**Development of a dual cylindrical microwave and ohmic combination heater
for minimization of thermal lags in the processing of particulate foods**

Seung Hyun Lee^a, Won Choi^a, Chong-Tai Kim^b, Soojin Jun^{a*}

Article Notes:

The authors are Seung Hyun Lee, Assistant Professor, ^aDepartment of Biosystems Machinery Engineering, Chungnam National University, 220 Gung-Dong, Yuseong-Gu, Daejeon, 305-764, South Korea;

Won Choi, Postdoctoral Researcher, ^aDepartment of Human Nutrition, Food and Animal Sciences, University of Hawaii, 1955 East West Road, Honolulu, HI 96822, USA;

Chong-Tai Kim, ^bKorea Food Research Institute, 1201-62 Anyangpangyo-ro, Bundang-gu, Seongnam-si, Gyeonggi-do, 463-746, South Korea;

Soojin Jun, Associate Professor, ^aDepartment of Human Nutrition, Food and Animal Sciences, University of Hawaii, Honolulu, HI 96822, USA

Corresponding author: Dr. Soojin Jun, University of Hawaii, 1955 East West Rd.,

Honolulu, HI 96822; voice (808) 956-8283; fax: (808) 956-4026; email: soojin@hawaii.edu

Abstract

Dual cylindrical microwave chambers equipped with ohmic heating tubes were designed to maximize the electric field strength for thermal treatment of particulate foods. Temperature profiles of particle-liquid mixtures containing sodium chloride solution (C_s , 5~ 20 g/L), chicken, and potato particulates at different mass fractions (M_f , 10 - 15 g/100g) were collected and compared for individual and combination heating modes. Results indicated that particle size (S_p , 0.5 and 1 cm cubes) and salt concentration affected temperature variations between solution and particulates in ohmic heating. For microwave heating, the solution temperature lagged behind the particle temperature up to 12.5 g/L salt concentrations, regardless of particle size and mass fraction; however, an opposite tendency was observed in the food mixtures including 20 g/L salt concentration. The maximum temperature differences between particles and solution obtained by individual microwave and ohmic heating were 7.1 ± 1.7 and 11.9 ± 2.9 °C, respectively, while the combination heating exhibited little significant temperature gaps (maximum difference < 3.08 °C) at 12.5 g/L salt concentrations. 3D block diagrams constructed using the controllable ranges of C_s , S_p , and M_f estimated by empirical equations could be used to describe temperature similarities between particles and solution when the combination heating was applied.

Keywords: Multiphase food, Thermal uniformity, Microwave, Ohmic heating, Simultaneous combination

1. Introduction

The minimally processed food products that retain fresher and nutritional quality have received great attention from customers recently. Conventional cooking approach for particulate foods requires long processing time and several procedures to achieve even temperature distribution in particulate foods because it depends upon convective and conductive heat transfer from heating source to food particles (Nguyen et al., 2013). Furthermore, it frequently causes serious quality deterioration in terms of nutritional and functional properties of foods due to excessive thermal treatment time (Singhal et al., 2011). The research on new food processing technologies has advanced much to satisfy the increasing demands from customer, and find out the alternatives to conventional methods. When solid-liquid mixture foods are aseptically processed, non-uniform temperature distribution in solid-liquid mixture foods would cause the danger of under-processing that is associated with food safety concern (Shim et al., 2010). One of the feasible solutions to reduce the temperature variation between solid and liquid phases with rapidity and quality maintenance is an application of advanced volumetric heating methods such as microwave and ohmic heating (Choi et al., 2011).

Ohmic heating involving the internal heat generation by applying alternating current through a food product has been applied to various food processing such as extraction and pasteurization since it provides constant heating rate for single solid or liquid phase food with high energy transfer efficiency (Leizerson & Shimoni, 2005; Icier & Ilcali, 2005; Shim et al., 2010). However, several studies for the thermal behaviors of multiphase foods under ohmic heating showed that the heating rate of solid particles lagged behind liquid having a higher electrical conductivity, and arbitrary temperature distribution in multiphase foods were often reported (Salengke & Sastry, 2007; Sarang et al., 2008; Shim et al., 2010). Therefore, the ohmic

heating process for multiphase foods required pre-estimation of electrical conductivities of solid and liquid phases (Zareifard et al., 2003). The pretreatment step in ohmic heating processing such as blanching or salt infusion process could improve the heating rate of multiphase foods by equilibrating electrical conductivities of solid and liquid phases; however, it is time consuming and requires additional energy (Shim et al., 2010).

Microwave heating has been used to heat up "ready to eat" foods because microwaves heat foods in a rapid and direct manner (Hossan et al., 2010). Since microwave heating has complete interaction with polar water molecules and charged ions within food, volumetric heating can be produced by friction energy (Wang et al., 2009). Microwave heating was effective for reduction of come-up-times and was less sensitive to food heterogeneities (Coronel et al., 2003). However, a major problem associated with microwave heating was localized heat zones related with the variation in dielectric, physical, and thermal properties of food components (Pitchai et al., 2012). In order to overcome the outstanding issues, a new microwave system consisting of 915 MHz, 10 kW microwave power generator and single mode cavity, was developed for sterilization of packaged foods (Tang et al., 2008). Although heating uniformity in packaged inhomogeneous foods was improved, cold spots that were not sufficiently treated by microwave propagation were observed at the front and rear edges of sample trays (Tang et al., 2008). Microwave heating assisted with conventional heating methods, such as vacuum and microwave absorbents was advantageous to diminish localized heat zones in foods (Goksoy et al., 1999; Xu et al., 2004). However, the aforementioned microwave combination methods required the specific conditions for processing and relied on physical and chemical properties of targeted foods.

