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Design Criteria of a Heat Exchanger for Microwave Sterilization System

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Abstract

Continuous-flow microwave sterilization system consisting of cylindrical microwave cavity (CMC) was developed for sterilization of liquid food. Two types of helical coil heat exchangers were fabricated with glass tubing for CMC heating system (CMC-HS), and their performances were tested for water at various flow rates under control of magnetron duty. Heating rates of water in CMC-HS heat exchangers were inversely proportional to flow rate of water, and diameter of helical coil did not affect outlet temperature at flow rates above 2.04 ml/sec. Duty ratio control of magnetron caused fluctuation of outlet temperature, and fluctuation gap was affected by diameter of helical coil and flow rate of water.

Key words: microwave, continuous, flow, cylindrical, cavity, sterilization

Introduction

For sterilization of food, microwave heating is preferred to the conventional heating primarily due to its instant heating capability, thus taking less time to reach the desired process temperature. Accordingly, it can attain benefits of high temperature-short time processing, whereby bacterial destruction is achieved (Sale *et al*., 1970; Stack, 1975; Marquez *et al.*, 1997).

In terms of heating efficiency, microwave cavity is an important design factor for the effective absorption of microwave energy by food. Focused electromagnetic field strength in the cavity was investigated by several workers to increase heating efficiency and maximize non-thermal effect of microwave (Mudgett, 1986; Tajchakavit *et al.*, 1995; kozempel *et al.*, 1998). Jun and Chun (1998) designed a cylindrical microwave cavity (CMC) to realize focused electromagnetic field strength and applied it to food extraction process equipped with a U-tube type glass extraction column positioned in CMC. Moreover, performance of CMC heating system (HS) at various duty cycles of magnetron was reported by Rho and Chun (1999) with respect to modeling. They found that CMC-HS could be controlled by adjusting the duty cycle, and thus applied it to the extraction processes of various food materials. The success in microwave power control of the CMC-HS enabled its application in other thermal processes such as sterilization of food.

The objective of this study was to design an effective heat exchanger to be placed in CMC-HS for the liquid foods.

Material and Method

Heat-sensing paper (Starfax G3, Hansol, Korea) was used for the detection of electrical power strength formed in the microwave cavity, and helical coil, filled and solidified with agar-agar solution (3%), was used to monitor the heat energy absorbed (Jun and Chun, 1998; Rho, 1999).

CMC-HS was set up as described by Jun and Chun (1998), and peristaltic pump was used to feed the specimen (Fig. 1). To control duty cycle of the magnetron and monitor temperatures, programmable

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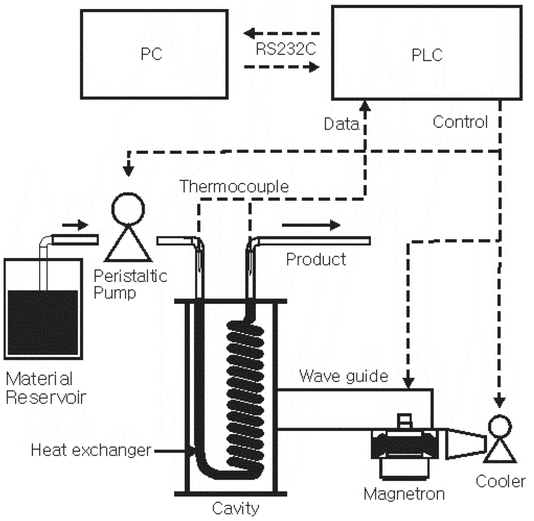


Fig. 1. Experimental set up for design study of the heat exchanger in CMC-HS.

logic controller (PLC-GLOFA GM3 PLC series LGFA) was incorporated.

Heat exchanger of CMC-HS was fabricated using Pyrex glass tubing (ID, 7 mm; OD, 10 mm).

Results and DIscussion

Design consideration of heat exchanger in cylindrical microwave cavity

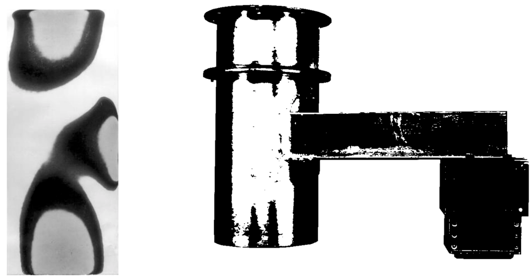
Microwave energy absorbed by food is influenced by the properties of microwave and food such as frequency permissivity of microwave and dielectric loss factor of food. Equation 1 describes the generation of heat in a microwave system per unit volume of food (Q/V) (Buffler, 1993; Datta and Anatheswaran, 2000).

