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Effects of Electromagnetic Heating on Quick Freezing

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Abstract

Purpose: Quick freezing is widely used in commercial food storage. Well-known freezing techniques such as individual quick freezing require a low-temperature coolant and small cuts for the heat-transfer efficiency. However, the freezing method for bulk food resembles techniques used in the 1970s. In this study, electromagnetic (EM) heating was applied to improve the quick freezing of bulk food. **Methods:** During freezing, the surface of food can be rapidly cooled by an outside coolant, but the inner parts of the food cool slowly owing to the latent heat from the phase change. EM waves can directly heat the inner parts of food to prevent it from freezing until the outer parts finish their phase change and are cooled rapidly. The center temperature of garlic cloves was probed with optical thermo sensors while liquid nitrogen (LN) was sprayed. **Results:** When EM heating was applied, the center cooling time of the garlic cloves from freezing until -10°C was 48 s, which was approximately half the value of 85 s obtained without EM heating. For the white radish cubes, the center cooling time was also improved, from 288 to 132 s. The samples frozen by LN spray with EM heating had a closer hardness to the unfrozen samples than the samples frozen by LN only. **Conclusions:** The EM heating during quick freezing functions to maintain the hardness of fresh food by reducing the freezing time from 0 to -10°C.

Keywords: Electromagnetic, Freezing, Heating, Quality, Quick

Introduction

Frozen foods are popular because they can be easily used and stored. However, they are not considered fresh, because their quality is severely deteriorated during the freezing and thawing by the growth of ice crystals (Ahmad et al., 2011; Yu et al., 2012). The size of the ice crystals is an important factor affecting the quality of frozen foods (Alizadeh et al., 2008; Alvarez et al., 2010; Jin et al., 2011; Le-Bail et al., 2010; Zaritzky, 2006). If ice crystals grow by absorbing water from the food cells, deterioration such as drip loss is increased because of the damaged cells. The ice-crystal size is related to the speed of freezing (Bald, 1991) because the maximum ice-crystal formation zone is immediately below the freezing point, and the time spent in this zone depends on the freezing speed (Bevilacqua and Zaritzky, 1980). The zone with the maximum ice-crystal formation is usually considered as the temperature range from -1 to -5°C (Ramaswamy and Marcotte, 2005), but Kiani and Sun (2011) identified the temperature zone from -1 to -8°C as the critical zone for water crystallization in food. For quick freezing, a low-temperature cooling agent and small food items are generally adopted, considering the heat-transfer principles (Kawano et al., 1993; Lee and Kim, 2008). Individual quick freezing is a good example of conventional quick freezing.

Experiments to prevent or promote ice-crystal growth using static magnetic fields (Aleksandrov et al., 1999), static electric fields (Orlowska et al., 2009; Ehre et al., 2010; Xanthakis et al., 2013), ultrasonic waves (Kiani et al., 2012; Yu et al. 2012), and oscillating magnetic fields (Kaku et al., 2010; Lin et al., 2013) have been performed. These stem from the idea that an electric or magnetic field

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Table 1. Comparison between the frequencies used for EM heating (Ohlsson, 1999)

RF frequency	Microwave
Advantages	
Better for large, thick foods	Higher heating rate
Lower investment costs	Design freedom
Easier to understand and control	Less sensitive to food
Disadvantages	
Risk of arching in RF	Limited penetration
Larger floor space	Higher investment costs
Narrow frequency bands	More engineering need
Lack of data on RF dielectric properties	

can disturb or initiate the alignment of water molecules during the crystal growth. Crystallization effects due to the use of static fields and ultrasonic waves were observed. On the other hand, a method using a cell alive system with a 60-Hz oscillating magnetic field was implemented to prevent ice-crystal growth. However, the effectiveness of this method was unclear, and other electromagnetic (EM) frequencies should be examined to study the quality of frozen food (Wowk, 2012). EM frequencies such as 13.56, 27.12, 40.68 (radio frequency (RF)), 915, and 2450 MHz (microwave) have dielectric heating effects on food (Piyasena el al., 2014) and are candidate frequencies for disturbing the crystal growth. According to the comparison of the frequencies used for EM heating shown in Table 1, the RF frequency can be used for thick foods.

The ice-crystal growth in food is difficult to monitor, like that in water clouds (Young, 1993). The detection of the temperature of food is one way to examine the ice-crystal growth. In this study, the temperature of garlic cloves and white radish cubes was monitored to calculate the passing time of the critical zone of ice crystallization during quick freezing in order to determine the effects of EM heating using 27.12 MHz for the quick freezing. The frequency of 27.12 MHz was selected, as it is effective for heating heterogeneous foods (Wang et al., 2012).

