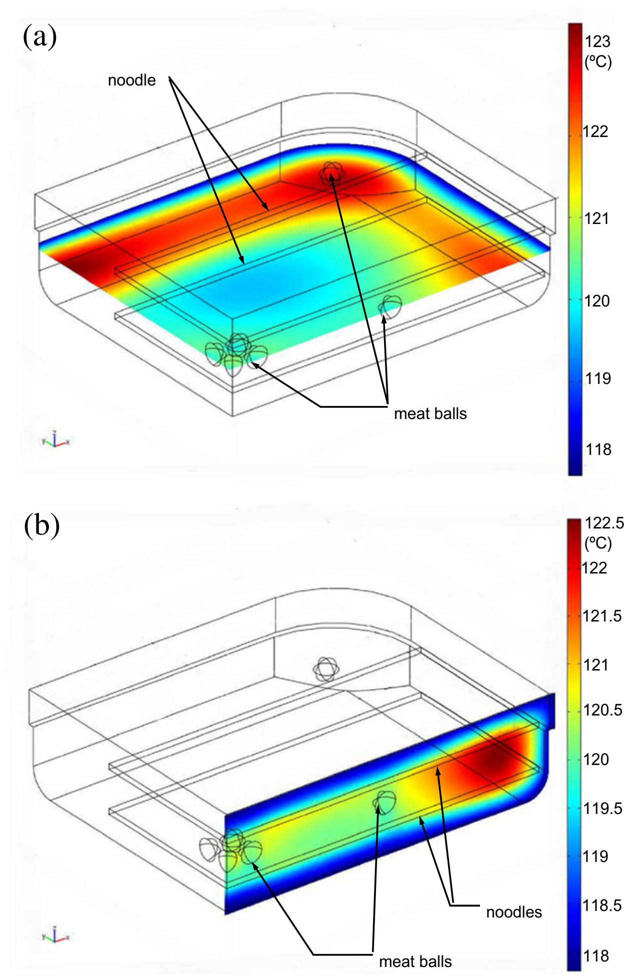

Fig. 11. Simulated temperature distribution at (a) plane 1 and (b) plane 2 (Fig. 9).

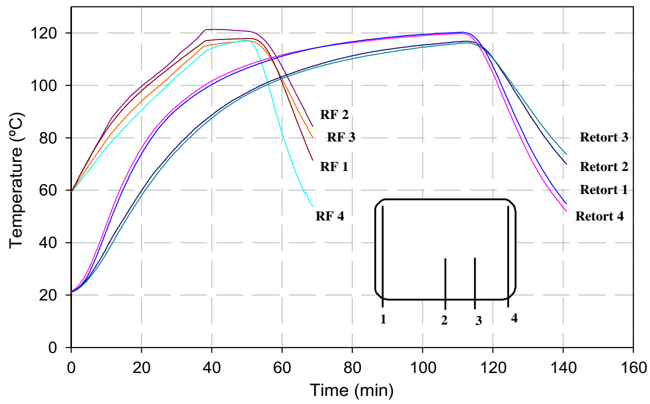

Fig. 12. Comparison of the temperature–time profile of beef meatballs at different locations inside a polymeric tray thermally processed by RF and retort heating. The sensors positions are shown in Fig. 2b.

less than that of mashed potato containing 0.8% salt under the same test conditions in 27.12 MHz RF cavities. Based on Eq. (2), the relatively low electric field intensity in sauce prevented it from overheating among other ingredients in spite of its twice as great relative loss factor.

The electric field was concentrated near the tray corners, caused mainly by the fringe effect of RF field due to the difference between the dielectric properties of the food sample and circulation water outside the food package. Simulated power density was relatively high near tray corners and in noodles as compared to the rest of the food (Fig. 10).

Similar temperature patterns were predicted in computer simulation (Fig. 11). But the temperature variations (<2 °C) among different food components in close proximity, in particular between sauces other food components, is much smaller than one would anticipate judging only from the large differences in their loss factors (Tables 2–5). We believe that sufficient heat transfer took place between the sauce, noodles, cheese, and beef to help mitigate the power density variations.

