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System Design and Performance Analysis of a Quick Freezer using Supercooling

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Abstract

Purpose: This study was conducted for enhancing the performance of a conventional quick freezer by introducing the supercooling state, using a low-temperature coolant. **Methods:** In the present investigation, the supercooling process was executed prior to quick freezing for reducing the time by which the temperature passes the zone of maximum ice crystal formation. Every food has different nucleation points and hence, we used silicone oil as the coolant for supercooling for easy modification of temperature. Additionally, for quick freezing, we used liquid nitrogen spray. **Results:** Using the heat exchanger-type precooler with silicone oil, the temperature of the chamber was easily changed for enabling supercooling. Particularly, the results of the freezing test with garlic indicated that this system improved the hardness of garlic after it was thawed, compared to the conventional freezing method. **Conclusions:** Before quick freezing, if the food item is subjected to the supercooling state, the time from nucleation to the temperature reaching the frozen state (-5°C, which is the maximum ice crystal formation zone) will be shorter than that incurred using quick freezing alone. The combination of the heat exchanger-type supercooler and liquid nitrogen sprayer is expected to serve as a promising technology for improving the physicochemical qualities of frozen foods.

Keywords: Heat exchanger type freezer, Ice crystallization, Nucleation, Quick freezing, Supercooling

Introduction

The consumption of frozen foods has increased owing to their cooking convenience and long-term availability. However, it is difficult to maintain high quality of frozen foods, and particularly, dehydration, physicochemical changes, and cell disruption during the freezing process accelerate their deterioration. To meet the market demand for high-quality frozen foods, it is necessary to improve refrigerating engineering and technology.

Although it is well known that the melting point of pure water is 0°C under atmospheric pressure, if water is cooled, then it remains in the liquid state well below the melting point, before nucleation occurs. This phenomenon is called supercooling. Many experiments have been conducted to lower the nucleation temperature of water to be near the homogeneous nucleation temperature (-41°C) under normal pressure and -92°C under 200 MPa (Kanno et al., 1975; Moore and Molinero, 2011). However, the mechanism of ice crystallization has not yet been completely understood. Nucleation consists of two processes, namely, primary and secondary nucleation. Primary nucleation involves the creation of ice crystals in the liquid state without existing ice crystals. This phenomenon can be further classified into homogeneous and heterogeneous nucleation (Zachariassen and Kristiansen, 2000). Secondary nucleation involves the formation of ice crystals in the liquid state with preexisting ice crystals. Almost all types of nucleation occurring in nature belong to the heterogeneous category

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(Mullin, 2001).

Nowadays supercooling is a compelling issue in the fields of organ preservation for transplantation (Berendsen el al., 2014) and storage of agricultural products (Martins and Lopes, 2007; James et al., 2009). In the field of food storage, although many researchers have conducted studies on decreasing the supercooling temperature, only two methods have been introduced in industrial practice. One of them involves using high pressure, such as 2000 times the atmospheric pressure, and follows the famous ice-water phase diagram schematic (LeBail et al., 2002). The other method involves using antifreeze proteins for frost protection in crop plants (Phoon et al., 2008; Duman and Wisniewski, 2014), cryopreservation of reproductive cells (Nishijima et al., 2014), etc. However, these methods pose problems with regard to their direct use with food because of cost or their antipathy to additives. Other trials using static magnetic field (Aleksandrov et al., 1999), static electric field (Orlowska et al., 2009; Ehre et al., 2010; Xanthakis et al., 2013), ultrasonic field (Kiani et al., 2012; Yu et al. 2012), oscillating magnetic field (Kaku et al., 2010; Lin et al., 2013), etc. have been conducted. However, the effect of the oscillating magnetic field such as that used in the Cell Alive System (CAS) freezer is subject to doubt (Wowk, 2012), whereas other methods that use static electric, static magnetic, and ultrasonic fields are known to decrease the effect of supercooling. Although extending the supercooling state by using the oscillating electric field (Wowk, 2012) is believed to be possible, more study is needed for confirming its effect.

Besides identifying a method for lowering the supercooling temperature, it is important to favorably utilize the supercooling state in industrial practice. However, the current industrial scale of practice involves supercooling to just below the equilibrium freezing temperature of the food. Generally, different foods have different supercooling temperatures based on the proportion of substances in them, such as water, carbohydrate, lipid, and protein (Fuller and Wisniewski, 1998; Mullin, 2001; James et al., 2005). Therefore, a freezer with temperature control such as a cold liquid bath is needed for studying the supercooling phenomena in different foods (Gholaminejad and Hosseini, 2013).

To reduce the time from nucleation to the temperature reaching -5°C (frozen state), the food may be subjected to the supercooling state prior to quick freezing. If we put a food item in a freezer with a specific temperature, the surface of the food undergoes complete supercooling but its center undergoes only partial supercooling (Martins and Lopes, 2007). Hence, two stages of freezing are required to impart the same extent of supercooling to the surface and the center of the food.

