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Study of Radio Frequency Thawing for Cylindrical Pork Sirloin

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Abstract

Purpose: Radio frequency (RF) heating is a promising thawing method, but it frequently causes undesirable problems such as non-uniform heating. This can occur because of the food shape, component distribution, and initial temperature differences between food parts. In this study, RF heating was applied to the thawing of cylindrically shaped pork sirloin by changing the shape of electrodes and the surrounding temperature. **Methods:** Curved electrodes were utilized to increase the thawing uniformity of cylindrically shaped frozen meat. Pork sirloin in the shape of a half-circle column was frozen in a deep freezer at -70℃ and then thawed by RF heating with flat and curved electrodes. In order to prevent fast defrosting of the food surface by heat transfer from air to the food, the temperature of the thawing chamber was varied by -5, -10, and -20℃. The temperature values of the frozen pork sirloin during RF thawing were measured using fiber-optic thermo sensors. **Results:** After multiple applications of curved electrodes resembling the food shape, and a cooled chamber at -20℃ the half-cylindrically shaped meat was thawed without surface burning, and the temperature values of each point were similarly increased. However, with the parallel electrode, the frozen meat was partially burned by RF heating and the temperature values of center were overheated. The uniform heating rate and heat transfer prevention from air to the food were crucial factors for RF thawing. In this study, these crucial factors were accomplished by using a curved electrode and lowering the chamber temperature. **Conclusions:** The curved shape of the electrode and the equipotential surface calculated from the modeling of the parallel capacitor showed the effect of uniform heating of cylindrically shaped frozen food. Moreover, the low chamber temperature was effective on the prevention of the surface burning during RF thawing

Keywords: Electromagnetic, Frozen food, Heating, Radio Frequency, Thawing

Introduction

Electromagnetic waves within the frequency range of 3 kHz to 300 GHz can directly heat the inner regions of food through the combination of dipole rotation and electric resistance heating resulting from the movement of dissolved ions following the alternating electric field (Ryynänen, 1995; Piyasena, 2003). The penetration depth of the electromagnetic waves significantly depends on the dielectric characteristics of the food (Bengtsson and Risman, 1971; Piyasena et al., 2003). A radio frequency (RF) has a deeper penetration depth than microwave (MW) frequencies for unfrozen food because of the longer wavelength. For example, the penetration depth for unfrozen lean beef at -1℃ was 18.4 cm and 1.6 cm at 27.12 MHz and 2.45 GHz, respectively (Farag et al., 2008). During MW thawing, the surface of the frozen food usually melts faster than the inner region due to the heat transfer from air to the food, and the defrosted surface of the frozen food absorbs most of the MW energy (Song and Park, 1995; Ohlsson, 1999; Uyar et al., 2015). Therefore, with MWs, the inner region of frozen food is thawed, not

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by direct heating, but by thermal conduction such as conventional thawing. Consequently, RF heating has been considered a promising thawing method because of the rapid and uniform heat distribution along with adequate penetration depth (Farag et al., 2011; Wang et al., 2012; Llave et al., 2014).

Specific radio frequencies such as 13.56, 27.12, and 40.68 MHz are permitted for use in industrial, scientific, and medical applications (ISM) by the International Telecommunication Convention (ITU Convention) because other radio frequencies can interfere with communication and radar systems. During the phase change from ice to water, the dielectric constant (D.C) was calculated to change from 3 to 88 using the Debye relaxation parameters and equations (Artemov and Volkov, 2014). For frozen tuna, the D.Cs at the RF frequencies of 13.56 and 27.12 MHz changed sharply within the defrosting temperature range from -5 to 0℃, and the variation was proportional to the moisture content of the tuna (Llave et al., 2014). The D.C of lean beef changed from 13 to 79 at 35 MHz and from 18 to 101 at 10 MHz in the temperature zone from -5 to 10℃ (Bengtsson et al., 1963). From this result, if some part of the frozen beef is defrosted, the D.C of that area changes from 13 to 79, and that area receives more energy than the frozen area. Therefore, uniform heating is the greatest concern during thawing.