The temperature histories of the beef meatballs at four different locations as shown in Fig. 2b within a tray were obtained in experiments with RF and from a conventional thermal process (Fig. 12). This conventional process was conducted with the same RF sterilization system by circulating hot water at 121 °C over food packages in the pressurized vessel without turning on RF power. During the RF heating, the greatest temperature difference among the four different locations was less than 5 °C. The time for the sample core to arise from 60 to 121 °C with RF energy was 35 min compared to 110 min with a conventional thermal process. As shown in Fig. 12, in a conventional thermal process, the foods close to the container walls (points 1 and 4) were exposed to temperatures above 100 °C for more than 80 min, as compared to 40 min in RF processing. Similar differences in processing times between conventional thermal processes and RF processing in the same size containers have been reported for mashed potatoes (Luechapattanaporn et al., 2004), scrambled eggs (Luechapattanaporn et al., 2005) and Macaroni and cheese (Wang et al., 2003c). The shortened exposure times of food to high temperatures in RF processing significantly reduced thermal degradation in those early studies.

The greatest temperature difference among the meatballs (shown in Fig. 12) as calculated by computer simulation during an RF process was 5 °C. The hottest parts of the food were at the corners of the trays (Fig. 11a). However, according to Fig. 12, the experiment exhibited center heating (i.e. the highest temperature occurred at the center of the food package). Three reasons might have contributed to the disagreement between the experiment and simulation. First, the simplification of the boundary conditions at the interface between food and circulating water underestimated the cooling effect of the circulating water to the food surface and corners. Second, the linear regression analysis applied to represent the relationship between the dielectric properties of the food components and their temperatures was based on the mean values of the measurement results, which inevitably included measurement errors. Nevertheless, the simulation results did provide an insight into the reason why highly anticipated thermal run away in sauce did not occur during RF sterilization of meat lasagna product used in this study.

5. Conclusions

The computer simulation revealed that different dielectric properties of components in heterogeneous foods caused large variations in electric field and dissipated energy in different food components. Results from pilot plant testing at 27.12 MHz and computer simulation indicated that the vastly different temperature dependent loss factors among different food components at 27.12 MHz did not cause major nonuniform heating inside heterogeneous foods, such as lasagna that contains beef meatballs, mozzarella cheese, noodles, and sauce, when different food components are evenly dispersed in close proximity. Reduced electric field intensity in sauce with much higher loss factor compared to the other food components prevented it from being over heated. The distribution, shape, size, and especially heat transfer ability of the food components should have important influences on the heating uniformity.

The results from this study show that RF heating has a potential to produce safe, high quality pre-packaged heterogeneous food. RF heating has advantages over retort heating when processing semi-solid food because of short heat-up times and relatively uniform temperature distribution, resulting in less degraded food products. Proper distribution and suitable amounts and sizes of each component, though with vastly different dielectric properties, can provide relatively uniform RF heating.

In spite of the encouraging results, we believe it remains a major engineering challenge to scale an RF sterilization system as described in this study for industrial applications, due to the complicated design requirements and need for precise control of circulation water temperature to reduce RF fringe effects on heating uniformity in food. Absorption of RF energy by the circulation water also reduces the effective use of RF energy.

Acknowledgments

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References

Barber, H., 1983. Electroheat. Sheridan House, Inc., Dobbs Ferry, New York, NY, USA.
Buffler, C.R., 1993. Microwave Cooking and Processing. Van Nostrand Reinhold. New York, NY, USA.
Chan, T.V., Tang, J., Younce, F., 2004. "3-dimensional numerical modelling of an industrial radio frequency heating system using finite elements". Journal of Microwave Power and Electromagnetic Energy 39 (2), 87–105.
COMSOL, 2005. Electromagnetics Module User's Guide. COMSOL Multiphysics, Burlington, MA, USA.
Decareau, R.V.,1985. Microwaves in the Food Processing Industry. Academic Press, Orlando, FL, USA.
Frazier, W.C., Westhoff, D.C., 1988. Food Microbiology. McGraw-Hill, New York, NY, USA.
Green, A.D., 1997. Measurements of the dielectric properties of cheddar cheese. Journal of Microwave Power and Electromagnetic Energy 32 (1), 16–27.

Guan, D., Cheng, M., Wang, Y., Tang, J., 2004. Dielectric properties of mashed potatoes relevant to microwave and radio-frequency pasteurization and sterilization processes. Journal of Food Science. 69 (1), E30–E37.