Materials and Methods

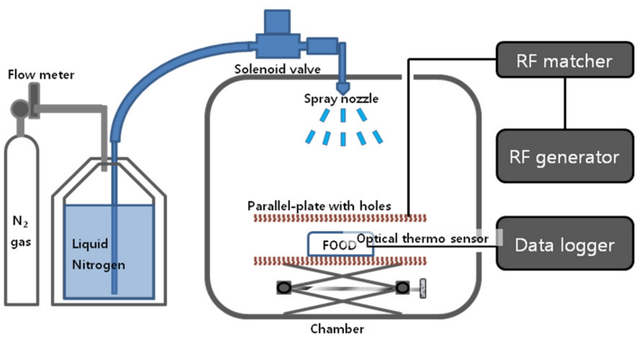
Materials

A white radish over 10 cm in diameter was obtained from a local supermarket and was cut into slices 3 cm thick. For equivalence, the 3-cm-thick cylinder was cut into four cubes symmetrically from the center.

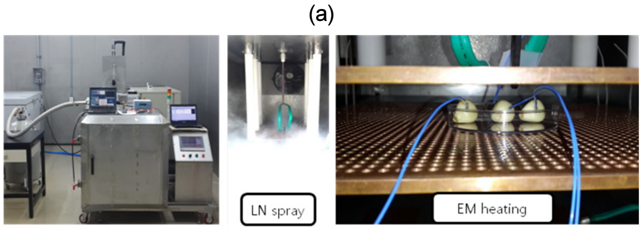
Garlic bulbs were obtained from the local supermarket. Four peeled garlic cloves were chosen according to the size around the thickness and shape from one garlic bulb. For a precise comparison of the quick freezing with and without EM heating, the two most similar samples in each bulb were used in the quick-freezing samples. The thickness of the garlic cloves was ~2 mm, and the average moisture content was 68.6%, with a standard deviation of 2.52%. To minimize the influence of the hardness distribution from the individual bulbs, each group of experiments used garlic cloves from the same bulbs.

Freezing methods

Three kinds of freezing were conducted to determine the effect of EM heating: quick freezing with EM heating, quick freezing alone, and slow freezing with a -20°C conventional freezer. This system used a liquid nitrogen (LN) sprayer as a quick freezer and RF heating at 27.12 MHz (Figure 1). An RF generator (TX-20, ADTEC Plasma Technology Co. Ltd., Hiroshima, Japan) and auto-matcher (TST-2720, TST co., Sungnam, Korea) were used for the RF power source. To give the RF power during the LN freezing, a custom-built parallel plate (5-mm-thick copper, 400 × 400 mm) with Φ4 holes was used. LN was sprayed until the center temperature of the garlic clove and the white radish cube reached -40°C. The temperature of the



(a)



(b)

Figure 1. Schematic (a) and pictures (b) of the quick freezer with EM heating.

samples was measured using an optical thermo sensor (TMI-4, FISO Technologies Inc., Quebec, Canada) to avoid the EM interference. The spraying system was assembled with an LN tank, a vacuum transfer line, a spraying nozzle, and a solenoid valve (Kim et al., 2014). The flow rates of the nitrogen gas were 10 and 8 L/min for the white radish cubes and garlic cloves, respectively. The EM heating power was 30 W per eight garlic cloves and 30 W per radish cube. The equilibrium temperature of the food was ~5° higher than the temperature of the surrounding air because of this EM heating power. At the start of the freezing, the initial matching point was determined with a power of 10 W. The power was increased to 30 W and supplied during the quick freezing. The EM power needed to be adjusted if the food size and cooling rate were changed. After the freezing, each frozen sample was placed in a freezer at -80°C (DFC-200, Operon, Gimpo, Korea) until it thawed.

Thawing methods

Among the conventional thawing methods, refrigerator thawing (4°C) is recommended for frozen meat because it offers the lowest loss of quality (Xia et al., 2012). However, when frozen samples obtained by different freezing methods were thawed by refrigerator thawing or lotic water thawing, the samples had a similar low hardness (data not shown) because of the re-crystallization during the thawing.

In this study, three kinds of frozen samples were thawed at once by 27.12-MHz EM heating (Figure 2). The samples were heated with a power of 200 W until the center temperature reached 20°C. The system is identical to the EM power source used in the freezing.

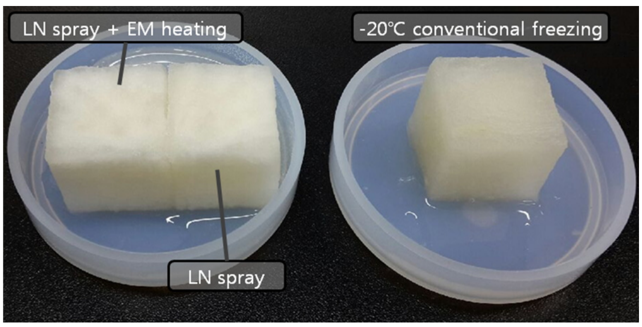


Figure 2. Thawed white radish cubes.

