

# The Study of Heat Penetration of Kimchi Soup on Stationary and Rotary Retorts

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**ABSTRACT:** The aim of this study was to determine the heat-penetration characteristics using stationary and rotary retorts to manufacture Kimchi soup. Both heat-penetration tests and computer simulation based on mathematical modeling were performed. The sterility was measured at five different positions in the pouch. The results revealed only a small deviation of  $F_0$  among the different positions, and the rate of heat transfer was increased by rotation of the retort. The thermal processing of retort-pouched Kimchi soup was analyzed mathematically using a finite-element model, and optimum models for predicting the time course of the temperature and  $F_0$  were developed. The mathematical models could accurately predict the actual heat penetration of retort-pouched Kimchi soup. The average deviation of the temperature between the experimental and mathematical predicted model was 2.46% ( $R^2=0.975$ ). The changes in nodal temperature and  $F_0$  caused by microbial inactivation in the finite-element model predicted using the NISA program were very similar to that of the experimental data of for the retorted Kimchi soup during sterilization with rotary retorts. The correlation coefficient between the simulation using the NISA program and the experimental data was very high, at 99%.

**Keywords:** retorted Kimchi soup, stationary and rotary retorts,  $F_0$  value, mathematical models

## INTRODUCTION

Consumers demand products with high sensory and nutritional quality, necessitating optimization for retort processing conditions. Excessive heat treatment is detrimental to food quality because it wastes energy, and should therefore be avoided, while reducing processing time will be advantageous to the sensory and nutritional qualities of thermally processed products.

Products are normally heated by mixed currents of conduction and convection. Convection induced by agitation, has been shown to increase the heating rate and reduce processing time (1,2). This is the underlying principle of rotary sterilization or retort systems. In such systems, the contents are agitated as the crate rotates, which eliminates cold points and reduces processing time by heating up the retort pouch faster and more evenly (3). Rotation of the retort crate also has a positive effect on the heat penetration in retort pouches during thermal processing (3).

In spite of the various aforementioned advantages of rotary retorts in food sterilization, only limited quantita-

tive heat-transfer data are available, and therefore the process is basically empirical in nature. There are few experimental data on the comparison and analysis of heat transfer-rates under various sterilization conditions. Therefore, further research to determine the optimum sterilization conditions as temperature, heating time and retort type on specific commercial retorted products is needed. And, the development of a useful mathematical model is a priority, since this could reduce the time and cost of applying rotary retorts commercially for new products.

The development of a mathematical model using finite-element modeling to predict the temperature distribution of a product during thermal processing requires consideration of the surface heat-transfer coefficient (4-6). The mathematical models used in most previous studies to evaluate the thermal processing of retort pouches have been based upon a very large value of heat-transfer coefficient  $h$ , assuming negligible resistance to heat transfer on the surface of the pouches (5-7). A review of the literature yielded no method for evaluating the thermal processing of retort pouches while tak-

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ing into account the value of coefficient  $h$  when using hot water as the heating medium (5,6).

Computer simulations are generally more accurate at reflecting the conditions of real food products when they employ a larger number of nodes, which require more processing time (1). This study used the commercial NISA program, which is an interpreter program that utilizes the finite-element method, to simulate the temperature profile relative to position and time during sterilization.

The objective of this study was to develop a predictive mathematical model using a finite-element model based on a computer simulation describing heat penetration for products under conditions of non-steady-state heat transfer, while taking heat-transfer coefficient  $h$  into account.

## MATERIALS AND METHODS

### Sample preparation

Experiments designed to compare the heat-penetration characteristics of retort-pouched Kimchi soup were conducted using stationary and rotary types of retort. The specifications of the ingredients and composition of the Kimchi soup are given in Table 1. The retortable pouches used (16.0×24.8×2.0 cm) were made from triple-layered laminating films (Sam-a Aluminium Co., Ltd., Seoul, Korea) composed of polyester (12  $\mu\text{m}$ ), aluminum (9  $\mu\text{m}$ ), and cast polypropylene (70  $\mu\text{m}$ ). The time course of the temperature and the sterility of the Kimchi soup and the retort during the sterilization process (49 min, 58 min on rotary and stationary retort, respectively) were monitored using an  $F_0$  (the time in minutes required to provide the lethality equivalent to that provided at 121°C for a stated time) sensor (TrackSense Pro, Ellab A/S, Hillerød, Denmark).