Frozen food is widely utilized for its usability and microbial safety, so there has been much research on the thawing of frozen food (Jo et al., 2014; Park et al., 2015). Because of the larger penetration depth and heating uniformity, RF heating has an advantage for heating large food sizes even though sometimes partial burning was found during thawing. For the uniform thawing of cylindrically shaped pork sirloin, the shape of the electrode was designed by calculating the heating rate of capacitors and then tested. The relation between the surface overheating and the chamber temperature was tested by varying the chamber temperature among -5, -10 and -20℃.

Materials and Methods

Sample preparation

Pork sirloin was purchased from a local distributer and cut into 20 cm lengths. The weight of each sample was around 1 kg. The outside fascia of the meat was trimmed to check the burning and color changes (Figure 1(a)). To achieve the half-cylindrical shape of the frozen pork sirloin, the meat was placed on an extra curved electrode and the upper side of the meat was pressed with a copper plate (Figure 1(b)). Therefore, the curved shape of the frozen meat was similar to the shape of the electrode (Figure 1). Each sample was frozen at -70℃ in a deep freezer (DFC-200, Operon, Gimpo, Korea). Before freezing, four fiber-optic thermo sensors (TS2, Optocon AG, Dresden, Germany) were inserted at different points to a depth of ~10 cm.

Electrode modeling

An RF heating system usually utilizes parallel plane

(a) (b) (c)

Figure 1. Making the half-cylindrically shaped frozen meat.

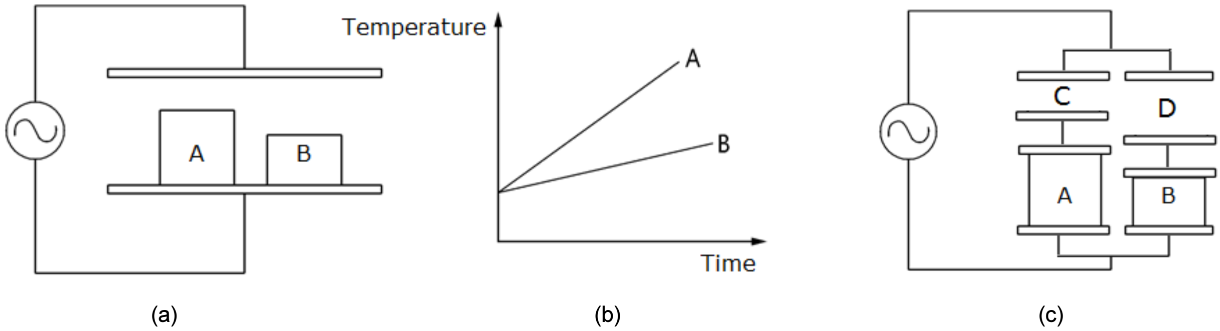


Figure 2. Heating rate difference considering food thicknesses.

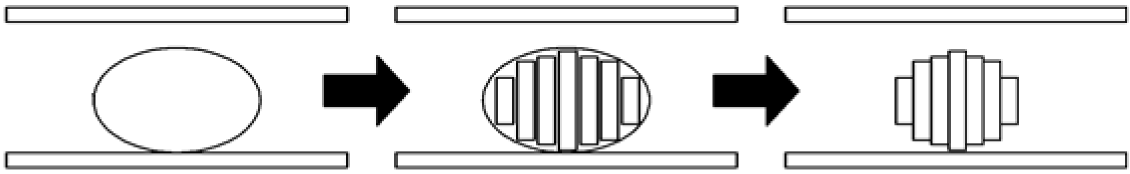


Figure 3. Schematic showing division of cylindrical food into a mixture of different rectangular parallelepiped heights.

