Research Article

Effect of Oscillating Magnetic Field on Freezing Rate, Phase Transition Time and Supercooling of Deionized Water

Pakjira Jarulertwattana, Suwit Siriwattanayotin and Suvaluk Asavasanti*
Food Security and Process Innovation Research Group, Food Engineering Department, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangkok, Thailand
Food Technology and Engineering Laboratory, Pilot Plant Development and Training Institute, King Mongkut's University of Technology Thonburi, Bangkok, Thailand

* Corresponding author. E-mail: suvaluk.asa@kmutt.ac.th

DOI: 10.14416/j.asep.2019.08.001
Received: 4 March 2019; Revised: 16 May 2019; Accepted: 23 May 2019;

Abstract
Due to a growing interest toward quality improvement of frozen foods, many advanced technologies have been combined with conventional freezing system to expedite rate of freezing and reduce ice crystal formation. This research aimed to investigate the effect of oscillating magnetic field (OMF) in the range of 0 to 12 mT (50 Hz) on freezing rate, phase transition time and supercooling of deionized water during freezing in an air blast freezer at –10°C. The sample was placed between two magnetic cores where an oscillating magnetic field (OMF) was generated and the temperature profile was recorded by a data logger at 1-minute interval. The magnetic field strength was varied at 0, 4, 8, and 12 mT. It was found that there was no significant difference in the freezing rate and phase transition time when different OMF strengths were applied ($p > 0.05$). Interestingly, the probability of supercooling occurrence increased when the OMF was applied; without OMF only 16% of the experiment exhibited supercooling phenomenon where 33% was detected when OMF in the range of 4–12 mT was applied. However, the probability of supercooling occurrence was independent of the OMF strength.

Keywords: Deionized water, Freezing rate, Oscillating magnetic field, Phase transition time, Supercooling

1 Introduction

Due to city lifestyle and changes in consumer behavior, the frozen food market is continuously expanding. One of the advantages of frozen foods is offering a significant convenience as it can save time to prepare foods. Moreover, the price of frozen foods is comparable to that of the fresh ones [1], which is the main factor that makes frozen foods popular. Freezing is a technique used in food preservation by reducing the temperature of the food to lower than its freezing point, resulting in transformation of water to ice crystals. Although the frozen products can be kept for long time, the product quality could be deteriorated during storage. Thus, new freezing techniques have been continuously developed. The aim is to generate small ice crystals so both physical and chemical qualities of frozen products can be preserved [2].

Nowadays, several new freezing technologies have been investigated [3]–[9], for example, the combination of electric, magnetic, electromagnetic or electrostatic field with freezing. These emerging technologies have been developed to control the crystallization process leading to the improvement of frozen product quality. However, Woo and Mujumdar [10] revealed that electric field resulted in the lower degree of supercooling leading to the larger ice crystal formation. Large ice crystals can cause structural damage of biological products leading to drip loss problem when frozen product is thawed.

Please cite this article as: P. Jarulertwattana, S. Siriwattanayotin, and S. Asavasanti, "Effect of oscillating magnetic field on freezing rate, phase transition time and supercooling of deionized water," *Applied Science and Engineering Progress*, vol. 13, no. 1, pp. 32–37, Jan.–Mar. 2020.

The application of magnetic field in food freezing has recently received much attention from both food industry and scientific communities. Many patents [11]–[13] have claimed that magnetic field can help maintain the food freshness and deliver high quality frozen products. They publicized that magnetic field applied interacts with the magnetic moment in water molecule and enhance the vibration of water molecule resulting in breakage of hydrogen bonds. Thus, the ice formation was limited leading to the prevention of ice nucleation and promotion of supercooling [10], [14].

