COLDSNAP, CORP

On-Demand, Dynamic-Freeze Ice Cream Maker Produces Creamy Ice Cream with Small Ice Crystals

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ABSTRACT
The science behind ice cream composition, processing, and storage is complex and technically nuanced. An important aspect of ice cream science is ice crystal size, which can impart a smooth (small ice crystals) or grainy (large ice crystals) texture on the end product. Ice crystal size can vary widely depending on the mix formulation, freezing process and parameters, and storage conditions. Dynamic freezing, the initial mixing and freezing step which happens immediately after blending the formulation, is where ice crystal formation occurs. The size of these ice crystals depends on several factors related to freezing time and freezing chamber parameters. For traditional hard ice cream, the dynamic freezing step is followed by static freezing, a hardening step which allows for widespread distribution of the ice cream. During the static freezing process, and especially during transportation and distribution, the ice crystals that were formed during dynamic freezing grow in size. ColdSnap, Corp. (Billerica, MA) is developing a single-serve, on-demand ice cream and frozen drink appliance which accepts shelf stable ColdSnap pods filled with liquid mix. The appliance freezes and dispenses the product in approximately two minutes, and the dispensed product only goes through the dynamic freezing cycle; thus ice crystals are extremely small, especially compared to store-bought ice cream. Additionally, no cleaning of the ColdSnap appliance is required, as the freezing and mixing occurs within the ColdSnap pod, and the contents of the pod are dispensed directly from the pod into a consumer's dish or bowl. In a study conducted at the Frozen Dessert Center at the University of Wisconsin-Madison, samples of ColdSnap ice cream mix and store-bought ice cream (melted) were frozen in the ColdSnap machine and compared to store-bought ice cream not frozen in the ColdSnap machine. Mean ice crystal size of the samples frozen in the ColdSnap machine ranged from 19.1 µm to 21.7 µm, while the comparison sample had a mean of 31.9 µm. By optimizing mixing parameters and circumventing the need for static freezing or the frozen supply chain, the ColdSnap machine successfully and consistently produces an on-demand ice cream with 30-40% smaller ice crystal size than store-bought ice cream.

Introduction

Despite its apparent simplicity, ice cream is a rather complex food. The best tasting ice creams are produced by carefully balancing the right mix of ingredients with ice cream making processes and post-process handling. "Premium ice cream" is typically associated with higher fat content; more fat results in lower water content, thereby minimizing the formation of large ice crystals and providing a creamier texture. Crystals larger than 50 µm create a grainy texture, whereas smaller ice crystals — ideally less than 20 µm — result in an optimal creamy texture.[1] Ice crystal formation and size are influenced by numerous factors during the formulation and freezing processes. Crystal size is also strongly influenced by transport and storage processes, in particular thermal fluctuations which can too often occur. This causes recrystallization and often results in further growth of crystals with a concomitant transition from a pleasant creamy product to an undesirable grainy one. It remains an ongoing challenge to balance and control all factors that impact crystal size throughout ice cream production, storage, and distribution in order to consistently deliver a rich, creamy product to consumers.

[1] Cook KLK and Hartel RW. Mechanisms of ice crystallization in ice cream production. Comprehensive Reviews in Food Science and Food Safety; 9: 213-222 (2010).

Impact of Ice Cream Formulation on Ice Crystal Size

Ice cream mix formulation is a critical factor that influences ice crystal size in the end product. The FDA has established a standard of identity (21 CFR 135.110) stating that, in order to be called "ice cream", the product must be a pasteurized mix containing at least 10% milk fat and have a total of at least 20% milk fat and nonfat milk solids, weighing 4.5 pounds per gallon.[2] While maintaining the standard, there is still wide variability permitted in formulating an ice cream recipe from ingredients like dairy, sugar, and flavorings. The formulator is responsible for creating a product that adheres to the FDA standard of identity while freezing properly and tasting great.

Sugars, salt, and stabilizers are key solute components of the formula that directly impact the ice cream mix freezing point and affect ice crystal size. Different sweeteners have differing molecular weights, which influences the freezing point of the ice cream mix. Salt also has an impact by depressing the freezing point. Stabilizers slow the melting rate of ice crystals, helping the ice cream to maintain the small ice crystals that form during the initial dynamic freezing phase. Adjusting the types and amounts of sweeteners, salt, and stabilizers has a direct effect on how quickly the mix freezes and helps determine the size of the ice crystals that form during the freezing process.[3]

Ice Crystal Size Growth During the Dynamic and Static Freezing Stages

After blending and homogenizing the ingredients to produce the base mixture, ice cream production consists of two major stages: 1) initial (or dynamic) freezing, and 2) hardening (or static) freezing. Dynamic freezing is most typically performed in a scraped-surface heat exchanger (SSHE).[4] Dynamic freezing sets the foundation for the size of ice crystal formation in any ice cream product; ice crystals formed during this process only become larger in subsequent stages.