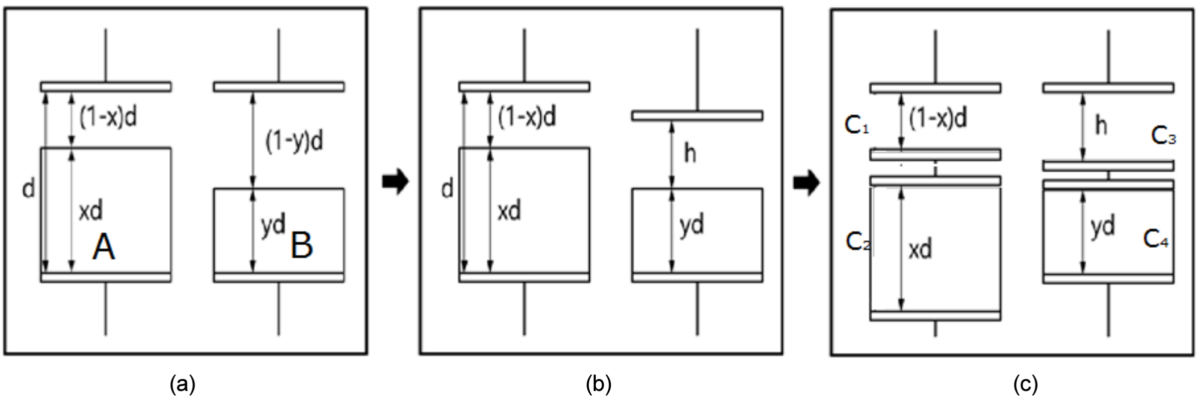


Figure 4. Schematic for calculating the height h for uniform heating.

electrodes. If two food blocks with different heights are heated like in Figure 2(a), the thicker one receives more RF energy than the thinner one (Figure 2(b)) because the capacitance of the thicker one is larger than that of thinner one, and the heating power is proportional to the capacitance according equation (2). For the calculation, Figure 2(a) can be separated by four capacitors as shown in Figure 2(c).

The cylindrically shaped food can be divided into rectangular parallelepipeds with different heights (Figure 2). To make a model of the electrode shape for uniform thawing, the distance h in Figure 3 was calculated for the same heating rate of two different food heights. From classical electrodynamics, the capacitance C of a parallel capacitor is proportional to the D.C $\varepsilon = \varepsilon_0 \varepsilon_r = \varepsilon_0(\varepsilon' - j\varepsilon'')$ and cross sectional area A, and inversely proportional to the thickness , as in the following equation.

$$C = \varepsilon \frac{A}{d} \tag{1}$$

The heating energy W of the parallel capacitor is proportional to the capacitance C and the square of the voltage V.

$$W = \frac{1}{2} C V^2 \tag{2}$$

If the heating rate of two different heights of food in Figure 4(a) is same, the heating powers of blocks A and B are proportional to the heights of food:

$$W_a : W_b = x : y \qquad (3)$$
$$W_a = \frac{x}{y} W_b$$

An easy expression for the capacitances in Figure 4(c) is:

$$C_1 = 1\frac{A}{(1-x)d},\ C_2 = \varepsilon_r \frac{A}{xd},\ C_3 = 1\frac{A}{h},\ C_4 = \varepsilon_r \frac{A}{yd} \qquad (4)$$

Then, the powers W_a, W_b can be expressed as:

$$W_a = \frac{1}{2} C_2 V_2^2 = \frac{1}{2} C_2 \left(\frac{C_a}{C_2} V \right)^2, \qquad (5)$$
$$W_b = \frac{1}{2} C_4 V_4^2 = \frac{1}{2} C_4 \left(\frac{C_b}{C_4} V \right)^2$$

Meanwhile,

$$C_a = \frac{C_1 C_2}{C_1 + C_2},\ C_b = \frac{C_3 C_4}{C_3 + C_4} \qquad (6)$$

To find the height h, equation (3) can be simplified as follows:

