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Serial Flow Microwave Thermal Process System for Liquid Foods

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Abstract Two single-magnetron heating systems (SM-HS), each with a helical glass heat exchanger and a cylindrical cavity, were combined to make a two-magnetron-in-series heating system (2MS-HS) in order to increase the heating capacity. A comparison using water showed that the heating performance of the 2MS-HS was increased by two-fold as compared to that of the SM-HS, resulting in energy saving of 7.0% in 2MS-HS. Pasteurization test of 2MS-HS conducted with model food (LB broth contaminated with *Bacillus subtilis*) showed two-fold higher treatment capacity compared to SM-HS. Relationships between outlet temperature of the processed food, flow rate, and residence time in the 2MS-HS were established for water. Optimum pasteurization capacity was 17 s, 73°C, at flow rate of 280 ml/min. The 2MS-HS could be applied to the small-scale pasteurization of liquid food.

Keywords: Microwave, serial heating, heat exchanger, food pasteurization, cylindrical cavity

Introduction

Microwave energy has been widely used in food technology for thawing (1, 2), blanching (3), drying (4, 5, 6), extracting (7, 8, 9, 10), and pasteurizing (11, 12, 13, 14, 15). For the rapid microwave treatment of liquid food, Jun and Chun (8) designed a cylindrical cavity to focus an electric field along the longitudinal axis of the cavity using a 1-kW magnetron and a glass tube heat exchanger. Lim and Chun (16) developed a helical coil microwave heat exchanger for a single magnetron heating system (SM-HS) and found that instant heating up to 80°C was possible at a water flow rate of 110 ml/min. This indicated that the heating rate was adequate for the pasteurization of food with respect to temperature elevation; however, the flow rate was too low for a practical food pasteurizer, necessitating an increase in the microwave power input.

The heat generation of food in a microwave cavity is proportional to the magnitude of the electric field (17), therefore, the use of a high-capacity magnetron is required. However, a heavy-duty magnetron over 1 kW is too expensive to apply to processing in a food pasteurizer. Fortunately, the magnetrons widely used in household microwave ovens are available for less than $30 from major magnetron suppliers (19). To increase the thermal treatment capacity of a microwave system, it is possible to double the microwave power input by using two magnetrons in series within the same range of heating rates.

Because the heating rate is proportional to the power input, the residence time needed to elevate liquid temperature (ΔT) can be derived from the energy balance equation (16) described by:

$$\Delta T = \frac{\eta P t}{\rho C_p V} = \frac{\eta}{\rho C_p} \frac{P}{v} \qquad (1)$$

where V: volume of food (ml), ρ: density of food (g/cm^3), C_p: specific heat capacity (J/g°C), ΔT: temperature increase (°C), η: efficiency of the system, P: total power consumption of the system (W), t: treatment time (s), and v: volumetric flow rate (ml/s).

Therefore, a dual magnetron microwave system was designed with two microwave cavities in series and the possibility of using the system to pasteurize liquid food was explored.

Materials and Methods

Foods Distilled water was used for the heating performance test. LB broth culture (18) contaminated with *Bacillus subtilis* at 10^7 CFU/ml was used as the model food for the pasteurization test.

Microwave heating system in series A single magnetron microwave heating system (SM-HS) equipped with one magnetron [2450 MHz, 1 kW, OM75P(31), Samsung Electronics, Korea] and a helical glass coil (glass tube: 7 mm ID, 10 mm OD, 75 mm coil diameter, 10 turns) in a cylindrical microwave cavity was used as the unit set of the magnetron heating system (16). Two units of the SM-HS set were connected with a Tygon tube (7 mm ID, 10 mm OD, 50mm length) to construct the two-magnetron-in-series heating system (2MS-HS) (Fig. 1).