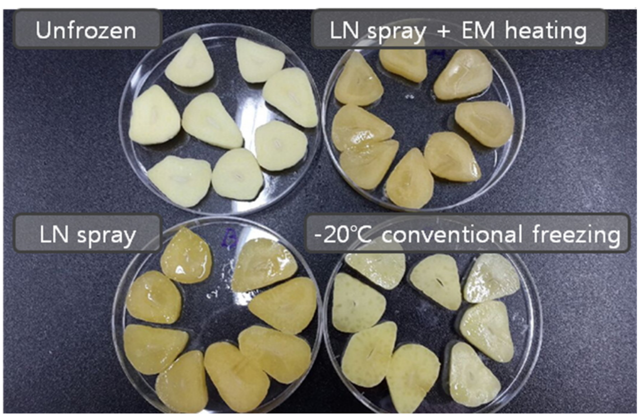


Figure 3. Sliced garlic cloves for the hardness test.

Texture analysis

Sliced garlic cloves 5 mm thick were used for checking the hardness (Figure 3). Cubes of white radish were sliced in half, and the center portions were employed. Their hardness was evaluated at room temperature using a texture analyzer (TA-XT2, Stable Micro System Ltd., Godalming, UK) equipped with a puncture probe (5 mm diameter) to penetrate the sliced garlic to a depth of 3 mm and the sliced white radish to a depth of 5 mm. During the hardness test, the following settings were used: a pre-test speed of 1.0 mm/s, test speed of 0.3 mm/s, and post-test speed of 1.0 mm/s. The hardness (g) was deduced from the resulting deformation and force responses, which were recorded by a software analysis program (Version 1.12, Stable Micro System Ltd., Godalming, UK) running in the texture analyzer. Each measurement was replicated more than five times.

Results and Discussion

The zone of the maximum ice-crystal formation is usually considered as the temperature range of -1 to -5°C (Ramaswamy and Marcotte, 2005), but Kiani and Sun (2011) chose the temperature range of -1 to -8°C as the critical zone for water crystallization in food. However, the initial freezing point of garlic is around -2.5°C (Song and Park, 1995); thus, the temperature range of 0 to -10°C was roughly considered as the critical zone of ice-crystal formation in this study. Quick freezing was conducted until the temperature of the center of the samples was -40°C. During the quick freezing of the garlic samples, the total freezing time until -40°C with LN spray and EM heating took longer than that with LN spray only, but the passing time of the critical zone with LN spray and EM heating took less time than that with LN spray only

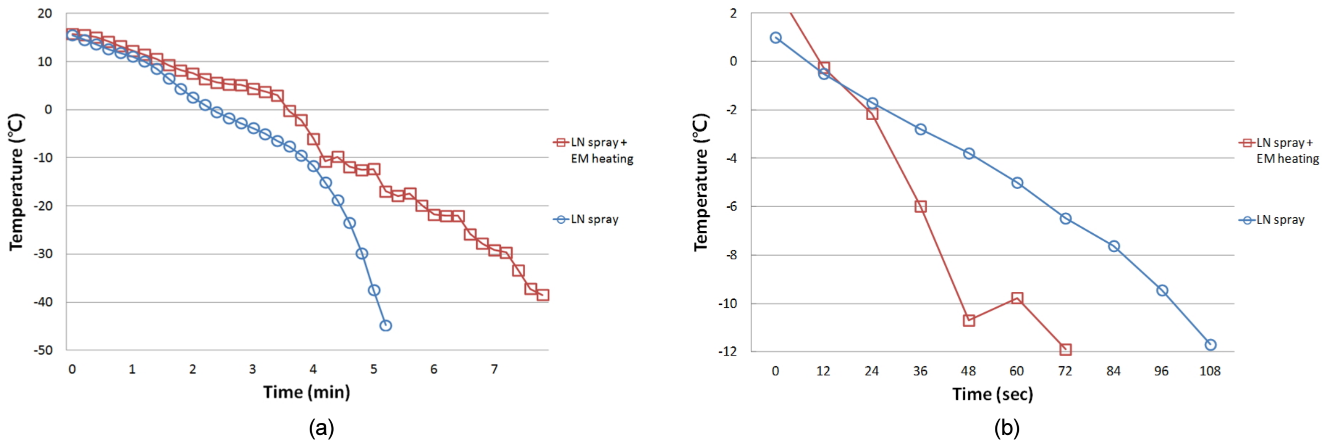


Figure 4. Time-temperature diagram comparison of the full range (a) and critical zone (b) between quick freezing (○) and quick freezing with EM heating (□) for garlic cloves.