$$\frac{1}{2}\frac{1}{C_2}\left(\frac{C_1 C_2}{C_1 + C_2} V \right)^2 = \frac{x}{y}\frac{1}{2}\frac{1}{C_4}\left(\frac{C_3 C_4}{C_3 + C_4} V \right)^2 \qquad (7)$$
$$\frac{1}{C_2}\left(\frac{C_1 C_2}{C_1 + C_2} \right)^2 = \frac{x}{y}\frac{1}{C_4}\left(\frac{C_3 C_4}{C_3 + C_4} \right)^2$$
$$C_2\left(\frac{1}{C_1} + \frac{1}{C_2} \right)^2 = \frac{y}{x} C_4 \left(\frac{1}{C_3} + \frac{1}{C_4} \right)^2$$
$$\varepsilon_r \frac{A}{xd}\left(\frac{1}{C_1} + \frac{1}{C_2} \right)^2 - \frac{y}{x}\varepsilon_r \frac{A}{yd}\left(\frac{1}{C_3} + \frac{1}{C_4} \right)^2$$
$$\frac{1}{C_1} + \frac{1}{C_2} = \frac{1}{C_3} + \frac{1}{C_4}$$
$$(1-x)d + \frac{xd}{\varepsilon_r} = h + \frac{yd}{\varepsilon_r}$$

Therefore, the height h can be calculated for the uniform heating:

$$h = (1-x)d + \frac{(x-y)d}{\varepsilon_r} \qquad (8)$$

Considering the D.C of frozen meat is around 10 at -10℃ (Bengtsson et al., 1963), h would be approximately equal to $(1-x)d$, and the shape of the electrodes can be simplified as in Figure 5(a). In the case of a small D.C, Figure 5(b) can be applied. The electrodes for the cylindrically shaped

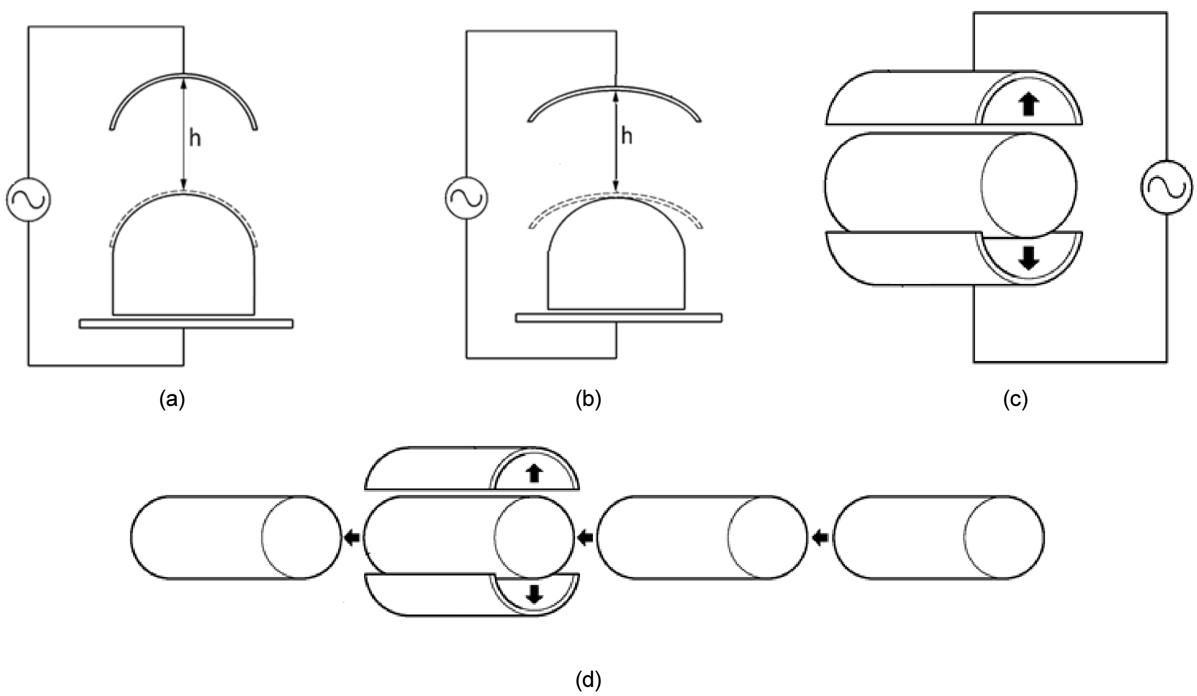


Figure 5. Electrode modeling for (a) high D.C, (b) low D.C, (c) cylindrical food, and (d) cylindrical food using a conveyer belt.

pork sirloin are shown in Figure 5(c) and 5(d).