**Table 1.** Specifications of the Kimchi soup used for the experiments

Ingredient	Specification	Composition
Kimchi	Chonggazip Kimchi (Daesang FNF, Seoul, Korea)	Chinese cabbage, radish, and red-pepper powder
Tofu	Happy Soy (CJ CheilJedang, Seoul, Korea) sliced 2.5×2.5×1.0 cm	Soybean and coagulant
Pork	Blanched in water at 100°C during 1 min and sliced 3.0×3.0×0.5 cm	Part of the jowl
Kimchi soup sauce	Boiled at 100°C for 15 min	Anchovy paste, anchovy powder, chopped garlic and green onion, pork extract, red pepper powder, rice powder, and water

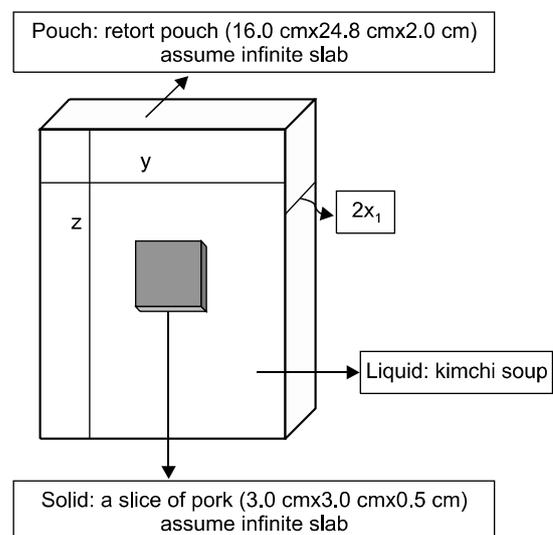
### Sterilization process

Each experiment of the heat-penetration characteristics focused on the cold point, which was assumed to be the center of the pork samples. The pouches were sterilized using a pilot-scale, one-basket, water-cascading retort (WS-PILOT-30s, WooSung Machinery MFG. Co., Ltd., Siheung, Korea) with both a static and rotary mode to study the effect of rotation on heat penetration. The rotation speed was 8 rpm, the sterilization temperature was set at 121°C, and the steam pressure was 2.0 kgf/cm<sup>2</sup> (200 kPa) during each experiment. All experiments were repeated at least five times, and the obtained data were subjected to statistical analysis.

### Assumptions for mathematical modeling

Steam/air and water retorts may have less consistent temperature distribution, so it is important that accurate cold point determination is carried out within such systems. In this study, the pork (3.0×3.0×0.5 cm, plate form) and tofu (2.5×2.5×1.0 cm, cube form) were the most important materials for determining the cold point. In preliminary experiments for the cold point selection in retorts, temperature rise occurred later in the geometric center of the pork compared to the tofu. In contrast to the thin thickness of pork compared to the tofu, large area and dense tissue structure of pork meat were considered to cause the temperature rise late. And considering the pork content and microbial safety aspects, we determined the geometric center of the pork as the cold point.

In order to develop appropriate mathematical models for predicting the temperature time course during sterilization, it was assumed that the retort pouch and the slice of pork were an infinite slab. The geometry for the heat conduction was a flat plate of thickness  $2x_1$  in the  $x$



**Fig. 1.** Diagram of non-steady-state conduction in a large flat plate.

direction, with large or infinite dimensions in the  $y$  and  $z$  directions, as shown in Fig. 1. Therefore, heat was conducted only from the two flat and parallel surfaces in the  $x$  direction, with characteristics of surface and internal resistance.

Fig. 2 shows the critical assumptions for each step of the modeling. First, it was assumed that the primary heating medium in the retort was hot water at 120.7°C since the actual sterilization temperature reached 120.7°C. The viscosity of Kimchi soup is sufficiently low so that it can be considered to be a simple Newtonian fluid, such as pure water (3,4,6). With the assumption that Kimchi soup was a secondary heating medium, a slice of pork placed into the soup would be heated by the soup sauce. Finally, the temperature at the center of the slice of pork was predicted using a non-steady-state conduction model.