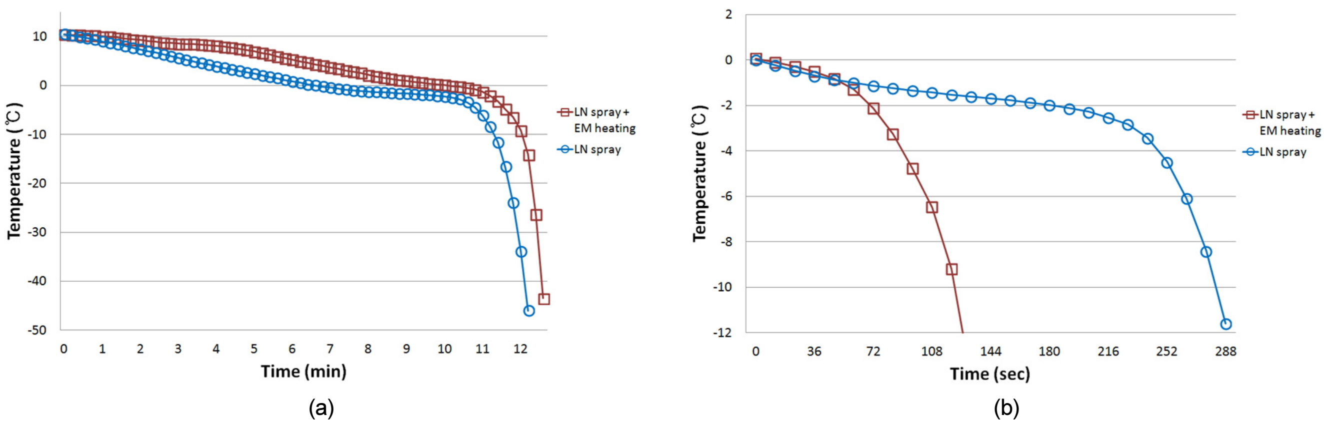


Figure 5. Time-temperature diagram comparison of the full range (a) and critical zone (b) between quick freezing (○) and quick freezing with EM heating (□) for white radish cubes.

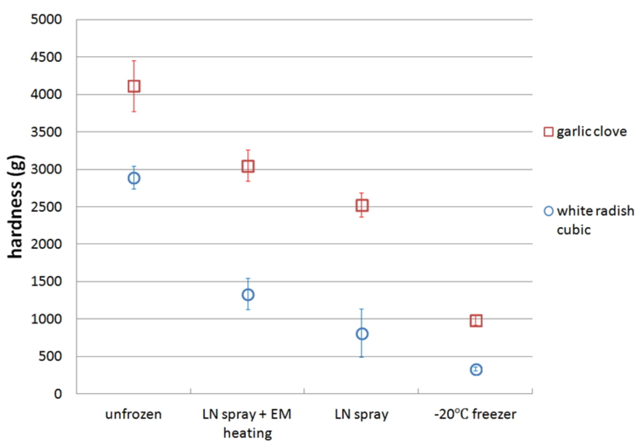


Figure 6. Hardness of unfrozen samples and thawed samples that were frozen by three freezing methods.

(Figure 4). The freezing time from 0 until -10°C was improved from 85 to 48 s by EM heating. The samples frozen by the conventional freezer at -20°C had a relatively long time to pass the critical zone; thus, the data is not shown in this figure. The time-temperature diagram for the white radish cubes exhibits the same results (Figure 5). The freezing time from 0 to -10°C was improved from 288 to 132 s by EM heating. These effects can be explained according to heat-transfer principles. The small amount of heating makes the inner point of food unfrozen until this point has a sufficiently large temperature gradient to overwhelm the heating. Owing to these effects, the hardness of garlic cloves frozen by LN spray with EM heating was 74% of that of unfrozen cloves, and this value was higher than the hardness of the quick frozen ones (Figure 6). For the white radish cubes, the values were lower than those for the garlic cloves, but the trend was similar. The moisture content of the white radish was 94%, and that of the garlic cloves was 69%. For the conservation of plant genetic resources, seed drying is used to reduce the freeze-thaw stress; thus, the high moisture content of white radish may be a reason for the degradation of the hardness. According to these results, the EM heating reduces the passing time of the critical zone of the ice-crystal formation during quick freezing and preserves the hardness of food.

Conclusions

During quick freezing, a small amount of EM heating reduces the passing time of the critical zone of ice-crystal formation in food. The freezing time from 0 until -10°C was halved by EM heating. An RF frequency of 27.12 MHz was chosen for use in freezing and thawing and was effective for both. Quick freezing with EM heating is potential method for improving the quality of bulk frozen food and may be applicable for industrial use.

Conflict of Interest

The authors have no conflicting interests, financial or otherwise.

Acknowledgments

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