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Melting Characteristics of Ice Cream Prepared with Various Agitation Speeds in Batch Freezer

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Ice cream consists of air bubbles, fat globules, ice crystals and unfrozen solution phase. The physical and chemical property of ice cream such as flavor or texture depends on its microstructure. Mainly, the microstructure is formed during freezing process. In this study, the effect of agitation speed during the freezing process on the melting characteristics was investigated. Samples prepared with various agitation speeds were used for melting tests. The melting rate of sample was quantified by measuring the mass that drips from the hardened ice cream through a mesh screen as a function of time. It was found that the melting rate increased with the increase in the agitation speed. This result means that the control of melting characteristics based on the agitation speed is possible. In addition, the increase in the amount of air cells and the size of fat globule aggregates led to the increase in the melting rate. In order to completely understand the thermal property of ice cream, the complex interaction between air cells and fat globules including ice crystal should be investigated.

1. Introduction

Ice cream is one of the most popular desserts and the global ice cream production is increasing year by year (Goff and Hartel, 2013). Besides, novel ice creams such as a vegan ice cream has been developed (Cimini and Moresi, 2019). Although the detailed composition of ice cream varies in different countries and markets within each country, as shown in Figure 1, it generally consists of four main components: air cells, ice crystals, fat globules and unfrozen solution (continuous phase). The quality of ice cream such as flavor or texture depends on the internal structure. For example, the ice cream without detectable ice crystals has a smooth texture (Marshall and Arbuckle, 1996; Vafiadis, 1997). According to Eisner et al. (2005), smaller bubbles in ice cream have a positive influence on the sensed creaminess during consumption. These means that the control of internal structure of ice cream is quite important for the improvement of ice cream quality. Although the detailed mechanism of fat destabilization is still unknown, the network structure of fat globules is quite important factor for the quality of ice cream such as the melting characteristics (Goff, 1997a; Goff et al, 1999).
In industries, manufacturing process of ice cream consists of several steps: blending and pasteurization of ice cream mix, aging, freezing, hardening and storage (Goff, 1997b). In order to control the internal structure of ice cream, freezing process should be focused on because the final state of it is determined during freezing process. The scraped heat exchanger which is a typical continuous freezer is generally used. The temperature of ice cream mix entering the freezer is about 4°C and it is drawn at about -6°C (Goff and Hartel, 2013). In the freezing process, three phenomena occur simultaneously: (i) the water phase crystallization, (ii) the breakup and coalescence of bubbles incorporated into the ice cream mix and (iii) the aggregation or partial coalescence of fat globules. Many researchers have investigated the effect of each phenomenon on ice cream properties from a viewpoint of food engineering. Russel et al. (1999) quantitatively reported that the mean ice crystal size decreases with the increase in the rotational speed of the dasher. Bolliger et al. (2000b) found that the stabilizer in ice cream mix contributes to recrystallization protection in ice due to a change in

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polysaccharide behavior. Chang and Hartel (2002) described that the rheological properties of ice cream can be controlled by the number of bubbles in ice cream. In order to obtain a finely dispersed microstructure, Wildmoser et al. (2004) proposed low temperature extrusion (LTE) processing. As a new technology to control the freezing process, Grossi et al. (2011) proposed a novel electrical technique to monitor the ice cream quality during freezing based on the electrical properties of ice cream. Although many researches about freezing process have been reported so far, further understanding from basic and practical viewpoints are required.

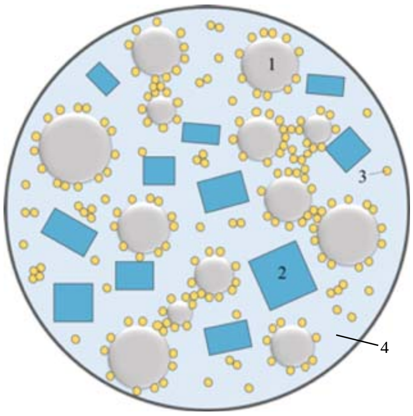

Figure 1: Microstructure in ice cream (1) air cell, (2) ice crystal, (3) far globule and (4) unfrozen solution