And this study used the commercial NISA program (NISA/Heat, Cranes Software Inc., Troy, MI, USA) which is an interpreter program that utilizes the finite-element method, to simulate the temperature profile relative to position and time during sterilization.

## RESULTS AND DISCUSSION

### Procedures for developing mathematical models

**Stationary retort:** A mathematical model was developed to predict the time course of the temperature for a stationary retort system. A dimensionless correlation involving the heat-transfer coefficient ( $h$ ) was used with the Nusselt number. Equations (1) and (2) require the values of  $a$ ,  $\rho$ ,  $\beta$ ,  $\mu$ ,  $k$ ,  $g$ ,  $C_p$ ,  $D$ , and  $L$  to calculate  $h$ :

$$N_{Nu} = a \left( \frac{L^3 \rho^2 g \beta \Delta T}{\mu^2} \times \frac{C_p \mu}{k} \right)^m = a (N_{Gr} N_{Pr})^m \quad (1)$$

$$N_{Nu} = \frac{hD}{k} \quad (2)$$

where  $N_{Nu}$  is Nusselt number,  $a$  and  $m$  are constants,  $L$  is characteristic length (m),  $\rho$  is density ( $\text{kg/m}^3$ ),  $g$  is gravitational force ( $\text{m/s}^2$ ),  $\beta$  is thermal expansion coefficient ( $\text{K}^{-1}$ ),  $\Delta T$  is temperature variation ( $^\circ\text{C}$ ),  $\mu$  is viscosity ( $\text{kg/m}\cdot\text{s}$ ),  $C_p$  is heat capacity ( $\text{kJ/kg}\cdot\text{K}$ ),  $k$  is thermal conductivity ( $\text{W/m}\cdot\text{K}$ ),  $N_{Gr}$  is Grashop number,  $N_{Pr}$  is Prandtle number,  $h$  is heat transfer coefficient ( $\text{W/m}^2\cdot\text{K}$ ), and  $D$  is diameter (m).

The assumed physical properties and the estimated convective heat-transfer coefficient of the primary heating medium (water at 120.7°C) are presented in Table 2. Using  $h$ ,  $N_{Bi}$  (Eq. 3) and  $m$  (Eq. 4) could be calculated as follows:

$$N_{Bi} = \frac{hx_1}{k} \quad (3)$$

$$m = \frac{k}{hx_1} \quad (4)$$

where  $N_{Bi}$  is Biot number, and  $m$  is a dimensionless parameter.

Each property listed in Table 2 was also used to generate the temperature profiles of the secondary heating medium, Kimchi soup, during the retort process. Temperature time course of the secondary heating medium was predicted using the Gurney-Lurie chart and assuming that the initial temperature of the retort pouch was 57.18°C. The next step involved predicting the temperature at the center of the pork. It was assumed that the slice of pork was heated by a second heating medium, the Kimchi soup sauce. The temperature of the Kimchi soup was already predicted in the previous step. Before predicting the temperature at the center of the pork,  $h$  should be evaluated preferentially. The heat-transfer coefficient between the secondary heating medium, the Kimchi soup sauce, and the pork was calculated using the Nusselt number and Eq. 1 and 2. The calculated physical properties of the secondary heating medium used for the analysis are summarized in Table 2, enabling evaluation of the heat-transfer coefficient between the Kimchi soup sauce and the pork (Table 2).  $N_{Bi}$  (Eq. 3) and  $m$  (Eq. 4) were also calculated using  $h$ .

Each property given in Table 2 was also used to generate pork temperature profiles, where  $T_1$  is the initial bulk temperature (57.18°C) and  $T_0$  is the initial solid surface temperature (57.18°C). The method designed for predicting the pork temperature during thermal process-