Therefore, this study was conducted to explain the design of a new freezer that utilizes the supercooling state, and provide experimental data for demonstrating why two-stage freezing is needed. Finally, this study also aims at elucidating the effect of supercooling in the quick freezing process.

Materials and Methods

System of freezer with supercooling

Gas-type coolers pose a problem in maintaining a designate temperature because gas has much lower specific heat than food. Liquid bath-type coolers have adequate thermal capacity but changing its temperature quickly is difficult. Therefore, we used the two-stage freezer for this study. The first stage of freezing uses a heat exchanger with silicon oil as the coolant (Figure 1). The conventional cooler reduces the oil temperature in the heat exchanger and thereafter, the oil circulation pump sends the cooled oil in the heat exchanger inside of he chamber. A fan helps to cool the air inside the chamber, through circulation. The oil can be cooled using the conventional cooler and heated using the heater, thus enabling easy control of oil temperature within the chamber. The second stage involves quick freezing using liquid nitrogen spray. The key items used for quick freezing were liquid nitrogen tank, vacuum transfer line, spraying nozzle, and solenoid valve.

A programmable logic controller (PLC) was used for controlling the chamber temperature in 48 steps. If nucleation was detected at the time of checking the food popup temperature, the PLC automatically opened the solenoid valve to supply liquid nitrogen to the chamber. A vacuum-insulated liquid nitrogen transfer line and a spray nozzle with a transfer speed of 3.1 L/min at a pressure of 0.5 bar and spraying angle of 45° were used. Additionally, an option to open the liquid nitrogen valve manually was provided. Nucleation occurred when the liquid nitrogen valve was opened when the food was in the supercooling state of the quick freezing process (Figure 2).

We used an optical thermosensor to monitor the room and food temperatures, as we planned to analyze the

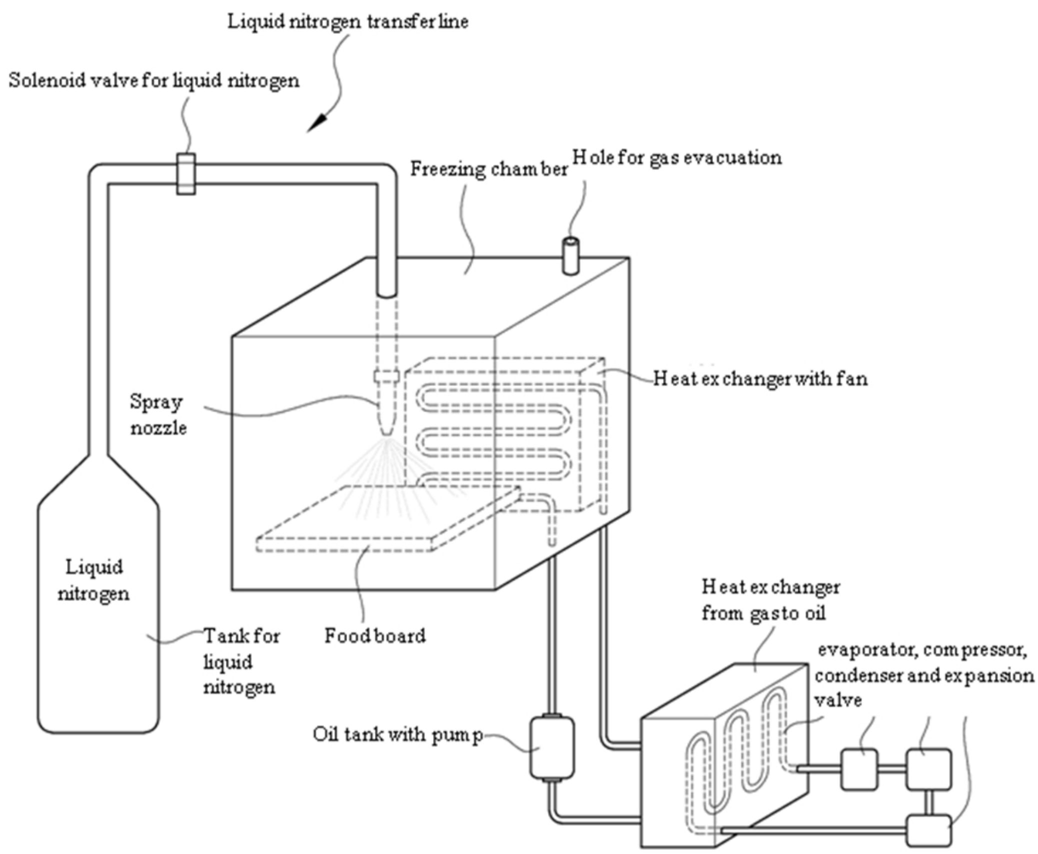

Figure 1. Schematic diagram of the customized freezer using supercooling.