RF Thawing methods

To prevent the surface from defrosting to fast via heat transfer from air to the food, a custom-built chamber with temperature control from -40 to 10℃ was used (Figure 6(a); Kim et al., 2014; Kim et al., 2015). An RF generator (TX-20, ADTEC Plasma Technology Co. Ltd., Hiroshima, Japan) and an auto-matcher (TST-2720, TST Co., Sungnam, Korea) were used for the RF power source. During the thawing, 27.12 MHz 800 W RF power was supplied. The temperature of the meat was data logged by a fiber optic thermo sensor (FOTEMP4, Optocon AG, Dresden, Germany). To decrease the effect of the heat transfer from the surrounding air to the frozen meat, three chamber temperatures of -5, -10, and -20℃ were tested. The frozen pork was placed in parallel with the curve electrode as shown in Figure 5(a) (Figure 6(b)).

Results and Discussion

Before using the curved electrode, the half-cylindrically shaped frozen pork was thawed with parallel plate type electrodes. The thicker part of the frozen meat seemed to be intensively heated (Figure 7(a)) and the temperature values near the center increased quickly (Figure 8(a)). By using the curved electrode, the meat was thawed with no surface burning (Figure 7(b)), and the temperature

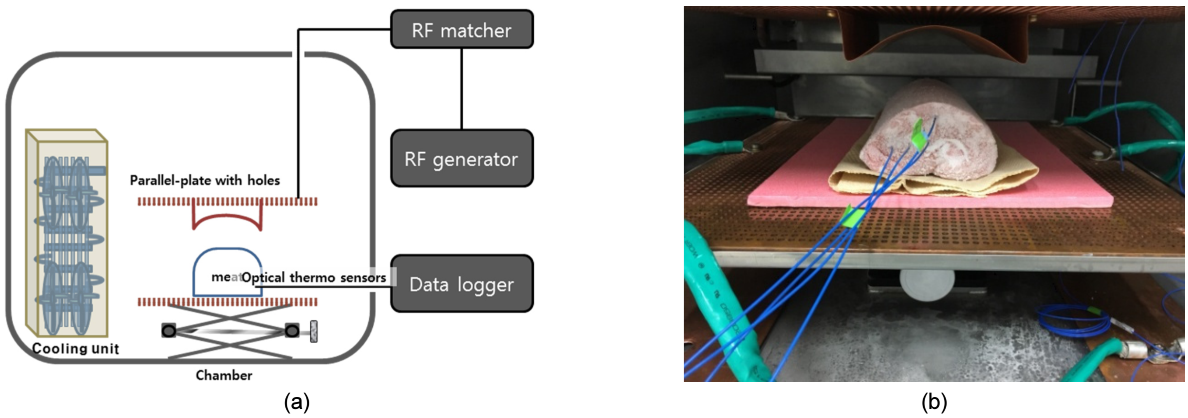


Figure 6. (a) Schematic and (b) pictures of the custom-built freezing-thawing chamber (Kim et al., 2015).