A simultaneous microwave and ohmic combination heater, coupled with a polytetrafluoroethylene (PTFE) ohmic tube with two electrodes at opposing ends fed through the center of a rectangular microwave chamber, was exploited to achieve uniform heating for multiphase foods (Nguyen et al., 2013). It was validated that solid particles and liquid were simultaneously heat treated via electromagnetic wave and electrical current, thus improving thermal treatment of multiphase foods without leaving solid particles under-processed. However, only limited microwave energy was transmitted to multiphase foods in a PTFE tube due to scattered field strength in multi-mode. For enhanced energy efficiency and precise process control, single mode microwave cavity with one standing wave at the source frequency has been utilized to heat treat food products having a limited volume and low dielectric properties (Asmussen et al., 1987). A continuous flow microwave heater occupied with a single mode elliptical resonant cavity was effectively functional for aseptically packaged vegetable purees (Coronel et al., 2005).

Therefore, a cylindrical microwave cavity was introduced as an alternative in this study to deliver maximum microwave energy to multiphase foods that were composed of two different particulate foods (chicken and potato in various sizes and mixing ratios) and carrier medium. The objectives of this study were (a) to explore the heating patterns of multiphase foods using the designed combination heater, and (b) to optimize the effect of the combination heating by tuning operation parameters.

2. Materials and Methods

2.1 Analyses of electric field strength under microwave and ohmic heating

Prior to fabrication of the developed hybrid combination heater, the electric field distribution in the heater were analyzed using COMSOL Multiphysics software (COMSOL 3.5, COMSOL, Inc., Palo Alto, CA) including various modules for specific applications. To obtain desired electric field distributions at the central axis of the chamber, the optimum dimensions of dual microwave chambers were numerically simulated. Electromagnetic field generated from a magnetron was determined using electromagnetic waves module with generalized minimal residual methods (GMRES). A conductive media DC module with parallel direct sparse solver (PARDISO) was used to simulate electric field distribution in the ohmic heating unit. The distribution of electric field under microwave and ohmic heating was analyzed in stationary state by filling water in the domain of a PTFE applicator. Dielectric properties (ϵ) and electrical conductivity (σ) of water built in COMSOL Multiphysics software were $77.54 + 8.87i$ and 0.05 S/m, respectively.

2.2 Design of microwave and ohmic combination heater

Dual cylindrical microwave heating chambers were designed and fabricated to concentrate and resonate the electric field strengths from ohmic and microwave power sources (Fig. 1 (a)). The chamber had two ports connected to waveguides (modified WR-430) that were built with nickel-coated brass and 5 towers for stub matching of microwave. Two magnetrons (2450 MHz; Model OM75S, Samsung) which could deliver up to 900 W each were mounted on the end of each waveguide (Fig. 1 (b) and (c)). One PTFE (outer diameter (OD) of 0.038 m and inner diameter (ID) of 0.025 m, Virgin electrical grade Teflon[®] PTFE, Santa Fe Springs, CA)

ohmic tube installed through the cavity was transparent to microwave, hence yielding negligible dielectric heating. Two titanium ring-shaped electrodes (0.025 m in length, OD 0.032 m, and ID 0.025 m) were placed at both ends of the ohmic heating tube with a gap of 0.17 m (Fig. 1 (d)). Electrodes were connected to a power supply based on an integrated-gate-bipolar-transistor (IGBT, SKYPER™, SEMIKRON Inc., Hudson, NH) to generate alternating pulsed waveform with the maximum frequency of 20 kHz, on/off duty cycle of 0.2, and a max current of 100 Amps.

2.3 Particle and liquid mixtures preparation

The particle sizes and the concentrations of sodium chloride and carboxymethyl cellulose (CMC) solutions in particle-liquid mixtures were imitated to be similar to commercialized canned chunky soup products. Chicken breast and potato purchased from a local market were used as chunky foods and cut into two fixed size cubes (0.5 and 1 cm in length). A base solution was prepared with 15 g/L CMC (Pre-Hydrated CMC 6000, TICGUM, White Marsh, MD) solution and NaCl solution (Morton Salt, Chicago, IL) with different concentrations (5, 12.5, and 20, g/L), and then evenly mixed with particle cubes. Base solutions at three different salt concentrations were used to test the capability of the combination heating technology on minimization of temperature gap between solid particles and solution. The solution with 15 g/L CMC concentration was suitable for the sine pump (MR 125, Waston-Marlow, Wilmington, MA) (Nguyen et al., 2013). Solid mass fractions in total volume of the mixtures were fixed at 10 and 15 g/100g. The volume of the microwave and ohmic heating applicator (PTFE tube) was 86.1 mL. When our model food mixture passed through the PTFE tube in the developed alignment, approximately 6 and 10 pieces of chicken breast and potato (1 cm³ cubes) in 15 g/100g mass

fraction could be simultaneously treated by microwave and ohmic combination heating in a given treatment time. Based on our hands-on experience, the selected solid concentrations are sufficient for validation of the effect of the combination heating technology on the heating uniformity. Further increase above mass fraction of 15 g/100g frequently caused the current PTFE tube to be clogged.