However, the effect of magnetic field on food freezing is still inconclusive. Xanthakis *et al*. [15] reported that magnetic field could decrease phase transition time, induce uniformity of ice crystal pattern and change the properties of water, such as melting point and thermal conductivity. In addition, Ino *et al*. [11] reported that an oscillating magnetic field (OMF) at < 100 mT (< 107 Hz) could enhance supercooling of water and inhibit ice nucleation. Mok *et al*. [16] also found that application of OMF at 50–100 mT (1 Hz) together with pulsed electric field (PEF) could help preserve the qualities chicken breast during freezing. On the other hand, Zhao *et al*. [9] revealed that a static magnetic field (SMF) at < 50 mT had no effect on nucleation temperature and phase transition time of deionized water. Otero *et al*. [7] also did not find any effect of OMF at < 2 mT (6–59 Hz) on freezing of crab stick and pork loin.

Although the results are still inconclusive, this technology is still interesting since it has been commercialized by many companies, for example DENBA+ from AGUA Shouji Co., Ltd., Japan and Cell Alive System (CAS) from ABI Co., Ltd., Japan. More evidence is needed to confirm the effect of magnetic field on food freezing. Therefore, the aim of this research is to investigate effect of OMF in the range of 0–12 mT (50 Hz) on freezing of deionized water using an air blast freezer at –10°C. The temperature profile (i.e. freezing rate and phase transition time) and an occurrence of supercooling was monitored during freezing under different magnetic field treatments.

2 Materials and Methods

2.1 *Sample preparation*

Figure 1: A 120-cc PE bottle.

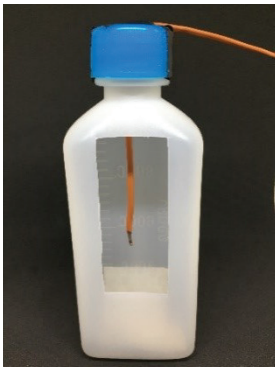


Figure 2: Thermocouple probe position.

As water plays an important role in food freezing, deionized water was used as a model food to simplify the system and eliminate an interference of ions and other food components on temperature profile during freezing under an influence of magnetic field.

One hundred milliliters of deionized water were filled into a 120-cc PE bottle (Figure 1). The bottle was closed with a screw bottle cap connected with type T thermocouple probe (W. Dhavepatana Co., Ltd., Bangkok, Thailand) as shown in Figure 2. The position of probe was set at the center of sample height.

2.2 *Freezing procedure*

The air blast freezer (Department of Food Engineering, KMUTT, Bangkok, Thailand) was set at –10°C. When the freezer temperature reached the set point, the sample was placed at the center of the electromagnetic coils. A thermocouple was placed below the circulating fan to measure the temperature inside the freezer. To generate an oscillating magnetic field, an AC current was applied to the electromagnet (Department of

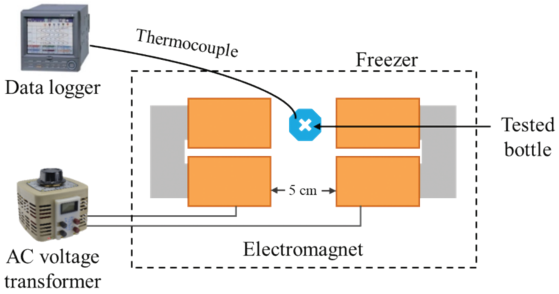


Figure 3: Equipment setup and sample position.

Food Engineering, KMUTT, Bangkok, Thailand) by an AC voltage transformer (TDGC2-10K (Output voltage 0-250 VAC, 40A), Silic Stable Service Co., Ltd., Pathum Thani, Thailand). The equipment setup and position of sample are illustrated in Figure 3. The magnetic field was operated until the end of the freezing process. During the experiment, the temperature profile of the sample and air was collected by using a data logger (FX112-4-2, Yokogawa (Thailand) Ltd., Bangkok, Thailand) at 1-minute interval. The freezing process finished when the core temperature of the deionized water reached –10°C. After that, the collected temperature histories were plotted and the freezing rate, phase transition time and an occurrence of supercooling were identified. The magnetic field strength used in the experiment was varied at 0, 4, 8, and 12 mT. The average magnetic field strength at the middle of the electromagnet, where the sample was placed, was determined by a tesla meter (Digital, PHYWE Systeme GmbH & Co. KG., Göttingen, Germany). The experiments were conducted using a completely randomized design (CRD) with six replications.