The liquid food was fed from the food reservoir using a metering pump (Masterflex L/S, Cole-Parmer, USA). The in-line temperature of the system was measured at locations T1, T2, and T3 using a thermocouple thermometer (T-type, 0.8mm diameter and 0.8 s response time, Pico Technology, UK). The process variables (temperature, flow rate, and power consumption) were acquired through PLC (Glofa GM3, LG FA, Korea) and monitored using a PC.

Measurement of power consumption and estimation of system efficiency The power consumption of the microwave heating system during the running process at

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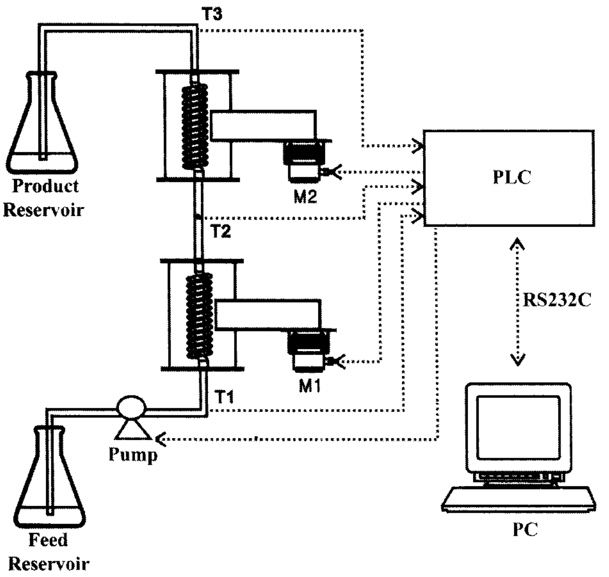

Fig. 1. Schematic of the experimental 2MS-HS system and data acquisition system for the process variables. T1, T2, and T3: inlet, intermediate, and outlet temperatures, respectively; M1, M2: magnetrons.

various flow rates was measured with power meter (2533E AC, Yokogawa, Japan).The total amount of absorbed energy of water was calculated based on the temperature elevation result. Energy efficiency of the system (η) was calculated using Eq. 1.

Thermal processing of model liquid food LB broth culture of *B. subtilis* (N_0=10^7 CFU/ml) at 25°C was treated in the 2MS-HS for a given time period (t), and the rate of microbe reduction (Log N/N_0) was measured by the plate counting method using a Petrifilm (3M, USA).

Results and Discussion

Construction of the 2MS-HS Two of the SM-HS developed by Lim and Chun (16) were connected in series and the resulting 2MS-HS is shown in Fig. 2.

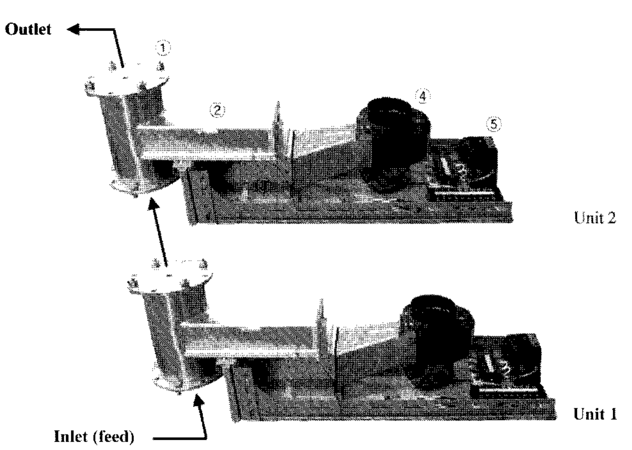

Fig. 2. Main parts of the 2MS-HS system unit: ① microwave cavity, ② wave-guide, ③ magnetron, ④ cooling fan, and ⑤ power supplier.

Construction of the heat exchanger of the 2MS-HS The glass tubing helical coil heat exchanger designed by Lim and Chun (16) was modified to increase its capacity and was used as the heat exchanger unit installed in the cylindrical cavity (Fig. 2, ①).