$$Q/V = 2\pi f \varepsilon_0 \varepsilon'' E^2 \qquad (1)$$

The heat energy absorbed by food can be expressed as follows:

$$Q/V = \rho \cdot C_p \cdot \frac{dT}{dt} \qquad (2)$$

Therefore, the heat balance equation can be written as Equation 3:



(a) Power mode (b) cavity structure

Fig. 2. Bipolar power mode (a) obtained in the cylindrical microwave cavity (b) where heat exchanger is positioned.

$$\frac{dT}{dt} = \frac{2\pi f \varepsilon_0 \varepsilon'' E^2}{\rho \cdot C_p} \qquad (3)$$

From Equation 3, the elevation of food temperature can be estimated.

Assuming uniform field strength in CMC, the degree of heating (**T-T$_0$**) and length of heat exchanger (**L**) can be related by Equation 4.

$$T - T_0 = \frac{2\pi f \varepsilon_0 \varepsilon'' E^2}{\rho \cdot C_p} \cdot \frac{A \cdot L}{\bar{v}} \qquad (4)$$

Because the first term on the right side of Equation 4 can be given by CMC-HS and material to be treated, the second term, $AL/\bar{v}$, determines the degree of heating. When the volume $(A \times L)$ is given, **v** becomes the manipulated variable of the heat exchanger.

Contrary to the assumption of uniform field strength, non-uniform strength with bipolar mode was generated in the cylindrical cavity (Fig. 2).

Due to the formation of bipolar and coaxial power modes in CMC (Jun and Chun, 1998), heat exchanger must be aligned along with the power mode to attain maximum absorption of microwave energy.

Penetration depth (**z**) of microwave can be estimated by Equation 6 (Von Hippel, 1954; Mugett, 1982).

$$z = \frac{1}{\alpha} = \frac{\lambda}{2\pi}\left[\frac{2}{k'\{(1+\tan^2\delta)^{1/2} - 1\}}\right]^{1/2} \qquad (6)$$

In the case of 2.45 GHz of microwave, penetration depth is about 28.4 mm in water having 76.7 dielectric constant and 0.157 loss tangent (Pozar, 1998). Considering 67% of effective penetration depth (Mugett, 1982), the optimum radius of glass tube of the heat exchanger is less than 19.1 mm.

Modified Reynolds number (**N_{Re}**) defined as Equation 7 was considered in the design of helical coil heat exchanger to obtain a good mixing effect.

$$N_{Re} = \frac{2r \cdot \rho \cdot v}{\mu} = \frac{2 \cdot F \cdot \rho}{r \cdot \pi \cdot \mu} \quad (7)$$

Given the diameter of glass tubing (7 mm ID), flow rate of water (F) should be greater than 18.1 ml/sec for the develop-ment of turbulent flow. As mentioned in Equation 4, meanwhile, fluid velocity is a manipulation variable when determining the appropriate residence time necessary for the outlet temperature to reach the pasteurization temperature. Therefore, optimized process condition can be determined by manipulating the fluid velocity through the compromise between residence time and outlet temperature.

Design of helical glass-tubing heat exchanger

To attain sufficient mean residence time to raise the temperature of the fluid up to the pasteurization temperature and the mixing effect at low Reynolds number, vertical coil structure was adopted. Glass tubing was used as a construction material due to the easiness of cleaning the fouling formed through repeated use. Two types of glass coil (small coil: OD 31 mm, L 780 mm with 13 coil turns, 30 ml volume; large coil: OD 47 mm, L 1250 mm, 12 coil turns, 48 ml volume) were designed and fabricated with Pyrex glass tube (ID, 7 mm; OD, 10 mm) (Fig. 3).

CMC-HS was constructed with CMC and helical coil glass tubing heat exchanger (Fig. 1).

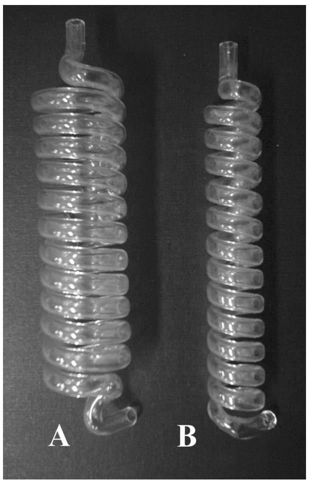


Fig. 3. Helical coil-type heat exchangers fabricated with pyrex glass tube.
(A) large coil, (B) small coil.