2.3 *Freezing rate*

The freezing rate could be determined for 2 periods which are pre-cooling and tempering periods. From Figure 4, the pre-cooling period was considered from the initial temperature of the sample to the intersection between a linear line drawn from pre-cooling temperature profile and a linear line drawn from phase transition temperature profile. In addition, the tempering period was considered from the intersection between a linear line drawn from phase transition temperature profile and a linear line drawn from tempering temperature profile to the final temperature of the sample.

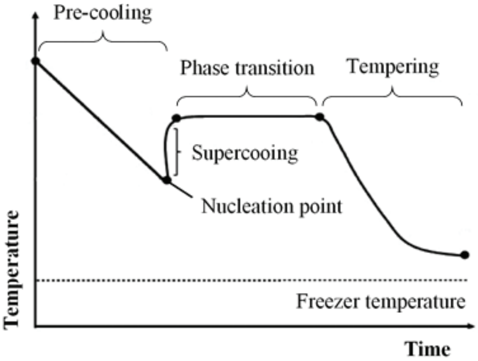


Figure 4: Typical freezing curve [14].

The freezing rate of pre-cooling and tempering periods was determined from the slope of linear temperature profile during each period using Microsoft Excel version 2016 (Microsoft Corporation, Washington D.C., USA). The freezing rates obtained from 4 magnetic field strengths were compared in order to determine effect of oscillating magnetic field on deionized water freezing.

2.4 *Phase transition*

Phase transition is an indication of the period of ice crystal grows in the product and also known as the range of temperature remaining constant [14]. Phase transition time is an important factor for selecting the freezing system to provide a high quality of frozen product. In theory, phase transition time can also be calculated from Plank's Equation as shown in Equation (1).

$$t_f = \frac{\rho L}{T_F - T_l}\left[Pa\left(\frac{1}{h}+\frac{b}{k_p}\right)+\frac{Ra^2}{k}\right] \tag{1}$$

where t_f is the freezing time (s), ρ is the density of sample (kg/m^3), L is the latent heat of fusion (J/kg), h is the convective heat transfer coefficient (W/m^{2}K), a is the sample thickness (m), b is the container thickness (m), k_p is the thermal conductivity of container (W/mK), k is the thermal conductivity of sample (W/mK), T_F is the freezing point of sample (K), T_l is the medium temperature (K), and P and R are the shape factors. In this research, the shape factors for infinite slab were used (i.e. 1/2 and 1/8, respectively).

The phase transition time was the period between the end of pre-cooling step and the beginning of tempering step. The end point of pre-cooling step and

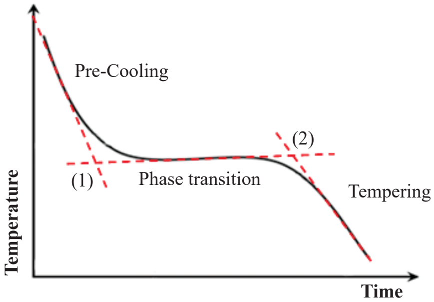


Figure 5: The intersection on freezing curve [14].

the initial point of tempering step were defined as the point which intersection between linear line from (1) pre-cooling and phase transition periods and (2) phase transition and tempering periods, as shown in Figure 5.

2.5 *Occurrence of supercooling*

Supercooling is a state where a liquid does not turn in to solid even at the temperature below its normal freezing point as shown in Figure 4. An occurrence of supercooling is determined from the characteristic of the freezing curves obtained.