2.4 Electrical conductivities and dielectric properties of food samples

The electrical conductivities of foods are the linear function of temperature and can be estimated by the following equation (Sarang *et al.*, 2008);

$$\sigma = \frac{I}{V} \cdot \frac{L}{A} \quad (1)$$

where V is the applied voltage (V), σ is the electrical conductivity (S/m), I is the current (A), L is the distance between the electrodes (m), and A is the contact area (m²).

For measuring electrical conductivities of samples, solid food samples (potato and chicken breast) were cut into cylindrical shape of 25.4 mm in diameter and 10 mm in height. Each sample was placed in PVC cylinder-shaped ohmic cell (25.4 mm in diameter and 60 mm in height) and was sandwiched between two electrodes. Then, a thermocouple (K-type KK-K-30, Omega Engineering Inc., Stamford, CT) was inserted at the center of sample via a small hole in the chamber surface. Electrical conductivities of base solutions with different salt concentrations were measured using the same procedure. A RMS voltage of 30V at the frequency of 20 kHz, with duty cycle of 0.2 was applied for the measurement. All data points of temperature, voltage, and current were recorded and monitored by a data logger (Agilent 34970A, Agilent Technologies, Santa Clara, CA).

Dielectric properties of base solutions with different salt concentrations were measured using a vector network analyzer coupled with a dielectric probe kit (85070E, Agilent Technologies, Santa Clara, CA) at the frequency of 2.45 GHz. During measurement, the base solution was filled in a 250 mL jacketed glass reaction beaker (Kontes, Vineland, NJ, USA) connected to water bath circulator. The top of the beaker was covered with an acrylic panel to retard water evaporation from the base solution at high temperature. The probe head was placed at the center of the beaker via a small hole of the acrylic panel and hold using a support stand with a clamp. Circulating water in the beaker was aimed to control the sample target temperature, which was measured using a thermocouple inserted at the center of the beaker.

2.5 Experimental protocol

Figure 2 shows a schematic of the experimental setup. After mixing solid food cubes with CMC base solution, the mixtures were kept at room temperature for 30 mins to equilibrate temperatures of solid and liquid phases. Samples in the feeder tank were pumped through the combination heater using a sine pump in which solid particles could move without any physical damages. Depending upon salt concentrations in the base solution, different power inputs for individual heating mode (MW and OH) and combination heating mode (MW & OH) were determined so that the exit temperature of either solid or liquid phase reached approximately 80 °C (Table. 1); however, the flow rate and the pump speed were fixed at 300 ± 8 ml/min and 85 rpm, respectively. The minimum core temperature poultry recommended by [USDA-FSIS \(1973\)](#) is 71.1 °C. [Approximately 80 °C was desired for exit temperature in order to achieve fully cooked chicken breast pieces in this study.](#) The temperature values of solid and liquid phases were measured using K-type thermocouple sensors. When solid-liquid mixture

consistently exited the heater after heat treatment, solution temperature was measured using the thermocouple sensor installed at the exit port; whereas temperature values of solid particles collected at the exit were quickly measured using custom-made thermocouple sensor (K-type, KK-K-30, Omega Engineering Inc., Stamford, CT) with spacers aimed to reach the cores of different sized particles. As soon as the wire typed thermocouple sensor was inserted to the core of particle, temperature of particles was measured in a second. Average values of 30 readings from liquid or solid phases in each experiment were used to investigate heating patterns of solid-liquid mixtures under different heating modes. A total thermal treatment time from the inlet of the system to the outlet was 50.7 ± 1.35 s. Transient values of voltage, current, and temperature were monitored and recorded using the data logger. All experiments were conducted in a duplicate.

Analysis of variance (ANOVA) and T-test ($P < 0.05$) analyses were performed to determine the temperature differences between potato, chicken, and CMC solution, depending on staple variables such as the heating method (OH, MW, and MW & OH), solid particle size (S_p , cm), particle mass fraction (M_f , %, W/V) and salt concentration (C_s , %, W/V) using the SPSS software (V. 11, SPSS Inc., Chicago, IL).

3. Results and Discussion

3.1 Simulated electric field under microwave and ohmic heating

Figure 3 shows the electric field distributions in the microwave and ohmic combination heater simulated using the COMSOL code. The electric field strength simulated for the microwave chamber ranged between 2.245 and 5.618 kV/m (Fig. 3(a)). The cross-sectional view of the chamber indicated that the electric field was intensively focused at the center while the

maximum microwave power density was found at the areas adjacent to inlet and outlet of applicator.