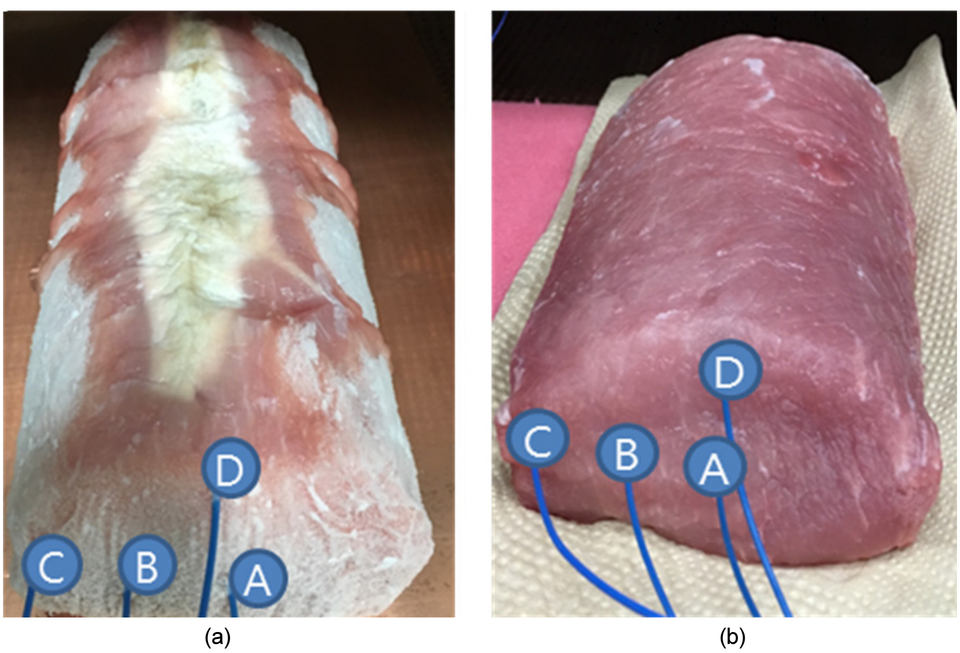
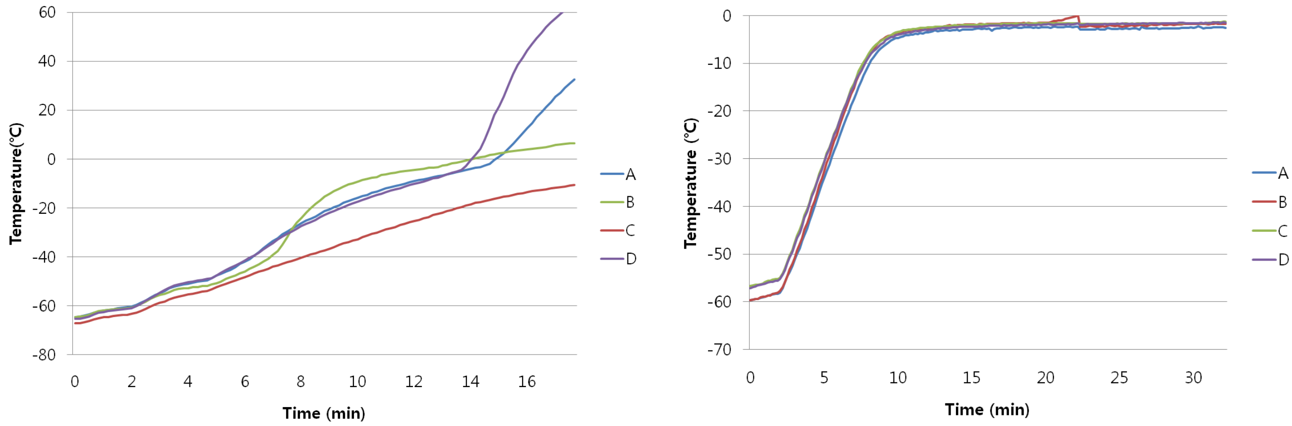
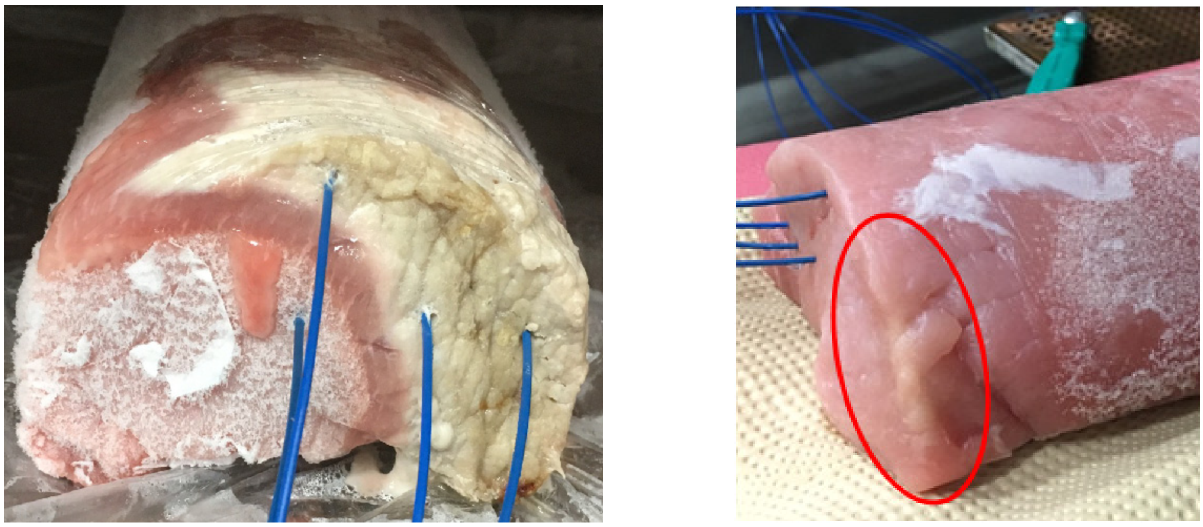