Heating performance of CMC-HS at various flow rates of water

At steady state heating process of CMC-HS, outlet temperature of water decreased linearly with increasing flow rate in small coil unit (Fig. 4 (a)). The large coil unit exhibited a similar pattern, such that, the outlet temperature increased steeply at flow rate 2.04 ml/sec

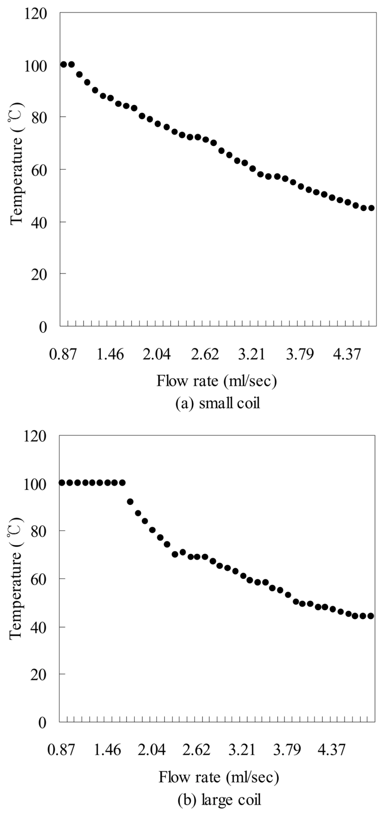


Fig. 4. Relationship between outlet temperature and flow rate in CMC-HS.

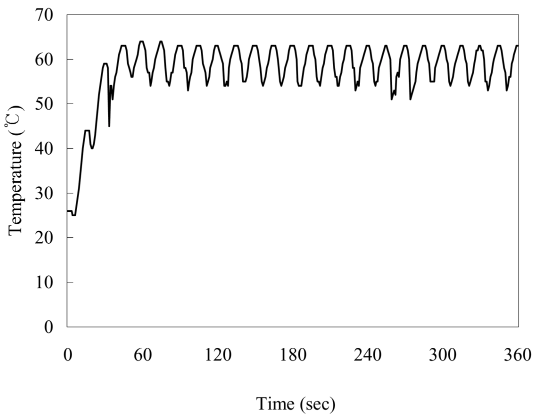


Fig. 5. Fluctuation of outlet temperature in CMC-HS under duty ratio (10 sec On/5 sec OFF).

and a plateau was found at 100^{o}C in low rage of flow rate, probably due to the vaporization of water. Vaporization was observed at flow rate lower than 1.85 ml/sec (Fig. 4(b)). Critical flow rate causing vaporization of the fluid was 2.04 ml/sec.

Relationship between duty ratio of magnetron and fluctuation of outlet temperature

Heating performance of CMC-HS operated under controlled duty ratio showed almost the same pattern as that of without control except the significant fluctuation of the outlet temperature. For the protection of magnetron, microwave heating was conducted by controlling the duty of magnetron, and altering the duty cycle caused fluctuation of the outlet temperature. Fluctuation span reached 9^{o}C at the small coil heat exchanger. Upon comparison of the fluctuation gaps of the two coil units at various flow rates, large coil exchanger showed smaller fluctuation gap than the small one.

Conclusion

In this study cylindrical microwave cavity was applied to the continuous sterilization of liquid food. Because focused electro-magnetic field strength could be used for intensive heating necessary to instantly inactivate microorganisms, helical coils were designed with glass tubing to effectively absorb the microwave energy. Instant and direct heating properties of micro-wave were ideal for the sterilization process due to the simplicity of temperature control with residence time of target liquid food. Although over-heating occurred at low flow rate in large coil, dimension of helical coil did not affect the process temperature at higher flow rate.

In the operation of magnetron based on duty cycle, significant fluctuation in temperature was observed due to ON and OFF operation of the magnetron. The degree of fluctuation was influenced by the size of heat exchanger.

Consequently, dimension of heat exchanger was an important design factor for microwave pasteurizer, whereas duty cycle and flow rate were reserved as manipulation factors, which could be handled by the operation program.

Nomenclature

A: Cross section area of heat exchanger, m^2
A: Attenuation factor
C_p: Specific heat capacity, kJ/kg·^{o}C
E: Strength of electric field of wave at that location, F
f : Frequency of the microwave, MHz
F: Flow rate, m^3/sec
k: Generalized dielectric constant
L: Length of heat exchanger, m
Q: Heat energy, W
r: The radius of glass coil, m
T_0: Initial temperature of materials, ^{o}C
T: Temperature of product, ^{o}C
t: Time, sec
tan δ: Loss tangent
V: Volume, m3
$\bar{v}$: Mean lineal velocity, m/sec
ε”: Dielectric loss factor
$\varepsilon_{0:}$ Permittivity of free space, F/m
λ: Wavelength of the field in free space, m
μ: Viscosity of food, N□/m^2
ρ: Density of material, kg/m^3

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