When COMSOL simulation for E field in the ohmic tube used 200 V as an applied RMS voltage, the estimated electric field strength was from 675.4 to 3650.2 V/m (Fig. 3(b)). Although even electric field distribution was observed between ring shaped electrodes, electric field strength in the areas adjacent top and bottom of solid particles was relatively low, probably due to particles' field disruption (Shim et al., 2010). Electrical resistance (Ω) in those particular areas was relatively lower than solid particles and the majority of electrical current passed through high conductive solution (Salengke & Sastry, 2007; Shim et al., 2010). Furthermore, the localized field overshoot (approximately 3.6 kV/m) occurred at both side edges of the electrodes. This phenomenon can result in numerous problems such as the corrosion on the edges of electrodes in batch system; however, the overall performance of the heater in a continuous flow mode was not significantly influenced by localized field overshoots (Nguyen et al., 2013).

3.2 Electrical conductivities and dielectric properties of solid and liquid food samples

Figure 4 shows electrical conductivities of both solid and liquid phases at different temperature values. It was observed that the electrical conductivities of solid particles were much lower than those of base solutions. Electrical conductivities of base solutions with different NaCl concentrations increased linearly with temperature increases. Electrical conductivity of potato showed biphasic linearity with increased temperature values. The significant changes in the electrical conductivity of potato treated by ohmic heating occurred in the temperature range between 40 and 50 °C or 75 and 80 °C because of starch gelatinization which leads the changes in thermal properties of samples such as heat capacity and thermal conductivity (Halden et al.,

1990; Shim *et al.*, 2010). However, electrical conductivity of chicken breast constantly increased without any considerable change.

As temperature increased, the dielectric constant (ϵ') values of base solutions at C_s of 5 and 12.5 g/L decreased; while ϵ' of 20 g/L salt solution decreased until 60 °C and increased again (Fig. 5 (a)). However, the dielectric loss factor (ϵ'') values of all base solutions increased with an increase in temperature values. Note that dielectric properties of potato and chicken breast were estimated from the equations reported by Sipahioglu and Barringer (2003a, 2003b). The changes in dielectric constant (ϵ') and dielectric loss (ϵ'') of chicken showed different trends as temperature increased (Fig. 5 (b)). Dielectric constant (ϵ') of potato decreased till 65 °C and increased in a biphasic pattern; however, dielectric loss factor (ϵ'') of potato did not significantly change during the measurement. In addition, dielectric loss factor values (ϵ'') of base solutions were higher than that of potato; therefore, base solutions could thermally lead potato cubes when individual microwave heating is applied because the dielectric loss factor (ϵ'') is associated with the conversion of microwave energy into thermal energy in a dielectric material (Grant *et al.*, 1998).

3.3 Heating patterns of particle-liquid mixtures under different heating methods

Temperature variations between solid particles and liquid in the mixtures with three different salt concentrations are shown in Figs. 6, 7, and 8.

Ohmic heating: When solid-liquid mixtures were treated by ohmic heating alone, the magnitudes of temperature differences ($\Delta T_{ps} = T_{\text{potato}} - T_{\text{solution}}$, $\Delta T_{cs} = T_{\text{chicken}} - T_{\text{solution}}$) for the mixtures with the same particle size (S_p) and mass fraction (M_f) increased with an increase in the salt concentrations (C_s) as shown in Figs. 6 and 7. The results showed that the ohmic heating

rates of solid-liquid mixtures varied depending upon electrical conductivities of solid and liquid phases. However, there were little significant temperature variations (ΔT_{ps} and ΔT_{cs}) when C_s ranged between 5 g/L and 12.5 g/L, and between 12.5 g/L and 20 g/L ($P > 0.05$). An increase of M_f with the same values of S_p and C_s did not make a significant impact on the magnitudes of ΔT_{ps} and ΔT_{cs} ($P > 0.05$).

Furthermore, the temperature variation between solid particles ($\Delta T_{cp} = T_{chicken} - T_{potato}$) at the fixed values of S_p and M_f did not substantially change even with an increase in the value of C_s ($P > 0.05$). It might be because electrical conductivities of chicken and potato were similar at the temperature range from 40 to 100 °C (Sarang et al., 2008; Shim et al., 2010). On the other hand, the large particle size ($S_p = 1\text{cm}$) led to the change in the magnitude of ΔT_{ps} , ΔT_{cs} , and ΔT_{cp} at low and medium C_s (5 and 12.5 g/L). In particular, the values of ΔT_{ps} and ΔT_{cp} at M_f of 10 g/100g was significantly affected by S_p ($P < 0.05$, Figs. 6 (a) and 7 (a)). It was noted that larger particle size could develop greater heat transfer resistance from liquid to solid particles, eventually resulting in arbitrary temperature distribution in multiphase foods (Chen et al., 2010). Numerous studies reported that the ohmic heating pattern of multiphase foods could vary due to several factors i.e., electrical conductivities of solid and liquid phases, the size, shape, and constituents of solid particle, and the applied electric field strength (Zareifard et al., 2003; Salengke & Sastry, 2007; Shim et al., 2010). During ohmic heating, in general, temperature of liquid phase was higher than solid particles. The maximum temperature variation found between solid and liquid phases was 11.87 ± 2.91 °C (Fig. 8, ΔT_{ps} , $C_s = 20$ g/L, $S_p = 1$ cm, $M_f = 10$ g/100g).

