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

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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/100 g) 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.

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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, Choi, Lee, & Jun, 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., 2012). 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, Lee, & Jun, 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, Nguyen, Lee, & Jun, 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 (Icier & Ilicali, 2005; Leizerson & Shimoni, 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, Sastry, & Knipe, 2008; Shim et al., 2010). Therefore, the ohmic heating

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process for multiphase foods required pre-estimation of electrical conductivities of solid and liquid phases (Zareifard, Ramaswamy, Trigui, & Marcotte, 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, Byun, & Dutta, 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, Simunovic, & Sandeep, 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, Birla, Jones, & Subbiah, 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, James, & James, 1998; Xu, Min, & Mujumdar, 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, Lin, Manring, & Fritz, 1987). A continuous flow microwave heater occupied with a single mode elliptical resonant cavity was effectively functional for aseptically packaged vegetable purees (Coronel, Truong, Simunovic, Sandeep, & Cartwright, 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/100 g. 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 cm^3 cubes) in 15 g/100 g 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/100 g frequently caused the current PTFE tube to be clogged.