Recently, Masuda et al. (2020) suggested that the agitation operation has possibility for the development of more flexible control of ice cream quality using a batch type freezer. According to their work, the number of bubbles incorporated into ice cream and the bubble size distribution are controlled by the agitation speed. Furthermore, they propose a method to measure the viscosity change during the freezing process from the torque imposed to the agitation blade. As a result, they successfully showed the apparent viscosity decreases with the increase in the agitation speed. The process design based on the agitation operation would be powerful procedure for the optimization of freezing process.
In this study, the control of melting characteristics was selected as a next target for process design based on the agitation operation. Melting characteristics of final products is one of the most important factors for consumers. As Goff and Hartel (2013) described, a fast-melting product is undesirable because it tends to become heat shocked rapidly. Thus, the effect of agitation speed on melting characteristics was investigated in this study. The ice cream mix was frozen using a batch freezer with various agitation speeds. After that, the sample was stored at -20 °C for 24 h. The melting rate of the sample at 25 °C was evaluated as melting characteristics of the sample based on the method proposed by Bolliger et al. (2000a).

2. Materials and methods

2.1 Experimental apparatus

In this study, a batch type freezer with an agitation blade shown in Figure 2 was utilized for the freezing process. As described in the previous section, the continuous freezer is more general in industries. However, in order to easily take the sample at any time (freezing time), the batch freezer was selected. The detailed information about the geometry of agitation blade is shown in the paper by Masuda et al. (2020). The agitation speed of the blade was accurately controlled by the torque meter (ST-3000II, Satake Chemical Equipment Mfg., Ltd.) while measuring the torque. After 750 g of ice cream mix (Yamada Milk Product Co., Ltd.) at 4 °C was poured in the freezer, the agitation and cooling operation was started immediately. The ice cream mix consists of 8.0 % fat, 10.0 % nonfat milk solids and unspecified amount of emulsifier, stabilizer and sugar. Unfortunately, the more detailed recipe of ice cream mix was not available. The agitation speed of the impeller, N, was varied from 20 to 150 rpm. The torque imposed to the impeller increased as the liquid phase freezes. The agitation was conducted until the torque reached a maximum rated torque (0.32 N·m). This means the final temperature of ice cream would be different at each agitation speed. In the future, the temperature distribution in the freezer and its change during freezing should be measured in detail. It was confirmed that the flow condition after the liquid phase started to freeze was laminar flow because of the high viscosity. In this study, the aeration operation during freezing was not conducted. Thus, air was incorporated from the free surface. Naturally, more air cells were incorporated at higher agitation speed because the free surface was disturbed more intensively. After the freezing finished, the ice cream sample was packed in a container having a constant volume (90 mL) and stored at -20 °C in a refrigerator for 24 h. The hardened sample was used in melting tests.

2.2 Measurement

In order to investigate the microstructure of ice cream, the amount of air cell and the fat globule size were measured. It is noted that the measurements were conducted using the sample before hardening. The amount of air cell was evaluated based on the overrun (*OR*). *OR* is defined as follows (Dhungana et al., 2020):

$$OR = \frac{W_0 - W}{W} \times 100\#(1)$$

where W_0 [kg/m^3] is the initial density of the ice cream mix and W [kg/m^3] is the density of the sample after freezing. The density of the sample was measured by carefully filling a cup of 10 cm^3 with the sample and weighing it. With respect to the fat globule size, a laser diffraction particle size distribution analyzer (LA-950V2, HORIBA Ltd.) was used. There was no ultrasonic irradiation before introducing the sample in order to avoid the breakup of fat aggregate.

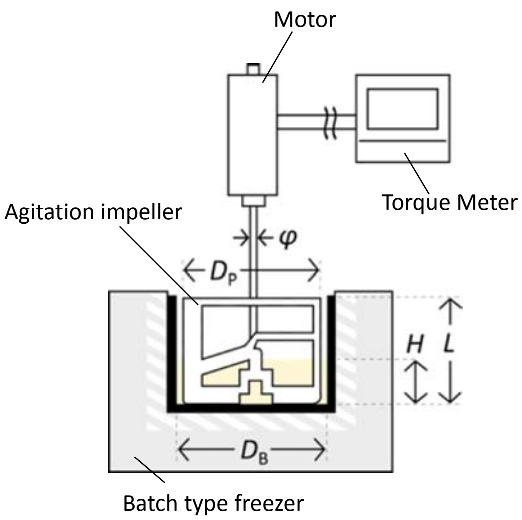

Figure 2: Experimental apparatus consisting of batch type freezer, motor agitation impeller and torque meter