Microwave heating: Although the dielectric loss factor values (ϵ'') of base solutions with C_s values of 5 g/L and 12.5 g/L were similar with or higher than those of chicken breast and potato, the temperature of solution lagged behind temperature values of solid particles. In general,

low dielectric constant (ϵ') is largely transparent to microwaves; thus, the dominant electric field strength might result in rapid ionic conduction within chicken and potato cubes.

For microwave heating, the magnitude of ΔT_{ps} , when M_f of 10 g/100g and identical values of S_p were used, did not substantially change as C_s increased from 5 g/L to 12.5 g/L ($P > 0.05$, Figs. 6 (a) and 7 (a)). However, as shown in Figs. 6 (b) and 7 (b), the value of ΔT_{ps} at M_f of 15 g/100g became smaller by increasing C_s up to 12.5 g/L and especially the difference in the values of ΔT_{ps} was found in Fig. 6 (b) ($P < 0.05$). In addition, the magnitude of ΔT_{ps} at M_f of 15 g/100g decreased with an increase in the value of S_p ; however, no statistical difference was found at C_s of 5 g/L ($P < 0.05$). An increase in C_s by 12.5 g/L did not substantially affect the change in the magnitude of ΔT_{cs} at M_f of 10% ($P > 0.05$, Figs. 6 (a) and 7 (a)). The value of ΔT_{cs} at S_p of 0.5 cm and M_f of 15 g/100g decreased with an increase in C_s by 12.5 g/L ($P < 0.05$, Figs. 6 (b) and 7 (b)). A relatively small temperature variation between solid particles (ΔT_{cs}) was obtained ($P > 0.05$).

The effect of the increase in S_p on the magnitude of temperature differences between solid particles and solution was observed at ΔT_{ps} with the values of M_f of 15 g/100g and C_s of 5 g/L. The experimental data reported by Kent and Kreess-Rogers (1986) also described that particle size did not affect microwave heating rate as compared to other factors, i.e. density and composition of solid particle. However, higher M_f under identical conditions of S_p and C_s slightly affected temperature variations between solid particles and liquid. The effect of M_f on those was observed at ΔT_{ps} at S_p of 1 cm and ΔT_{cs} at S_p of 0.5 cm ($P < 0.05$, Fig. 7). Potato and chicken particles thermally led to the base solution at low and medium C_s (5 g/L and 12.5 g/L) and a maximum thermal lead was 7.11 ± 1.74 °C (ΔT_{ps} , $C_s = 5$ g/L, $S_p = 0.5$ cm, $M_f = 15$ g/100g, Figs. 6 and 7); however, the temperature of solution was higher than those of solid particles at

high C_s (20 g/L). This finding was in an agreement with the study of Koskiniemi et al. (2011), reporting that an increase of salt concentration in liquid phase attenuated microwave penetration into unblanched vegetable cubes and decreased average temperatures of solid particles.

Combination heating: When microwave and ohmic heating simultaneously treated the solid-liquid mixture, the magnitudes of ΔT_{ps} , ΔT_{cs} , and ΔT_{cp} at low and medium C_s (5 and 12.5 g/L) were small and there were not considerable temperature differences between chicken, potato, and solution (less than 3.08 °C), irrespective of S_p and M_f ($P > 0.05$). The experimental data could be used to support the aforementioned hypothesis. For combination heating, even temperature distribution of both solid and liquid phases was obtained because microwaves with strong penetration depth heated up solid particles having low electrical conductivities rather than carrier medium and ohmic current could treat liquid phase with higher salt concentration (Figs. 6 and 7). However, the temperature variation between solid particles and liquid increased when combination heating was applied to heat up particulate solution at high C_s (20 g/L) as compared with ΔT_{ps} and ΔT_{cs} at low and medium C_s ($P < 0.05$, Fig. 8). Although the combination heating mode could obtain the temperature similarity between solid and liquid phases as C_s increased by 12.5 g/L, its effectiveness could vary depending upon multiphase foods of which electrical conductivities and dielectric properties are significantly different. However, such limitation can be resolved by designing the protocol recipes to manipulate the mixing ratios of individual microwave and ohmic heating resources at first and second stage heaters. The optimized hybrid power heating modulation will lead to uniform heating of food mixtures with various electrical conductivities and dielectric properties.

The estimation of the control ranges of key variables (i.e. C_s , S_p , and M_f) used in the combination heater was an essential process in this study to achieve the adequate range of

temperature variations between solid and liquid phases. The concept similar to the discriminant analysis was applied to build up the acceptable ranges of key variables for the optimized combination heating method (Press and Wilson, 1978). Prior to the estimation of the workable range of key variables, temperatures of solution, chicken, and potato have been predicted using the empirical polynomial equations given by:

$$Temperature_{solution, chicken, and potato} = [(a1 \cdot M_f + a2) \cdot S_p + (a3 \cdot M_f + a4)]C_s^2 + [(b1 \cdot M_f + b2) \cdot S_p + (b3 \cdot M_f + b4)]C_s + (c1 \cdot M_f + c2) \cdot S_p + c3 \cdot M_f + c4 \quad (2)$$

The predicted temperatures values of solution, chicken, and potato were accurately consistent with experimental observations with the r^2 values close to 1 and the constants of polynomial equations for each variable were listed in Table. 2.