The SSHE consists of a mixing chamber, typically cylindrical in shape, with one or more resident scraper blades, or dashers.[4] The walls of the chamber act as a heat transfer surface, freezing the ingredients in direct contact, while the scraper blades continually rotate and remove the freshly frozen material, directing it toward the center of the mixture and exposing a fresh layer of unfrozen material to the chamber. Cook and Hartel provided a comprehensive review of ice crystal formation in ice cream production where they describe several stages of crystallization consisting of nucleation, growth, and recrystallization (or ripening/coarsening).[1] Nucleation occurs at the chamber wall; the rate of nucleation determines how many crystals are formed, and ultimately, their size. The growth phase defines the final morphology (size and shape) of the crystals, which are optimally disc-shaped after dynamic freezing. Recrystallization occurs during both the dynamic and static freezing processes and results in changes to the size and shape of existing crystals without a change in crystal mass. When the ice cream completes the dynamic freezing process, the average size of the ice crystals is 10-30 µm.[1,5] During the static freezing process, the crystals typically grow to an average of 25-45 µm.[1] Figure 1 shows a typical distribution of ice crystal sizes after both the dynamic and static freezing processes.

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[2] "21CFR135.110." *Accessdata.fda.gov*, U.S. Food and Drug Administration, https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/cfrsearch.cfm?fr=135.110. Accessed Mar. 20, 2023

[3] Rohrig, Brian. "Ice, Cream... and Chemistry." *American Chemical Society*, ACS Chemistry for Life, Feb. 2014, https://www.acs.org/education/resources/highschool/chemmatters/past-issues/archive-2013-2014/ice-cream-chemistry.html. Accessed Mar. 20, 2023.

[4] Rao CS and Hartel RW. Scaped surface heat exchangers. Crit Rev Food Sci Nutr; 46(3): 207-219 (2006).

[5] Goff HD and Hartel RW. Ice Cream, Seventh Edition. Springer. (2013).

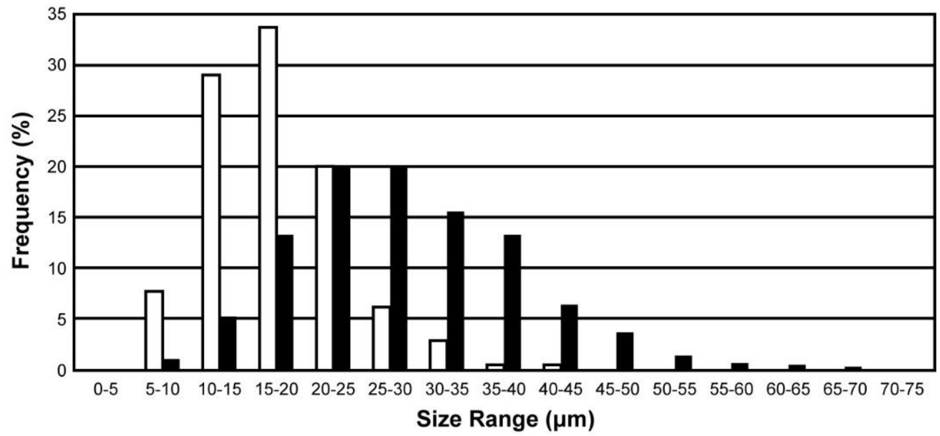


Figure 1. Distribution of ice crystal size in ice cream immediately after dynamic freezing in the scraped-surface heat exchanger (white bars) and after hardening in the static freezing process (black bars). From Reference 5.

Impact of Machine Configuration and Mixing Parameters on Ice Crystal Size

Various studies have shown that factors relating to the dynamic freezing process, including the physical attributes of the mixing machine and the processing parameters used to produce the ice cream, can profoundly affect ice crystal size in the final product. In particular, the following factors are known to impact crystal size: residence (or mixing) time, mixing chamber size and shape, temperature of the refrigeration fluid and heat transfer to the chamber wall, the mixing paddle speed and scraping efficiency, and draw temperature. While residence time and draw temperature are generally recognized as the most critical of these factors, all are important with many interdependencies. Each processing factor is discussed in more detail below.