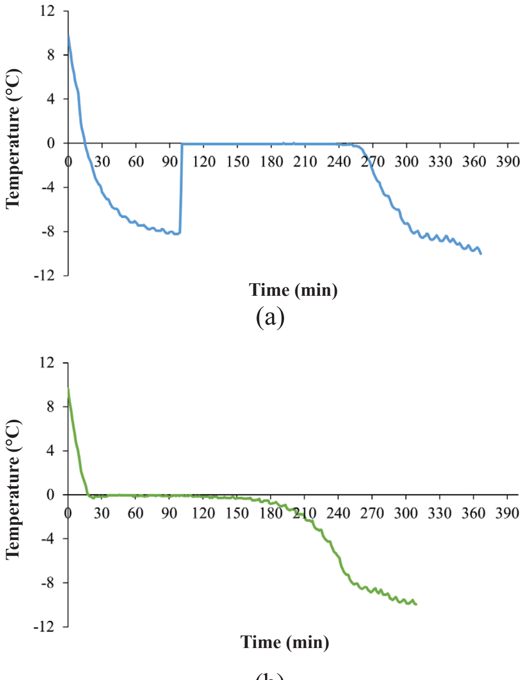
2.6 *Statistical analysis*

The statistical analysis was conducted to determine effect of oscillating magnetic field strength on freezing rate and phase transition time of deionized water using one-way ANOVA. If there was a significant difference among the means ($p < 0.05$), Fisher's Least Significant Difference were performed. The statistical analysis was conducted by using Minitab for Windows version 17 software (Minitab Inc., Pennsylvania, USA).

3 Results and Discussion

The experiment results showed that there are two types of freezing curves of deionized water under the oscillating magnetic field, which are the freezing with supercooling [Figure 6(a)] and the freezing without supercooling [Figure 6(b)]. The freezing rate, phase transition time and occurrence of supercooling were analyzed from the freezing curves and summarized in Tables 1 and 2.

Since SMF and OMF are different in oscillation pattern of magnetic field, they impose different effects on cellular structure. SMF induces electric charges in tissues that they come into contact with, while OMF is significantly more dynamic than SMF. OMF is able to reach more deeply into the body than SMF do and also creating a cascade of physiologic effects on a sub-cellular level [17].



(b)

Figure 6: Examples of freezing curve of deionized water when (a) supercooling and (b) no supercooling occurs.

3.1 *Effect of OMF on freezing rate*

The freezing rate of deionized water was determined for both pre-cooling and tempering steps, as shown in Table 1. The rate from cooling step was 0.55±0.03, 0.53±0.03, 0.49±0.02, and 0.58±0.07°C/min when applied field strength at 0, 4, 8, and 12 mT, respectively. Moreover, 0.07±0.01, 0.09±0.02, 0.07±0.01 and 0.08±0.02°C/min were the rate from tempering step under magnetic field strength of 0, 4, 8, and 12 mT, respectively.

The results of freezing rate of deionized water from both pre-cooling and tempering steps were showed in Table 1. It was obvious that the freezing rates during pre-cooling step were much greater than those during tempering step because of the greater driving force for heat transfer (ΔT) in pre-cooling step. However, when oscillating magnetic field at 4, 8 and 12 mT was applied, the freezing rate was not significantly different from the control. This might due to the fact that the applied field strength was too low; the field strength was not sufficient to vibrate and break the hydrogen bond of water molecules [18]. This finding is contrast to the previous studies [7], [11] which reported that the application of oscillating magnetic field in the range of 2 to 100 mT significantly affected the freezing profile and food quality. Zhou *et al*. [17] reported that the magnetic field strength about 200 mT resulted in a significant difference in the water properties, i.e. internal energy and heat capacity. However, the researchers did not mention the type of magnetic field.