The heating curve for liquid food in the 2MS-HS The heating profiles of water at a flow rate of 250 ml/min in the 2MS-HS and SM-HS are plotted in Fig. 3. The heating rate of the 2MS-HS was twofold higher than that of the SM-HS. Moreover, the heating pattern of liquid food in the 2MS-HS differed from that of the SM-HS showing a shoulder in the middle of the heat curve (↘ in Fig. 3) equivalent to an exponential heating period. This shoulder was probably caused by the unheated section of the heat exchanger exposed to ambient air at the connection tubing between the two units.

At a steady state of microwave heating, the temperature elevation (ΔT) of water was 53 and 27°C in 2MS-HS and SM-HS, respectively, at a flow rate of 250 ml/min, indicating that the heating performance of the 2MS-HS was almost twofold higher than that observed in the SM-HS.

Heating performance of the 2MS-HS The performance of the 2MS-HS was tested using water at various flow rates ranging from 140 to 350 ml/min. The heating profiles at various flow rates had similar heating patterns, with typical shoulders, and the maximum temperature of the processed water was inversely proportional to the flow rate, as observed with the SM-HS (Figs. 3-5). The average heating performance of 2MS-HS was 1.95 times higher than that of SM-HS.

A good linear relationship between the heating rate and residence time (Eq. 1) was observed in the experimental plots of 2MS-HS and SM-HS data, except the water boiled at a low flow rate (140 ml/min). Fig. 6 shows the relationship between temperature elevation and the residence time in the system.

Comparison of power consumptions in 2MS-HS and SM-HS The power consumptions of 2MS-HS and SM-HS under the running condition of 250 ml/min flow rate were compared in Fig. 7. The power consumption patterns were similarly peaked at the initial stage and remained almost constant with a negligible decrease with time. Power consumptions per unit magnetron of SM-HS and 2MS-HS were 1.546 and 1.445 kW, respectively, showing a power saving of 7.0% in the 2MS-HS.

Comparison of heating efficiency of 2MS-HS and SM-HS at various flow rates The amounts of absorbed power by water in 2MS-HS and SM-HS, and the heating efficiencies of 2MS-HS and SM-HS were plotted against various flow rates (Fig. 8,(a)). The efficiency of 2MS-HS was higher than that of SM-HS at each flow rate, and increased with the increase of flow rate. The efficiency dependence on the flow rate might be due to the temperature dependence of dielectric properties of water. The temperature dependence of the efficiency was confirmed by plotting against the temperature of flowing fluid (Fig. 8-(b)).

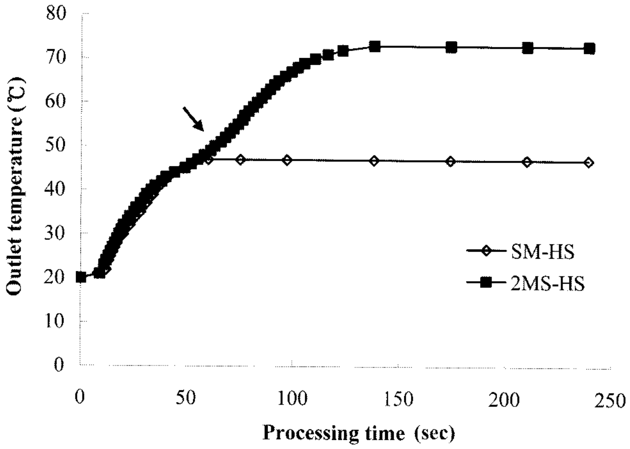

Fig. 3. Comparison of the heating curves of the 2MS-HS and SM-HS.