Figure 7. Frozen pork thawed by (a) parallel type and (b) curved electrodes with a chamber temperature of -20℃.



(a) (b)

Figure 8. Time-temperature graph thawed by (a) parallel and (b) curved electrodes.



(a) (b)

Figure 9. Burning and surface color changes of frozen meat heated by RF (a) with no cooling and (b) cooling of chamber to -5℃.

values were similar to each other (Figure 8(b)). The curved electrode was designed using the model in Figure 5 and it seemed to affect the uniform thawing.

The temperature control of the chamber was also used in the food thawing in Figure 7(b). Before cooling, the initial temperature difference between the surrounding air and the frozen meat was over 80°, and the corner surface of the frozen meat was quickly thawed and burned by RF heating and heat transfer from the surrounding air (Figure 9(a)). By cooling the chamber to -5℃, the surface burning was moderated (Figure 9(b)), and the temperature values did not diverge (Figure 10(a)). The initial temperature of the frozen meat in this study was under -60℃, so the lower -20℃ temperature was the most effective at preventing fast defrosting of the surface among three chamber temperature -5, -10, and -20℃ (Figure 7(b), Figure 10). However, if the initial temperature of the frozen meat is around -20℃, the chamber temperatures of -10 and -5℃ may be enough to prevent fast surface defrosting during RF thawing.

Conclusions

During RF thawing of the cylindrically shaped pork sirloin, the curved electrode was effective at improving the temperature uniformity. The heat transfer from air to the frozen meat caused surface overheating, which needed to be minimized. This could be done by decreasing the chamber temperature. From these results, multiple applications of the curved electrodes and temperature control of the chamber could improve the quality of the