Table 1: Freezing rate of deionized water

Field Strength (mT)	Pre-cooling Step (°C/min)	Tempering Step^{ns} (°C/min)
Control (0)	0.55±0.03^{ab}	0.07±0.01
4	0.53±0.03^{ab}	0.09±0.02
8	0.49±0.02^{b}	0.07±0.01
12	0.58±0.07^{a}	0.08±0.02

3.2 *Effect of OMF on phase transition time*

Table 2 shows theoretical and actual phase transition times of deionized water under the OMF treatment at different magnetic field strengths (i.e. 0, 4, 8, and 12 mT). Actual phase transition time was calculated from the freezing profile (Figure 4). It was defined as the period that temperature of sample remains constant and latent heat of crystallization is removed.

Table 2: Phase transition time and occurrence of supercooling of deionized water

Field Strength (mT)	Phase Transition Time		Occurrence of Supercooling (%)
	Theoretical (min)	Actual^{ns} (min)	
Control (0)	185	186±4	16
4		182±6	33
8		191±10	33
12		175±17	33

The theoretical phase transition time was calculated by a Plank's equation by assuming that the shape of sample was an infinite slab. The theoretical phase transition time was 185 min, while the actual phase transition time obtained from 4 different magnetic field treatments was varied from 175±17 min to 191±10 min.

The actual and theoretical phase transition times of deionized water under the oscillating magnetic field treatment at different magnetic field strengths (i.e. 0, 4, 8, and 12 mT) were showed in Table 2. Variation in the effective freezing time may cause by the slight shift in thermocouple position from sample to sample. If the probe shifted toward the bottle wall, the phase transition period could be shorter than the one located in the centre due to the nature of ice crystal formation from the outside-in. Moreover, the reason why the phase transition time was not influenced by the applied magnetic field might be due to diamagnetic material property of water. The repulsive response of water molecules to the magnetic field might cause water's hydrogen bond to inhibit the magnetic effect [19]. The statistical analysis also indicated that, an oscillating magnetic field up to 12 mT had no significant effect on phase transition time of deionized water ($p > 0.05$).

3.3 *Effect of OMF on occurrence of supercooling*

Occurrence of supercooling was observed when the deionized water was frozen under the oscillating magnetic field (Table 2). This result was similar to the findings of Woo and Mujumdar [10] and Owada [12]. Interestingly, probability of occurrence of supercooling was 16% with non-OMF treatment and increase to 33% when applied OMF (4–12 mT). Although applying OMF could promote the supercooling, probability of occurrence of supercooling was not different when apply OMF in range of 4–12 mT of field strength. Thus, it was inconclusive that OMF could promote occurrence of supercooling.

4 Conclusions

The effect of oscillating magnetic field (OMF) in the range of 0–12 mT (50 Hz) on freezing process of deionized water in the air blast freezer at –10°C had been investigated. It was found that there was no significant difference in the freezing rate and phase transition time when different OMF strengths were applied ($p > 0.05$). Moreover, the probability of supercooling occurrence increased when the OMF was applied; without OMF field only 16% of the experiment exhibited supercooling phenomenon where

33% was detected when OMF in the range of 4–12 mT was applied. However, the probability of supercooling occurrence was independent on the OMF strength. There was not enough evidence to confirm the effect of OMF on freezing process.

Acknowledgments

The authors would like to thank NSTDA for the financial support via Food Engineering Practice School (FEPS) scholarship.

References

[1] Z. Mylona, M. Kolokotroni, and S. A. Tassou, “Frozen food retail: Measuring and modelling energy use and space Environmental systems in an operational supermarket,” *Energy and Buildings*, vol. 144, pp. 129–143, Jun. 2017.

[2] S. J. James and C. James, “Innovative freezing technologies for foods,” *New Food*, vol. 15, pp. 21–24, Sep. 2012.

[3] V. D. Aleksandrov, A. A. Barannikov, and N. V. Dobritsa, “Effect of magnetic field on the supercooling of water drops,” *Inorganic Materials*, vol. 36, pp. 895–898, Sep. 2000.