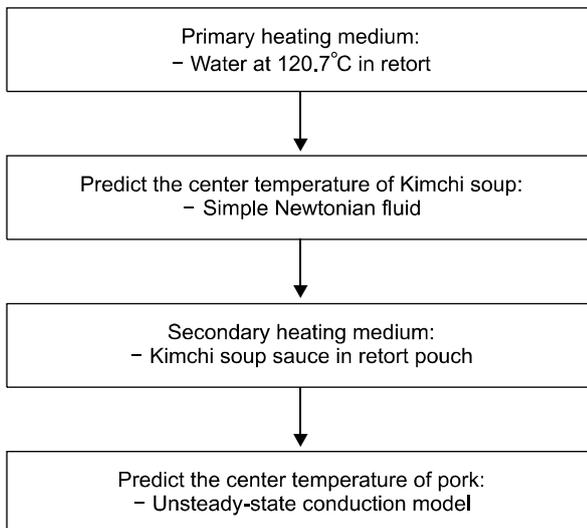
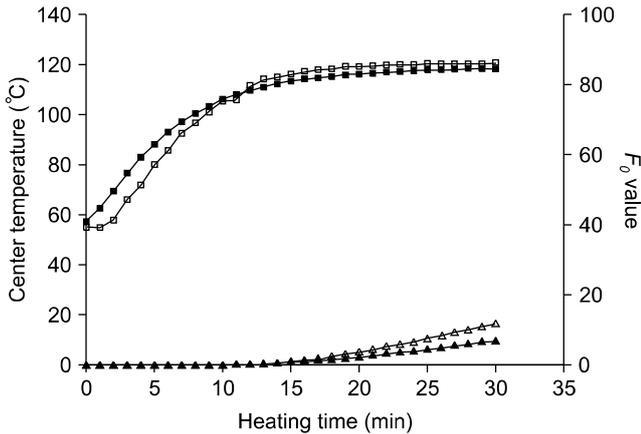


Fig. 2. Prediction procedure for the temperature of pork.

**Table 2.** Physical and thermal properties of the primary and secondary heating media for the stationary retort

Primary heating medium						
$L$ (m)	$\rho$ (kg/m <sup>3</sup> )	$\beta$ (K <sup>-1</sup> )	$\Delta T$ (°C)	$\mu$ (kg/m·s)	$C_p$ (KJ/kg·K)	$k$ (W/m·K)
0.248	965.68	$6.41 \times 10^{-4}$	63.52	$0.3261 \times 10^{-3}$	4.222	0.6775
Constants			Values	Calculation basis		
$h$ (W/m <sup>2</sup> ·K)			3,208	Natural convection		
$\alpha$ (m <sup>2</sup> /s)			$1.616 \times 10^{-7}$	[0.057363 W+0.000288(7+273)] $\times 10^{-6}$ m <sup>2</sup> /s		
$x$ (m)			0.01	Heat transfer considered only in $x$ direction		
$N_{Bi}$			47.351	Eq. 3		
$m$			0.0211	Eq. 4		
Secondary heating medium						
$L$ (m)	$\rho$ (kg/m <sup>3</sup> )	$\beta$ (K <sup>-1</sup> )	$\Delta T$ (°C)	$\mu$ (kg/m·s)	$C_p$ (KJ/kg·K)	$k$ (W/m·K)
0.03	965.68	$6.41 \times 10^{-4}$	63.52	$0.3261 \times 10^{-3}$	4.222	0.46
Constants			Values	Calculation basis		
$h$ (W/m <sup>2</sup> ·K)			10,997	Natural convection		
$\alpha$ (m <sup>2</sup> /s)			$1.33 \times 10^{-7}$	Referring to literature		
$x$ (m)			0.0025	Heat transfer considered only in $x$ direction		
$N_{Bi}$			49.766	Eq. 3		
$m$			0.0167	Eq. 4		

W: water content (%).



**Fig. 3.** Comparison of experimental and predicted temperatures and  $F_0$  values for the stationary retort. ■, experimental temperature; □, predicted temperature; ▲, experimental  $F_0$  value; △, predicted  $F_0$  value.

ing was same as that used in the previous step. The prediction data for the temperature at the center of the pork are presented in Fig. 3.

**Rotary retort:** We assumed that the circulation of hot water and Kimchi soup on the rotary retort was turbulent flow by rotation. For this reason, we used the equation related to forced convection heat transfer on this study (4-6).