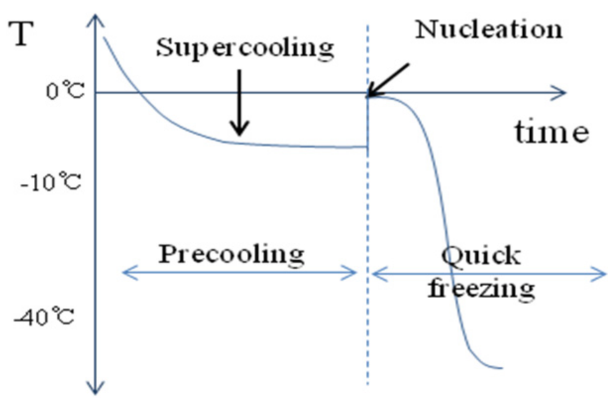

Figure 2. Time-temperature diagram of the freezer with precooling and quick freezing.

effect of the electromagnetic field on supercooling. Hence, a thermocouple was regarded to suffice if an electromagnetic field is not required.

Test of heat exchanger-type precooler

Conducting a supercooling test with water is an effective way of analyzing the performance of the precooler. We prepared 500 ml-sized mineral water bottles with a hole in each for mounting the thermosensor, and filled approximately 300 ml of distilled water in them. The hole allowed the bottle to be exposed to the atmosphere. We varied the cooling speed by altering the step and duration of temperature change to study the relation between the cooling speed and nucleation.

Test of quick freezer with supercooling

We chose garlic as the food item for testing our freezer and understanding the effect of supercooling, because peeled garlic cloves can be stored at approximately -6°C for up to 69 h without freezing (James et al., 2009). To impart adequate supercooling from the surface to the center of the food, we subjected the garlic to 0°C for 12 h and -6°C for over 1 h. The garlic was then subjected to a liquid nitrogen shower for 3 min. The controls applied were fresh, conventional freezing, and quick freezing. For comparison, the test garlic cloves were subjected to the abovementioned controls and thawed in the same water bath at 23°C.

Sliced garlic cloves with a thickness of 5 mm were used for checking the hardness. 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. During the hardness test, the following settings were used: 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 recorded by the software analysis program (Version 1.12, Stable Micro System Ltd., Godalming, UK) running in the texture analyzer. Each measurement was replicated five times.

Results and Discussion

Air cooling-type freezers are regarded to pose a problem in controlling temperature constantly. Therefore, liquid cooling-type freezers are preferred for studying the freezing performance. During our water cooling test, nucleation of distilled water occurred at approximately -12°C (Figure 3). Moreover, at this temperature, supercooling became unstable and the results were similar to those of the experiments conducted by Gholaminejad and Hosseini (2013).

If the food is frozen quickly, its center does not undergo adequate supercooling because of the time consumed for heat transfer from the surface to the center. Although the heat transfer coefficient of a PET bottle is similar to that of water, the actual heat transfer rate of water is much faster than that of PET, owing to convection in water. We used commercial water bottles with thicknesses of 0.2 mm and 0.11 mm. To analyze the relationship between the cooling speed and supercooling temperature of water, six times of cooling tests were performed at different cooling speeds (Figure 4). Owing to the faster heat transfer rate of water than that of PET, there was no significant difference observed in the tests when water was cooled slower than the cooling speed, -5°C/h. However, when the water was cooled at a cooling rate faster than -5°C/h, the nucleation temperature was observed to rise to the freezing temperature. For quick freezing, a thin package is usually used for reducing the heat transfer time through the packaging materials, and in such a case, the nucleation temperature remains closer to the freezing temperature. This means that quick freezing does not impart adequate supercooling to food like slow freezing. This result supports the need for a two-stage freezer for improving the performance of the conventional quick freezer.

Additionally, the thickness of PET relieves the difference in the temperatures and hence, the use of plastic wrapping can ensure more constant temperature of the food even when the temperature of the warehouse fluctuates. The results of this study were similar to those on the use of plastic films for the preservation of Chinese cabbage (Lim et al., 2014).

For executing the quick freezing function of the freezer in the second stage of cooling, we used a liquid nitrogen sprayer for two reasons: (a) the cost of liquid nitrogen

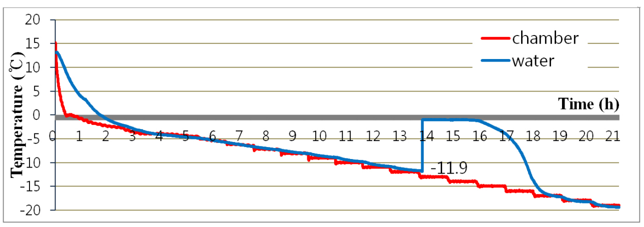

Figure 3. Time-temperature diagram of the freezer.