Table 1: Geometrical parameters (dimensions in mm)

D_B	D_P	L	H	φ
140 ± 2	140	105	50	8

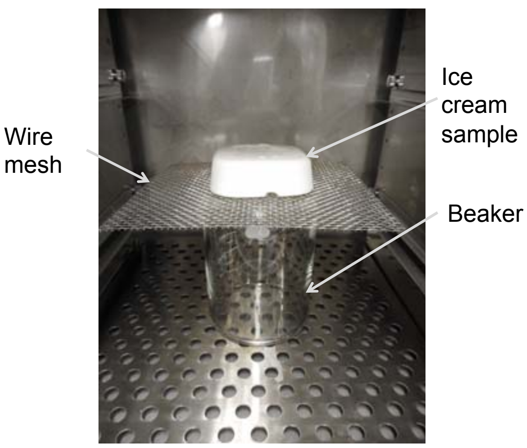

Figure 3: Experimental setup for melting test

The melting characteristics were investigated by the measurement of melting rate of the sample (Bolliger et al., 2000a, 2000b). It is noted that the sample stored in a refrigerator for 24 h was used in this experiment. The experimental setup is shown in Figure 3. The sample placed on a wire mesh melted and dripped into the beaker below. The weight of dripped portion collected in the beaker was measured over time. The rate of increase in weight was defined as the melting rate. This experiment was conducted at 25 °C in the incubator (APCW-36, ASTEC Co., Ltd.).
Each experiment was repeated more than three times. One sample was measured and analysed at each experiment. The average value of results is shown in this paper.

3. Results and discussion

Figure 4 shows the melting curve of ice cream sample prepared by various agitation speeds in freezing process. The time means the elapsed time since the sample was set in the incubator. The sample prepared at N = 100 rpm started to melt at first among other samples. In addition, the time required for the complete melting was shortest. On the other hand, the sample prepared at N = 20 rpm required the most time for the complete melting. One of the most important findings is that the control of melting characteristics is possible based on the agitation speed. As shown in Figure 4, except for N = 150 rpm, the increase in the agitation speed during the freezing process seems to be negative to the improvement of heat resistant performance of ice cream. Roughly speaking, the gradient of melted portion during the time from starting melting to finishing it is regarded as the melting rate. It should be noted that some deviation from the linear approximation was observed near the final melting time. Thus, the slope at the relatively initial stage was used for the estimation of melting rate.

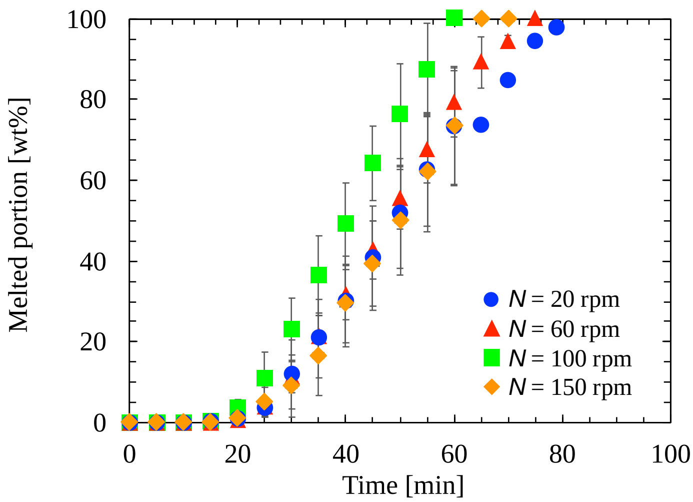

Figure 4: Melting curve for samples prepared with various agitation speeds in freezing process