A mathematical model was developed to predict the time course of the temperature for a rotary retort system. A dimensionless correlation involving the heat-transfer coefficient ( $h$ ) was used with the Nusselt number. Eq. 2 and Eq. 5 required the values of  $\nu$ ,  $\rho$ ,  $\beta$ ,  $\mu$ ,  $k$ ,  $C_p$ ,  $D$ , and  $L$  to calculate  $h$ :

$$N_{Nu} = \frac{h_1 D}{k} = 0.023 N_{Re}^{0.8} N_{Pr}^{\frac{1}{3}} \left( \frac{\mu_b}{\mu_w} \right)^{0.14} \quad (5)$$

where  $N_{Re}$  is Reynold number.

The assumed physical and thermal properties of the primary heating (water at 120.7°C) and secondary heating media (Kimchi soup sauce) for the rotary retort are presented in Table 3, respectively. The applied method was the same as for the prediction procedure on the stationary retort system. Each property given in Table 3 was also used to generate pork temperature profiles, where  $T_1$  is the initial bulk temperature (57.66°C) and  $T_0$  is the initial solid surface temperature (57.66°C). The method designed for predicting the pork temperature during thermal processing was same as that used in the previous step, and the prediction results for the temperature at the center of the pork are presented in Fig. 4.

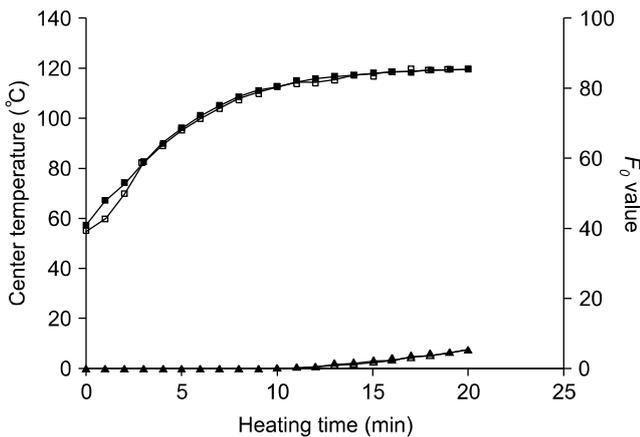
The goal of this study was to develop models that could be used to accurately predict the conditions of thermal processing of retort-pouched foods. The main feature of these models was the ability to predict the time course of the temperature at the center of the product over the time, with knowledge of the initial conditions of the product and retort temperature during treatment.

The temperature and  $F_0$  profiles at the center of the pork predicted by optimum mathematical models for stationary and rotary retort modes are shown in Fig. 3 and 4, respectively. These figures show comparisons of the simulation data with the experimental data. For the stationary retort, the predicted temperatures were a little lower than the experimental temperatures in the early part of the heating stage (before 11 min), but during

**Table 3.** Physical and thermal properties of the primary and secondary heating media for the rotary retort

Primary heating medium						
$D$ (m)	$\rho$ (kg/m <sup>3</sup> )	$\nu$ (m/s)	$\mu$ (kg/m·s)	$C_p$ (KJ/kg·K)	$k$ (W/m·K)	$L$ (m)
0.6	965.68	0.25	$0.3261 \times 10^{-3}$	4.222	0.6775	0.9
Constants			Values		Calculation basis	
$h$ (W/m <sup>2</sup> ·K)			52,973		Forced convection	
$\alpha$ (m <sup>2</sup> /s)			$1.616 \times 10^{-7}$		$[0.057363 W + 0.000288(T + 273)] \times 10^{-6}$ m <sup>2</sup> /s	
$x_1$ (m)			0.01		Heat transfer considered only in $x$ direction	
$N_{Bi}$			731.89		Eq. 3	
$m$			0.0013		Eq. 4	
Secondary heating medium						
$D$ (m)	$\rho$ (kg/m <sup>3</sup> )	$\nu$ (m/s)	$\mu$ (kg/m·s)	$C_p$ (KJ/kg·K)	$k$ (W/m·K)	$L$ (m)
0.005	965.68	$8.38 \times 10^{-3}$	$0.3261 \times 10^{-3}$	4.222	0.64	0.03
Constants			Values		Calculation basis	
$h$ (W/m <sup>2</sup> ·K)			1,456		Forced convection	
$\alpha$ (m <sup>2</sup> /s)			$1.33 \times 10^{-7}$		Refer to literature	
$x$ (m)			0.0025		Heat transfer considered only in $x$ direction	
$N_{Bi}$			7.913		Eq. 3	
$m$			0.1264		Eq. 4	

W: water content (%).