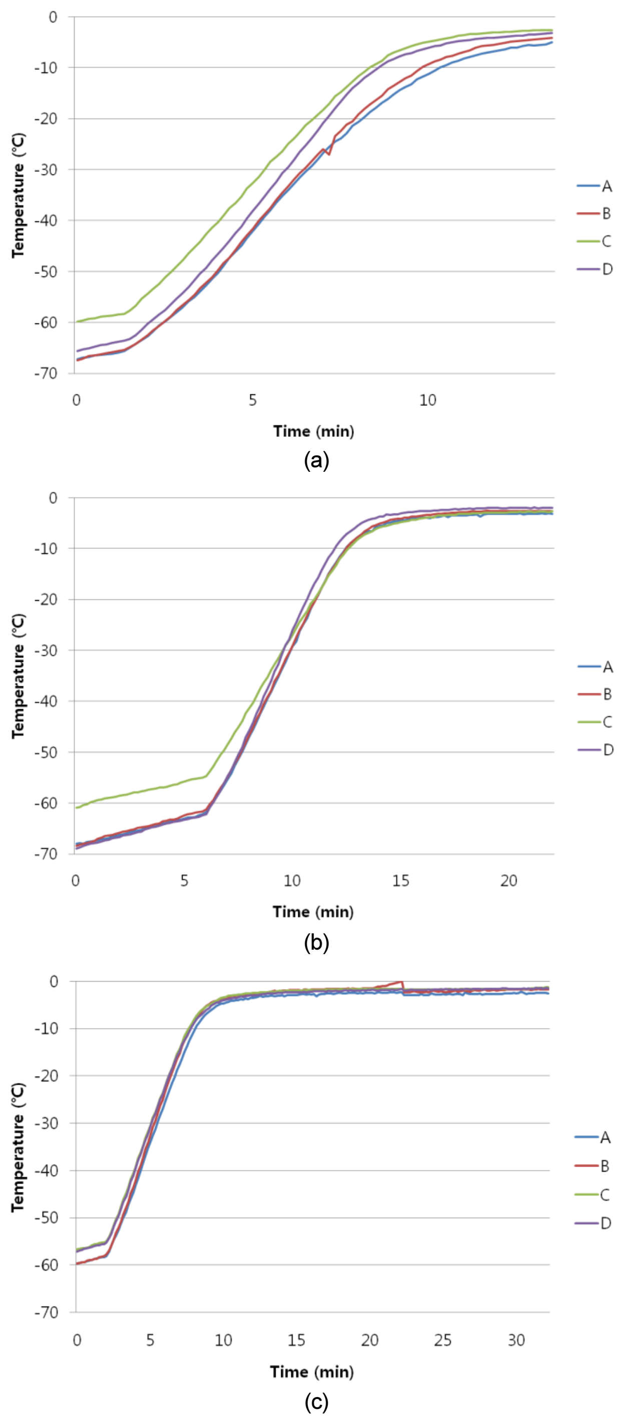


Figure 10. Time-temperature graph of frozen meat thawed by different chamber temperatures (a) -5℃, (b) -10℃, and (c) -20℃.

thawed frozen food. As in the model in Figure 5, a third equipotential electrode with a curved shape can be applied. The main idea for using curved electrodes was to obtain an equipotential surface similar to that for food with a curved surface; hence, a floating equipotential surface can be applied to an RF heater with parallel electrodes and improve the uniformity of the temperature (Figure 11).

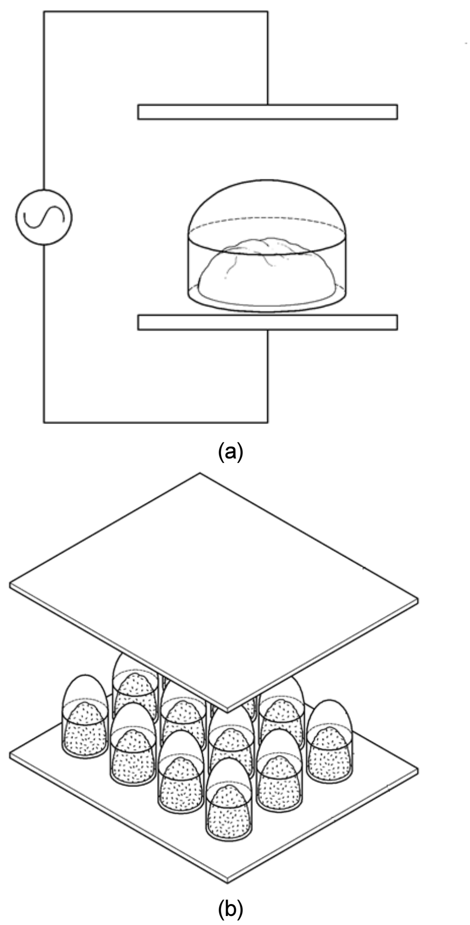


Figure 11. Third equipotential electrode for (a) frozen dumplings and (b) frozen strawberries.

Conflict of Interest

The authors have no conflicting interests, financial or otherwise.

Acknowledgments

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