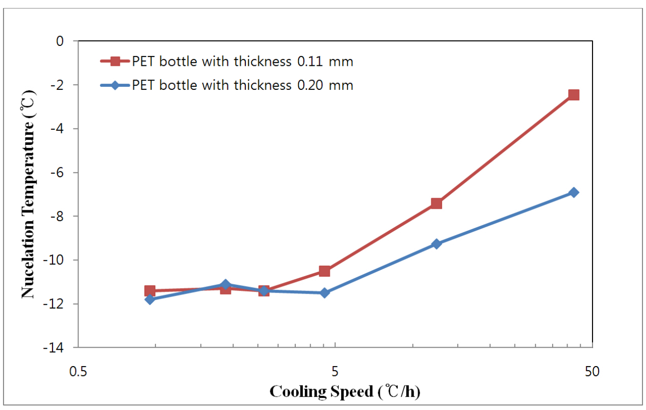

Figure 4. Relation between cooling speed and nucleation temperature of distilled water.

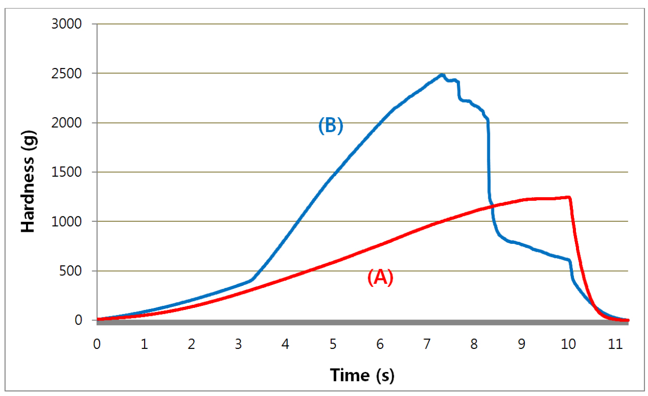

Figure 5. Time-Force graphs for thawed garlic after being sprayed with liquid nitrogen (A); and after being supercooled and sprayed with liquid nitrogen (B).

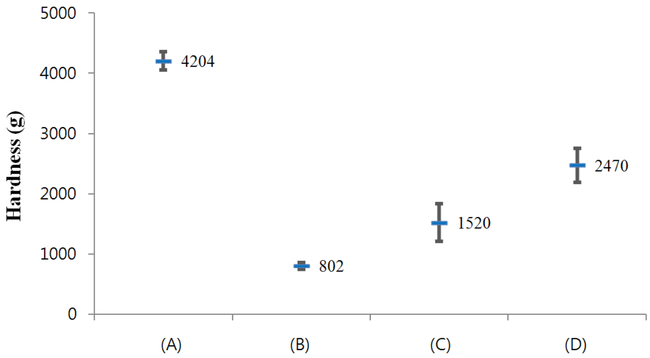

Figure 6. Hardness of fresh garlic (A), thawed garlic after placing in refrigerator (B), thawed garlic after being sprayed with liquid nitrogen (C), and thawed garlic after being supercooled and sprayed with liquid nitrogen (D).

spraying equipment is cheaper than that of a liquid bath; and (b) the liquid nitrogen sprayer can be directly used with food. From the data on the hardness of garlic across four kinds of preservation methods (Figures 5 and 6), the data pertaining to the application of the supercooling step before the quick freezing step was seen to be better than that pertaining to the use of quick freezing only. Although garlic may undergo recrystallization during thawing, its hardness when preserved using our system was found to be only half of the hardness of fresh garlic. Nevertheless, adopting improved thawing methods will ensure that the hardness values of thawed and fresh garlic are similar.

Conclusions

If a bulk-sized food item is quickly frozen, the temperature at which ice forms from the surface of the food to its center is the freezing point. The center of the food is believed to undergo a small amount of supercooling. Our results with water freezing support this belief and that higher cooling speed reduces the possibility of the food undergoing adequate supercooling. Hence, the combined technology of the supercooler and quick freezer is believed to be necessary for improving the performance of the conventional quick freezer. The supercooler imparts adequate supercooling to the center of food whereas the quick freezer reduces the time by which the temperature passes the maximum ice crystal formation zone. In this study, the heat exchanger-type air freezer offered various chamber temperature options, from 0°C to -20°C for the supercooling experiments. Additionally, the combination of heat exchanger-type precooler and liquid nitrogen sprayer reduced the time taken for the temperature to pass the zone of maximum ice crystal formation compared to the case of using liquid nitrogen spray alone. Finally, this combination is expected to serve as a promising technology for improving the physicochemical qualities of frozen foods.

Conflict of Interest

The authors have no conflicting financial or other interests.

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