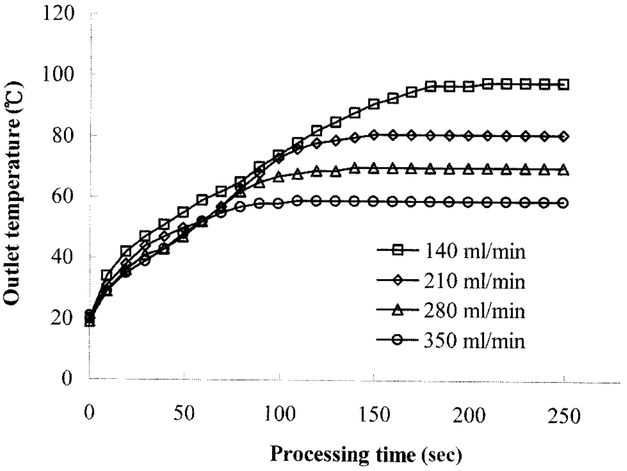

Fig. 4. Heating pattern of the 2MS-HS at various flow rates.

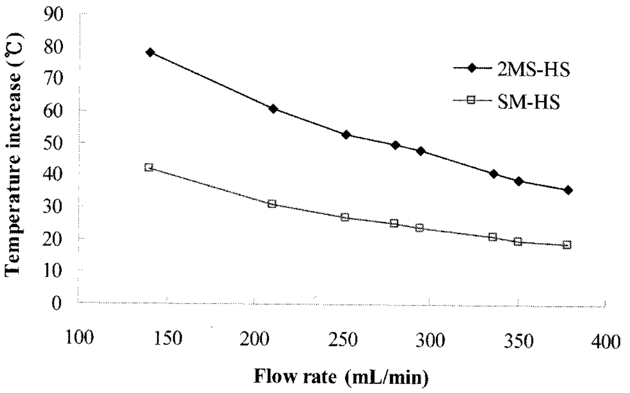

Fig. 5. Comparison of the heating performances of the 2MS-HS and SM-HS at various flow rates.

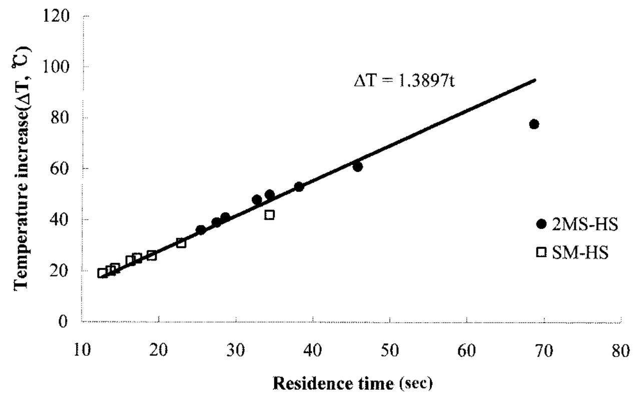

Fig. 6. Relationship between temperature increase and residence time of liquid food in the 2MS-HS and SM-HS.

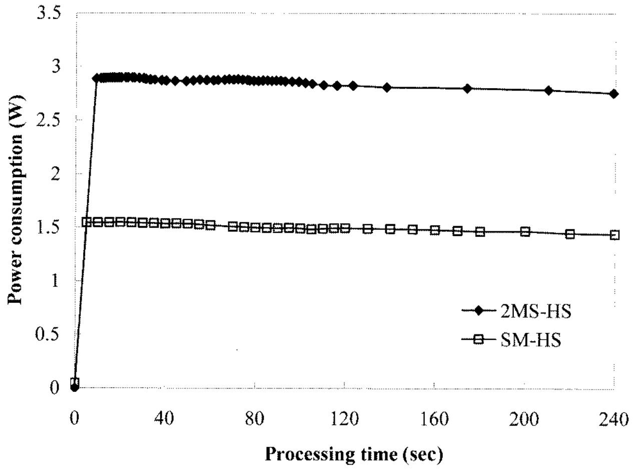

Fig. 7. Comparison of power consumption during heating process.

Pasteurization of model food in the 2MS-HS Because the heating performance of 2MS-HS was good, the feasibility of using it to pasteurize liquid foods was tested, using a model food contaminated with *B. subtilis*. The microwave treatment conditions tested were residence times from 12 to 28 s and flow rates from 170 to 380 ml/min. The thermal death curve of the model food was plotted as the rate of reduction of the target microorganisms versus the residence times along with the temperature profile of the outlet product (Fig. 9).