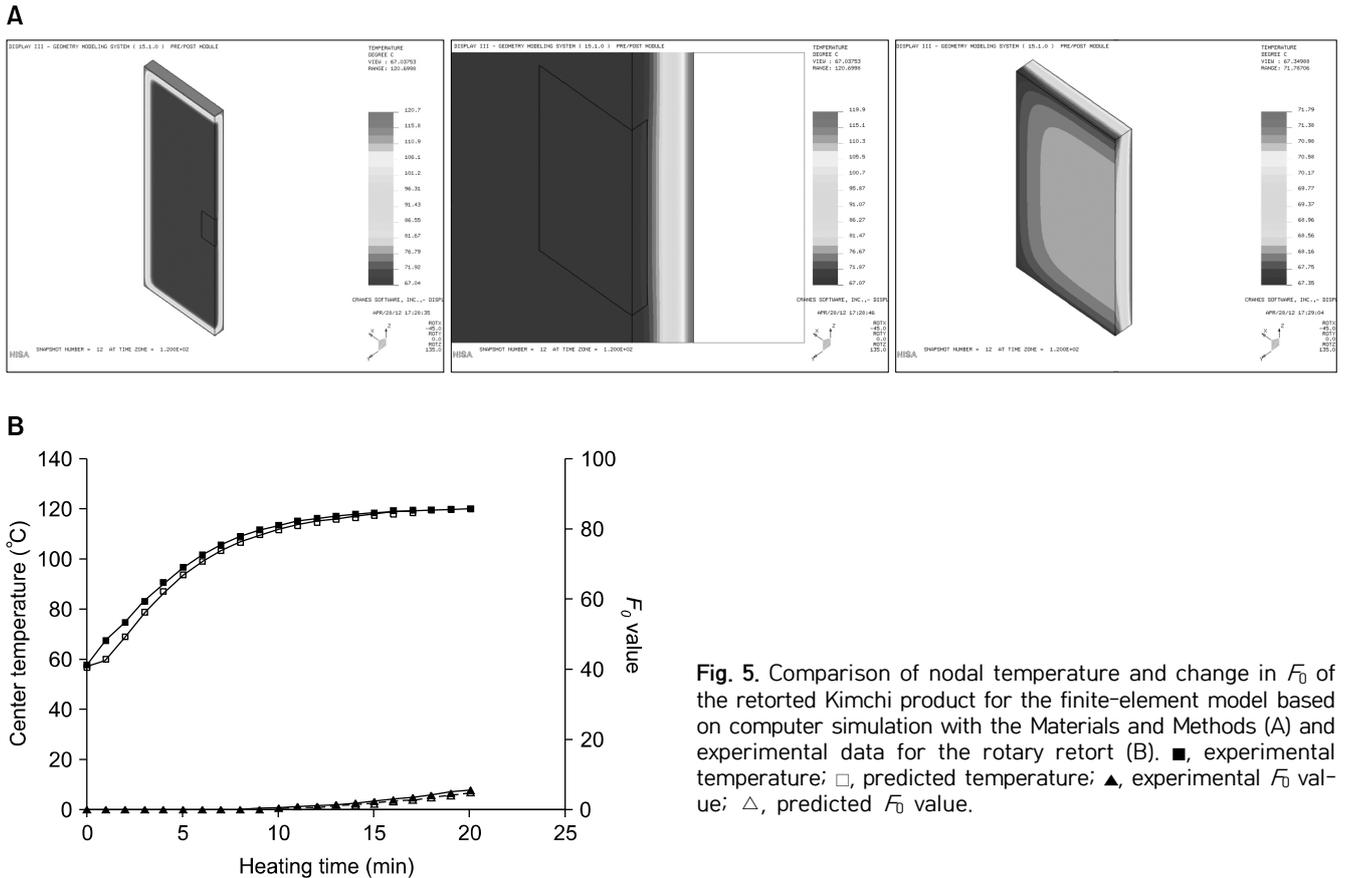
**Fig. 4.** Comparison of experimental and predicted temperatures and  $F_0$  values for the rotary retort. ■, experimental temperature; □, predicted temperature; ▲, experimental  $F_0$  value; △, predicted  $F_0$  value.