In order to clarify the effect of microstructure of ice cream on the melting characteristics, the relation between the amount of air cells (*OR*) and the melting rate should be considered. According to Masuda et al. (2020), higher agitation speed leads to higher *OR* using the batch type freezer. Actually, the tendency was confirmed in this study. By combining those results and Figure 4, the tendency that higher *OR* leads to higher melting rate can be found except for N = 150 rpm. Generally speaking, the thermal conductivity of air is quite low compared to ice or fat (Carson, 2006). As a result, the effective thermal conductivity of gas/solid or gas/liquid mixture food is lower than pure solid or liquid food. In addition, the effectivity thermal conductivity of mixture decreases with the increase in the amount of gas phase. Actually, Goff and Hartel (2013) described that air cells in ice cream play a role as an insulator. Cogné et al. (2003a, 2003b) proposed the model of effective thermal conductivity of ice cream as a function of porosity corresponds to *OR*. The model represents the increase in *OR* leads to the decrease in the effective thermal conductivity. However, the opposite result that higher *OR* (higher agitation speed) increases the melting rate (decreases the effective thermal conductivity) was obtained as shown in Figure 4. Sofjan and Hartel (2004) reported that the melting rate decreases with the increase in *OR*. However, it is considered that not only the amount of air cells (*OR*) but also the air cell size and its distribution is important factor for the melting characteristics. According to Goff and Hartel (2013), ice cream with larger air cells, given a constant *OR*, might be expected to melt more quickly since the lamellar gap between bubbles would be on average larger than for the same ice cream with smaller air cells. However, Masuda et al. (2020) showed larger air cells are obtained at lower agitation speed. Thus, other factors should be considered to understand the melting characteristics.

It is widely accepted that fat globules play an important role in the melting characteristics. Figure 5 shows the fat globule size distribution in the ice cream prepared at various agitation speeds. It is noted that the measurements were conducted using the sample without storing in the refrigerator. As shown in Figure 5, the fat size distribution in the ice cream mix used in this study was bimodal originally. In addition, it is found that aggregation of fat globules was promoted by the increase in the agitation speed during freezing. Usually, fat destabilization reduces the melting rate (Muse and Hartel, 2004). Based on their report, the sample having larger aggregates of fat globules is desirable for the low melting rate. It is considered that results shown in Figs. 4 and 5 agree with their report. However, Koxholt et al. (2001) pointed out that the size of fat aggregates to air cells is important to block the foam lamellae and impede the drainage. In the future, the comprehensive investigation from the viewpoint of the size of air cells and fat globules will be conducted using the direct measurement system such as low-temperature scanning electron microscopy.

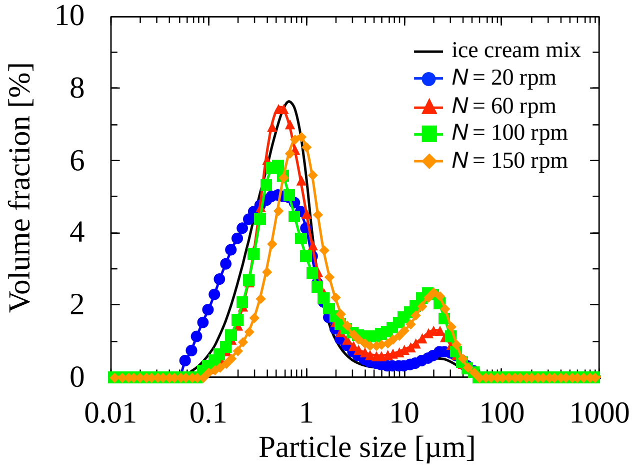

Figure 5: Particle size distribution of fat globules in ice cream and ice cream mix

4. Conclusions

This study investigated the effect of agitation speed during freezing on melting characteristics using a batch type freezer. The following conclusions were deduced:

1. Higher melting rate was obtained with higher agitation speed except when the agitation speed was 150 rpm. This result indicates the melting characteristics can be controlled by the agitation speed. However, the tendency is inconsistent with the well-known model of effective thermal conductivity because the sample prepared with higher agitation speed contained much more air cells.
2. The aggregation of fat globules was promoted by the increase in the agitations speed.

In the future, further consideration including the interaction between air cells and fat globules should be conducted. Especially, only results that fat globule aggregation is promoted by higher agitation speed was confirmed. The comprehensive discussion including the average size of aggregates and the shape of size distribution of fat globules should be investigated.

Acknowledgments

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