For practical application for the processing of food products, the value of S_p was normalized as a particle diagonal per a tube diameter within the combination heating applicator. The normalized values of S_p and M_f in the combination heater were determined to range between 0 and 0.9 cm, and between 0 and 25 g/100g, respectively. The controllable ranges of salt concentration for the combination heater to achieve the desired temperature variations (± 2 °C at targeted exit temperature, 80 °C) defined for ΔT_{ps} and ΔT_{cs} were between 0 and 16.8 g/L, and between 0 and 17.1 g/L, respectively. In addition, a 3D block diagram, which could identify and quantify heating uniformity between solids and carrier medium, were constructed using the controllable ranges of key variables (Fig. 8). The desired temperature variations of ΔT_{ps} or ΔT_{cs} (± 2 °C at targeted exit temperature, 80 °C) can be obtained when the values of key variables are located within each block unit.

The appropriate ranges of ΔT_{ps} and ΔT_{cs} imply that the combination heating technique leads to improved temperature similarities between solid and liquid phases and enhanced energy efficiency of the combination heating technology. This finding could explain that the

combination heating has the potential to thermally treat multiphase foods with uniformity of temperature distribution in various ranges of salt concentration, particle size, and mass fraction.

4. Conclusion

A continuous flow, simultaneous microwave and ohmic combination heater was successfully fabricated and tested for thermal uniformity of multiphase foods. Temperature differences between solid and liquid phases was substantially high under individual heating modes; however, there was little temperature lag at low salt concentrations (up to 12.5 g/L) in a relatively short time (50 s) when microwave and ohmic heating were simultaneously applied. Temperature lag of solid particles in multiphase foods was observed when high salt concentration (20 g/L) was applied, which, however, seems to be unrealistic in food systems. This finding could highlight potential opportunities to thermally process particulate foods with improved thermal analogy and no need for pretreatment steps. A future study will include validation of the effectiveness of the combination heating technology in terms of physicochemical and microbiological achievement, i.e. lethality testing for liquid juice with chunky mixed fruits.

Acknowledgment

This project was supported by Agriculture and Food Research Initiative Grant 2009-65503-05786 from the USDA National Institute of Food and Agriculture.

References

- Asmussen, J., Lin, H. H., Manring, B., & Fritz, R. (1987). Single-mode or controlled multimode microwave cavity applicators for precision materials processing. *Review of Scientific Instruments*, 58(8), 1477-1486.
- Chen, C., Abdelrahim, K., & Beckerich, I. (2010). Sensitivity analysis of continuous ohmic heating process for multiphase foods. *Journal of Food Engineering*, 98(2), 257-265.
- Choi, W., Nguyen, L. T., Lee, S. H., & Jun, S. (2011). A Microwave and Ohmic Combination Heater for Uniform Heating of Liquid-Particle Food Mixtures. *Journal of Food Science*, 76(9), E576-E585.
- Coronel, P., Simunovic, J., & Sandeep, K. P. (2003). Temperature Profiles Within Milk after Heating in a Continuous-flow Tubular Microwave System Operating at 915 MHz. *Journal of Food Science*, 68(6), 1976-1981.
- Coronel, P., Truong, V. D., Simunovic, J., Sandeep, K. P., & Cartwright, G. D. (2005). Aseptic processing of sweetpotato purees using a continuous flow microwave system. *Journal of Food Science*, 70(9), E531-E536.
- Goksoy, E. O., James, C., & James, S. J. (1998). Non-uniformity of surface temperatures after microwave heating of poultry meat. *The Journal of microwave power and electromagnetic energy: a publication of the International Microwave Power Institute*, 34(3), 149-160.
- Grant, E., & Halstead, B. J. (1998). Dielectric parameters relevant to microwave dielectric heating. *Chemical Society Reviews*, 27(3), 213-224.
- Halden, K., de Alwis, A. A. P., & Fryer, P. J. (1990). Changes in the electrical conductivity of foods during ohmic heating. *International Journal of Food Science and Technology*, 25 (1), 9-25.

412 Hossan, M. R., Byun, D., & Dutta, P. (2010). Analysis of microwave heating for cylindrical
 413 shaped objects. *International Journal of Heat and Mass Transfer*, 53(23), 5129-5138.

414 Icier, F., & Ilicali, C. (2005). The effects of concentration on electrical conductivity of
 415 orange juice concentrates during ohmic heating. *European Food Research and*
 416 *Technology*, 220(3-4), 406-414.

417 Kent, M., & Kress-Rogers, E. (1986). Microwave moisture and density measurements in
 418 particulate solids. *Transactions of the Institute of Measurement and Control*, 8(3), 161-168.

419 Koskiniemi, C. B., Truong, V. D., Simunovic, J., & McFeeters, R. F. (2011). Improvement of
 420 heating uniformity in packaged acidified vegetables pasteurized with a 915MHz continuous
 421 microwave system. *Journal of Food Engineering*, 105(1), 149-160.

422 Leizeron, S., & Shimoni, E. (2005). Stability and sensory shelf life of orange juice
 423 pasteurized by continuous ohmic heating. *Journal of Agricultural and Food Chemistry*, 53(10),
 424 4012-4018.