A seven-fold reduction in the microbial reduction was achieved and the greatest drop was over the temperature range from 58 to 73°C (Fig. 9). Effective pasteurization occurred from 12.5 to 17 s of the residence times. Compared to the SM-HS, the 2MS-HS was twice as effective in terms of treatment capacity, showing that the validity of the serial treatments (Fig. 6) carried over to the pasteurization performance. Therefore, 2MS-HS is feasible for pasteurizing liquid foods. However, before applying 2MS-HS to the thermal processing of liquid foods, further study on the cavity design and control system are needed.

For practical application of a microwave-aided process, the bottleneck is the high cost of the high duty magnetron. We attempted to resolve this problem using multiple, inexpensive magnetron units of the type used in home microwave ovens. The 2MS-HS having two magnetrons showed that the linear proportionality of the power inputs was validated by the two-fold increase in the heating capacity for the water sample. The use of the 2MS-HS as a food pasteurizer was demonstrated successfully with a model liquid food contaminated with *B.subtilis*. In terms of the microbe reduction index, effectiveness of 2MS-HS was equally as good as the SM-HS unit, indicating that

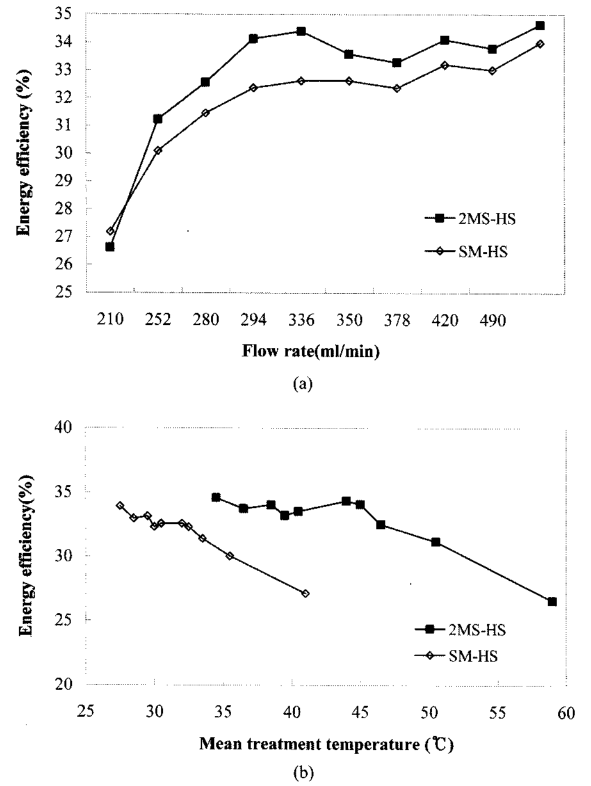

Fig. 8. Comparison of energy efficiency of 2MS-HS and SM-HS at (a) various flow rates, and (b) various mean treatment temperatures.

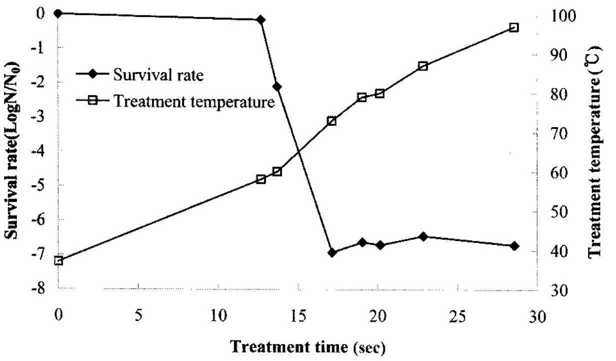

Fig. 9. Pasteurization of model food in 2MS-HS for various residence times.

microwave heating or pasteurization system made with multiple low-cost magnetrons in series has practical applications.

Acknowledgments

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