the later stage, the predicted temperatures provided a good match to the experimental temperatures. The average deviation of temperature between the experimental and mathematical predicted models was 2.68% ( $R^2=0.975$ ). A similar pattern was observed for the rotary retort. Good predictions (deviation=2.24%,  $R^2=0.974$ ) were also obtained when induced agitation was employed (especially after 3 min). The discrepancy during the early stage may be due to several factors. First, there was a natural acceptable error range of 0.5~1.0°C in the thermocouple response. Second, there was an experimental error of unmeasurable magnitude with respect to where the thermocouples were placed inside the pouch, including the accuracy of the recorder (7). In addition, there are many processing factors that could influence

the rate of heat penetration. For example, the rate of heat transfer on the surface of the pouch depends upon the circulation rate of the heating medium across the pouch surface (8-10).

For the prediction of  $F_0$ , the data for the rotary retort (Fig. 4) revealed a strong correlation ( $R^2=0.995$ ) between the experimental and predicted values throughout the process. However, the stationary retort data were not satisfactory to predict  $F_0$ , as shown in Fig. 3. Various factors could be responsible for these differences. For example, they could be explained by the presence of a headspace bubble preventing heat transfer in the stationary retort, resulting in a lower sterilization value than expected. Furthermore, comparison of the experimental and predicted values obtained using the mathematical model revealed that the measured temperatures increased faster than the predicted temperatures. This is because the shortest path between the surface and the center of the product determines the heating rate of particulates, and thus dimensional changes in the meat could have influenced the measured temperatures. However, after a few minutes, the measured temperature profile exhibited a similar shape to that of the predicted center temperature. This was considered to indicate that no more significant dimensional changes had occurred. On the other hand, for the rotary retort there is a threshold rotational speed above which agitation is induced and heating rates increase dramatically (11-13), which may improve the sterilization effect.

In the rotary retort, the deviation between the experimental and mathematical total sterilization values was 17.57%. This shows that the temperatures in the retort-pouched Kimchi soup were predicted satisfactorily.



**Fig. 5.** Comparison of nodal temperature and change in  $F_0$  of the retorted Kimchi product for the finite-element model based on computer simulation with the Materials and Methods (A) and experimental data for the rotary retort (B). ■, experimental temperature; □, predicted temperature; ▲, experimental  $F_0$  value; △, predicted  $F_0$  value.

The mathematical model may therefore be used to optimize conditions for new products where induced agitation is employed (14,15). However, for the stationary retort, additional research is needed to determine whether the approach presented in this study can be applied to other food products, since the deviation between the experimental and mathematical total sterilization values was 53.87%. This large discrepancy is due to the deviation of the average experimental sterilization value being relatively large, and it indicates that the average experimental and mathematical values were incorrect. In addition, during stationary retorting, the headspace in the retort pouch functioned as a resistance that prevented the experimental value reaching the predicted sterilization value. Additional methods that compensate for such deviations of the average experimental value and resistance are needed. If such revisions are made to this method, the predicted heat-penetration curve is expected to better fit the experimental curve.

After preprocessing was completed, the results were generated by running the NISA solver. Results such as the time courses of the various nodal temperatures and the temperature distribution of the Kimchi soup product were identified both visibly and numerically, and were compared to the experimental data. The degree of lethality predicted through finite-element modeling was also compared to that calculated from the experimental data.

The changes in nodal temperature and  $F_0$  caused by microbial inactivation in the finite-element model predicted using the Materials and Methods were very similar to that in of the experimental data of the retorted Kimchi soup product during sterilization with rotary retorts. The correlation coefficient between the simulation and experimental data was very high, at 99% (Fig. 5).

In summary, the heat transfer in retort-pouched Kimchi soup was investigated to compare the heat-penetration characteristics of stationary and rotary retorts and to develop mathematical models. Optimum models for predicting the time course of the temperature and  $F_0$  were developed. The mathematical models developed for the rotary retort could be used to rapidly determine the optimal sterilization conditions for new commercial products. However, the mathematical models for stationary retort require additional research in order to reduce the discrepancy from the experimental data.

## AUTHOR DISCLOSURE STATEMENT

The authors declare no conflict of interest.

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