425 Nguyen, L. T., Choi, W., Lee, S. H., & Jun, S. (2013). Exploring the heating patterns of
 426 multiphase foods in a continuous flow, simultaneous microwave and ohmic combination
 427 heater. *Journal of Food Engineering*, 116(1), 65-71.

428 Pitchai, K., Birla, S. L., Jones, D., & Subbiah, J. (2012). Assessment of heating rate and non-
 429 uniform heating in domestic microwave ovens. *Journal of Microwave Power and*
 430 *Electromagnetic Energy*, 46(4), 229-240.

431 Press, S. J., & Wilson, S. (1978). Choosing between logistic regression and discriminant
 432 analysis. *Journal of the American Statistical Association*, 73(364), 699-705.

433 Salengke, S., & Sastry, S. K. (2007). Experimental investigation of ohmic heating of solid-
 434 liquid mixtures under worst-case heating scenarios. *Journal of Food Engineering*, 83(3), 324-336.

435 Sarang, S., Sastry, S. K., & Knipe, L. (2008). Electrical conductivity of fruits and meats
 436 during ohmic heating. *Journal of Food Engineering*, 87(3), 351-356.

437 Shim, J., Lee, S. H., & Jun, S. (2010). Modeling of ohmic heating patterns of multiphase
 438 food products using computational fluid dynamics codes. *Journal of Food Engineering*, 99(2),
 439 136-141.

440 Singhal, R. S., Pandit, A. B., Joshi, J. B., Patel, S. B., Danao, S. P., Shinde, Y. H., & Tarade,
 441 K. M. (2012). Development of Efficient Designs of Cooking Systems. III. Kinetics of Cooking
 442 and Quality of Cooked Food, Including Nutrients, Anti-Nutrients, Taste, and Flavor. *Industrial*
 443 *and Engineering Chemistry Research*, 51(4), 1923-1937.

444 Sipahioglu, O., & Barringer, S.A. (2003a). Dielectric properties of vegetables and fruits as a
 445 function of temperature, ash, and moisture content. *Journal of Food Science*, 68(1), 234–239.

446 Sipahioglu, O., Barringer, S. A., & Bircan, C. (2003b). Dielectric properties of meats as a
 447 function of temperature and composition. *Journal of Microwave Power and Electromagnetic*
 448 *Energy*, 38(3).

449 Tang, Z., Mikhaylenko, G., Liu, F., Mah, J. H., Pandit, R., Younce, F., & Tang, J. (2008).
 450 Microwave sterilization of sliced beef in gravy in 7-oz trays. *Journal of Food Engineering*, 89(4),
 451 375-383.

452 [USDA-FSIS. \(1973\). *Meat and Poultry Inspection Manual*. Part 18G, Article 37. Washington,](#)
 453 [DC: USDA- Food Safety and Inspection Service.](#)

454 Wang, D., Liu, Y., Liu, X., Zhou, F., Liu, W., & Xue, Q. (2009). Towards a tunable and
 455 switchable water adhesion on a TiO₂ nanotube film with patterned wettability. *Chemical*
 456 *Communications*, 45, 7018-7020.

457 Zareifard, M. R., Ramaswamy, H. S., Trigui, M., & Marcotte, M. (2003). Ohmic heating
458 behaviour and electrical conductivity of two-phase food systems. *Innovative Food Science and*
459 *Emerging Technologies*, 4(1), 45-55.
460

461 **List of tables**

462 Table 1. Microwave power and Ohmic voltages applied for microwave (MW), ohmic (OH), and
463 combination heating modes (MW & OH) depending on NaCl concentrations.

464 Table 2. The constants of polynomial equations for the prediction of temperatures of solution,
465 chicken, and potato

466

467

468

469 Table 1. Microwave power and Ohmic voltages applied for microwave (MW), ohmic (OH), and
470 combination heating modes (MW & OH) depending on NaCl concentrations.

NaCl (g/L)	MW (W)	OH (V)	MW & OH (W & V)
5	1000	320	800 & 240
12.5	800	230	700 & 185
20	700	180	600 & 140

471
472
473
474
475

476 Table 2. The constants of polynomial equations for the prediction of temperatures of solution,
 477 chicken, and potato

	Solution	Chicken	Potato
a1	-214.30	25.03	-137.65
a2	13.45	-21.85	8.68
a3	168.54	-3.38	51.02
a4	-11.93	7.49	-4.87
b1	529.11	70.38	868.13
b2	-43.60	25.13	-100.25
b3	-443.21	-78.35	-442.08
b4	38.73	-3.03	56.22
c1	-303.62	-7.98	-713.47
c2	28.87	-10.86	90.07
c3	224.24	18.60	383.08
c4	60.13	81.98	30.01

478

479

List of figures

Figure 1. A schematic diagram of the microwave and ohmic combination heater: (a) A front view, (b) A side view, (c) A 3D schematic, and (d) A cross-sectional view of the chamber.

Figure 2. A schematic of the experimental set-up.

Figure 3. Dielectric properties of (a) base solutions with different salt concentrations, and (b) potato, and chicken breast.