Herve, A.G., Tang, J., Luedechke, L., Feng, H., 1998. Dielectric properties of cottage cheese and surface treatment using microwaves. Journal of Food Engineering 37 (4), 389–410.

Haus, H. A. and Melcher, J. R., 1989. Electromagnetic Fields and Energy. Prentice Hall, Englewood Cliffs, NJ, USA

Luechapattanaporn, K., Wang, Y., Wang, J., Al-Holy, M., Kang, D.H., Tang, J., Hallberg, L.M., 2004. Microbial safety in radio-frequency processing of packaged foods. Journal of Food Science 69 (7), 201–206.

Luechapattanaporn, K., Wang, Y.F., Wang, J., Tang, J.M., Hallberg, L.M., Dunne, C.P., 2005. Sterilization of scrambled eggs in military polymeric trays by radio frequency energy. Journal of Food Science 70 (4), 288–294.

Metzger, L.E., Barbano, D.M., Rudan, M.A., Kindstedt, P.S., Guo, M.R., 2000. Whiteness change during heating and cooling of mozzarella cheese. Journal of Dairy Science. 83 (1), 1–10.

Mudgett, R.E., 1986. Electrical properties of foods. In: Mao, A., Rizvi, S.S.H. (Eds.), Engineering Properties of Food. Marcel Dekker, New York, NY, USA, pp. 329–390.

Nelson, S.O., Datta, A.K., 2001. Dielectric properties of food materials and electric field interactions. In: Datta, A.K., Anantheswaran, R.C. (Eds.), Handbook of Microwave Technology for Food Applications. Marcel Dekker, New York, NY, USA, pp. 69–114.

Rowley, A.T., 2001. Radio frequency heating. In: Richardson, P. (Ed.), Thermal Technologies in Food Processing. Cambridge, England, Woodhead Publishing. pp. 163–177.

Seaman, R., Seals, J., 1991. Fruit pulp and skin dielectric properties for 150 MHz to 6400 MHz. Journal of Microwave Power and Electromagnetic Energy 26, 72–81.

Sheen, N., Woodhead, I., 1999. An open-ended coaxial probe for broad-band permittivity measurement of agricultural products. Journal of Agricultural Engineering Research 74, 193–203.

Stumbo, C.R., 1973. Thermobacteriology in Food Processing. Academic Press, New York, NY, USA.

Tang, J., Feng, H., Lau, M., 2002. Microwave heating in food processing. In: Young, X., Tang, J. (Eds.), Advances in Bioprocessing Engineering. World Scientific Publishing, New Jersey, pp. 1–44.

Teixeira, A., 1992. Thermal process calculation. In: Heldman, D.R., Lund, D.B. (Eds.), Handbook of Food Engineering. Marcel Dekker, New York, NY, USA, pp. 563–619.

Wang, S., Tang, J., Cavalieri, R.P., Davis, D.C., 2003a. Differential heating of insects in dried nuts and fruits associated with radio frequency and microwave treatments. Transactions of the ASAE. 46 (4), 1175–1182.

Wang, Y., Wig, T., Tang, J., Hallberg, L., 2003b. Dielectric properties of foods relevant to RF and microwave pasteurization and sterilization. Journal of Food Engineering 57 (3), 257–268.

Wang, Y., Wig, T.D., Tang, J., Hallberg, L.M., 2003c. Sterilization of foodstuffs using radio frequency heating. Journal of Food Science 68 (2), 539–544.

Wang, J., Tang, Z., Olsen, B., Tang, J., 2008a. Influence of mashed potato dielectric properties and circulation water electric conductivity on radio frequency heating. Journal of Microwave Power and Electromagnetic Energy 42 (2), 31–46.

Wang, Y., Tang, J., Rasco, B., Kang, F.B., Wang, S., 2008b. Dielectric properties of salmon fillets as a function of temperature and composition. Journal of Food Engineering 87, 236–246.

Zhao, Y., Flugstad, B., Kolbe, E., Park, J.W., Wells, J.H., 2000. Using capacitive (radio frequency) dielectric heating in food processing and preservation – a review. Journal of Food Process Engineering 23, 25–55.