[4] Y. J. Lou, H. X. Zhao, W. B. Li, and J. T. Han, “Experimental of the effects of static magnetic field on carp frozen process,” *Journal of Shandong University*, vol. 43, pp. 89–95, Jun. 2013.

[5] C. James, B. Reitz, and S. J. James, “The freezing characteristics of garlic bulbs (*Allium sativum* L.) frozen conventionally or with the assistance of an oscillating weak magnetic field,” *Food and Bioprocess Technology*, vol. 8, pp. 705–708, Mar. 2015.

[6] J. H. Mok, W. Choi, S. H. Park, S. H. Lee, and S. J. Jun, “Emerging pulsed electric field (PEF) and static magnetic field (SMF) combination technology for food freezing,” *International Journal of Refrigeration*, vol. 50, pp. 137–145, Feb. 2015.

[7] L. Otero, M. Pérez-Mateos, A. C. Rodríguez, and P. D. Sanz, “Electromagnetic freezing: Effects of weak oscillating magnetic fields on crab sticks,” *Journal of Food Engineering*, vol. 200, pp. 87–94, May. 2017.

[8] A. C. Rodríguez, C. James, and S. J. James, “Effects of weak oscillating magnetic fields on the freezing of pork loin,” *Food and Bioprocess Technology*, vol. 10, pp. 1615–1621, Sep. 2017.

[9] H. X. Zhao, H. Q. Hu, S. Liu, and J. T. Han, “Experimental study on freezing of liquids under static magnetic field,” *Chinese Journal of Chemical Engineering*, vol. 25, pp. 1288–1293, Sep. 2017.

[10] M. W. Woo and A. S. Mujumdar, “Effects of electric and magnetic field on freezing and possible relevance in freeze drying,” *Drying Technology*, vol. 28, pp. 433–443, Apr. 2010.

[11] H. Ino, Y. Suzuki, T. Katamura, S. Tsuji, and Y. Kurihara, “Food freezer and food thawing apparatus,” JP Patent 2005–291525, 2005.

[12] N. Owada, “Highly-efficient freezing apparatus and high-efficient freezing method,” U.S. Patent US 7, 237, 400B2, 2007.

[13] N. Owada and S. Saito, “Quick freezing apparatus and quick freezing method,” U.S. Patent US 7, 810, 340 B2, 2010.

[14] L. Otero, A. C. Rodríguez, M. Pérez-Mateos, and P. D. Sanz, “Effects of magnetic fields on freezing: Application to biological products, *Comprehensive Reviews in Food Science and Food Safety*, vol. 15, pp. 646–667, May 2016.

[15] E. Xanthakis, A. Le-Bail, and M. Havet, “Freezing combined with electrical and magnetic disturbances,” in *Proceedings Emerging Technologies for Food Processing (Second Edition)*, 2014, pp. 566–567.

[16] J. H. Mok, J. Y. Her, T. Y. Kang, R. Hoptowit, and S. J. Jun, “Effects of pulsed electric field (PEF) and oscillating magnetic field (OMF) combination technology on the extension of supercooling for chicken breasts,” *Journal of Food Engineering*, vol. 196, pp. 27–35, Mar. 2017.

[17] W. Pawluk. (2019, Apr.). *Static Magnetic Field VS. Pulsed Magnetic Field*. Maryland, US [Online]. Available: https://www.drpawluk.com/education/magnetic-science/static-vs-pulsed-magnetic-fields

[18] K. X. Zhou, G. W. Lu, Q. C. Zhou, and J. H. Song, “Monte Carlo simulation of liquid water in magnetic field,” *Journal of Applied Physics*, vol. 88, pp. 1802–1805, Jul. 2000.

[19] D. Jiles, *Introduction to Magnetic and Magnetic Materials*. London, England: Chapman and Hall, 1991, pp. 27–33.