Figure 4. Electrical conductivities of potato, chicken breast, and base solutions with different salt concentrations depending upon various temperature values: black solid line (—): potato; black dashed line (---): chicken breast; grey solid line (—): 5 g/L NaCl solution; grey dashed line (---): 12.5 g/L NaCl solution; grey dotted line (....): 20 g/L NaCl solution.

Figure 5. Dielectric properties of (a) base solutions with different salt concentrations (black color: dielectric constant (ϵ'); grey color: dielectric loss (ϵ''), solid line (—): 5 g/L NaCl solution, dashed line (---): 12.5 g/L NaCl solution, dotted line (....): 20 g/L NaCl solution) and (b) potato, and chicken breast (solid line: chicken breast, dashed line: potato).

Figure 6. Heating patterns of particle-liquid mixtures (5 g/L salt concentration) under microwave, ohmic, and combination heating. (a) 10 g/100g mass fraction, and (b) 15 g/100g mass fraction.

Figure 7. Heating patterns of particle-liquid mixtures (12.5 g/L salt concentration) under microwave, ohmic, and combination heating. (a) 10 g/100g mass fraction, and (b) 15 g/100g mass fraction.

Figure 8. Heating patterns of particle-liquid mixtures (20 g/L salt concentration) under microwave, ohmic, and combination heating. (a) 10 g/100g mass fraction, and (b) 15 g/100g mass fraction

502 Figure 9. 3D block diagram constructed at different controllable ranges of key variables for the
503 prediction of (a) ΔT_{ps} and (b) ΔT_{cs} falling in the variations less than ± 2 °C from targeted exit
504 temperature, 80 °C.

505 Figure 1. A schematic diagram of the microwave and ohmic combination heater: (a) A front view,
 506 (b) A side view, (c) A 3D schematic, and (d) A cross-sectional view of the chamber.

509 Figure 2. A schematic of the experimental set-up.

510

511 Figure 3. Electric field distribution in the heater: (a) microwave chamber, and (b) ohmic heater.

512

513 Figure 4. Electrical conductivities of potato, chicken breast, and base solutions with different salt
 514 concentrations depending upon various temperature values: black solid line (—): potato; black
 515 dashed line (---): chicken breast; grey solid line (—): 5 g/L NaCl solution; grey dashed line (---):
 516 12.5 g/L NaCl solution; grey dotted line (....): 20 g/L NaCl solution.

517

Figure 5. Dielectric properties of (a) base solutions with different salt concentrations (black color: dielectric constant (ϵ'); grey color: dielectric loss (ϵ''), solid line (—): 5 g/L NaCl solution, dashed line (---): 12.5 g/L NaCl solution, dotted line (....): 20 g/L NaCl solution) and (b) potato, and chicken breast (solid line: chicken breast, dashed line: potato).

NOTE: Dielectric properties of potato and chicken breast were estimated from the equations reported by Sipahioglu and Barringer (2003a, 2003b)

Figure 6. Heating patterns of particle-liquid mixtures (5 g/L salt concentration) under microwave, ohmic, and combination heating. (a) 10 g/100g mass fraction, and (b) 15 g/100g mass fraction.

NOTE: Error bars indicate the 95% confidence intervals (CI) based on the average of temperature difference between particulates and solution
 $\Delta T_{ps} = T_{potato} - T_{solution}$, $\Delta T_{cs} = T_{chicken} - T_{solution}$, $\Delta T_{cp} = T_{chicken} - T_{potato}$

MW
OH
MW & OH
Sp: 0.5cm
Sp: 1cm

Figure 7. Heating patterns of particle-liquid mixtures (12.5 g/L salt concentration) under microwave, ohmic, and combination heating. (a) 10 g/100g mass fraction, and (b) 15 g/100g mass fraction.

NOTE: Error bars indicate the 95% confidence intervals (CI) based on the average of temperature difference between particulates and solution

$$\Delta T_{ps} = T_{\text{potato}} - T_{\text{solution}}, \Delta T_{cs} = T_{\text{chicken}} - T_{\text{solution}}, \Delta T_{cp} = T_{\text{chicken}} - T_{\text{potato}}$$

MW
OH
MW & OH
Sp: 0.5cm
Sp: 1cm

Figure 8. Heating patterns of particle-liquid mixtures (20 g/L salt concentration) under microwave, ohmic, and combination heating. (a) 10 g/100g mass fraction, and (b) 15 g/100g mass fraction

NOTE: Error bars indicate the 95% confidence intervals (CI) based on the average of temperature difference between particulates and solution
 $\Delta T_{ps} = T_{potato} - T_{solution}$, $\Delta T_{cs} = T_{chicken} - T_{solution}$, $\Delta T_{cp} = T_{chicken} - T_{potato}$

MW
OH
MW & OH
Sp: 0.5cm
Sp: 1cm

Figure 9. 3D block diagram constructed at different controllable ranges of key variables for the prediction of (a) ΔT_{ps} and (b) ΔT_{cs} falling in the variations less than ± 2 °C from targeted exit temperature, 80 °C.

(a)

(b)

Note) S_p : Particle size (cm), M_f : Mass fraction (g/100g), C_s : Salt concentration (g/L)