Residence time in the SSHE during the dynamic freezing process is profoundly impactful on ice crystal size. Shorter freezing time almost always results in smaller ice crystals.[6] With longer residence times, ice crystals in the warmer interior (bulk) region have longer to recrystallize, or ripen and grow larger. Conversely, shorter residence times help maintain crystals closer to their original nucleation size. Smaller gaps between the scraper blade and walls of the mixing chamber tend to result in more effective removal of ice from the chamber side walls, and consequently, smaller ice crystal size. Having more numerous, smaller ice crystals is favorable for a smoother texture, and intimate contact of the blade to the wall helps remove small dendritic ice crystals along the wall as they form and before they can develop into larger crystals.[1] These dendrites ripen into disc-shaped crystals in the bulk region. Close contact between the scraper blade and chamber also helps prevent the build-up of an ice layer along the wall, which can function as an insulator and reduce cooling efficiency of the remaining mixture. Higher cooling rates result in quicker freezing and shorter residence times.

Mixing chamber size and shape also directly impacts ice crystal formation, and thus, ice cream quality. Generally, larger wall surface area-to-volume ratios are desirable in a mixing chamber. Since ice crystal formation occurs on the chamber walls, having a larger wall surface area increases the rate of ice crystal formation during the dynamic freezing process. Additionally, having a smaller bulk volume reduces the time ice crystals spend ripening, thus reducing the effects of recrystallization. The net effect is the ability to reduce residence time while achieving overall smaller crystal sizes. Given these dynamics, longer skinnier chambers are typically more favorable than shorter fatter chambers to achieve the formation of

[6] Russell AB, Burmester SSH, and Winch PJ. Influence of freezing conditions on ice crystallization in ice cream. J Food Eng; 39(2): 179-191 (1999).

smaller ice crystals. However, if the surface-to-volume ratio grows too large, there is a chance of freeze-up within the chamber,[5] so the chamber design must be carefully designed and balanced.

Refrigerant fluid and, correspondingly, mixing chamber wall temperature, also influence crystal size. The colder the chamber wall, the quicker the heat transfer, which results in faster ice crystal nucleation rates and thus larger numbers of smaller crystals. Furthermore, lower wall temperatures result in lower ice cream bulk temperatures, which reduces residence time and prevents growth and recrystallization.

Mixing paddle speed can impact ice crystal size, but there are competing effects to consider. Faster mixing speeds help reduce crystal size by continually scraping off newly formed dendrites and maintaining a thinner insulating ice layer. However, the mixing paddle can also generate frictional heat as it scrapes against the chamber wall, increasing the temperature and precipitating larger crystal growth. Therefore, a proper balance between mixing paddle speed and frictional heat must be considered to achieve optimal performance. Typically, mixing paddle speed is between 100-200 rpm.

Draw temperature, which is the temperature at which the ice cream leaves the mixing chamber, is important for several reasons. Lower draw temperatures mean that the ice cream will spend less time in the subsequent static freezing stage, resulting in less crystal growth, and therefore smaller crystals. However, achieving lower draw temperatures typically means longer residence time, which by itself results in larger crystals, and very low draw temperatures make the product difficult to package. Thus, there are trade-offs with respect to draw temperature in conventional ice cream production. Most commercial systems operate at a draw temperature of about -4^{o}C to -6^{o}C (21^{o}F to 25^{o}F).

Ice Cream Machines: Commercial and Consumer-Level Systems

Commercial production of ice cream occurs in either a batch freezer, for small quantity production, or a continuous freezer, which is used for larger quantities. In either case, the system design and operating parameters can be established to produce a creamy product with small crystal size during the dynamic freezing stage; thus, consuming the ice cream at this stage would be ideal. However, immediate consumption is impractical since commercial ice cream makers are not typically located near the point of sale, and even small batch freezers are expensive and require cumbersome maintenance and cleaning. As noted above, commercially produced ice cream subsequently undergoes a static freezing where ice crystals grow larger, and temperature fluctuations during transportation and distribution cause even more growth, leading to a grainier ice cream experience for the consumer.

A wide range of consumer-level ice cream makers are also available. These generally fall into two categories: 1) machines that require the bowls and/or ingredients to be pre-frozen, and 2) machines that have a built-in compressor that do not require the mixing bowls to be pre-frozen (but may still require the ingredients to be chilled). In either case, the machines typically take between 20-40 minutes to produce ice cream, although there are some that simply churn a pre-frozen ice cream mix and are ready in minutes. Ice cream produced by these consumer-level machines varies in quality, but many produce high-quality, creamy ice cream with small crystal size. These higher-performance machines often embody built-in compressors and/or good mixing paddle design that, in turn, result in a short residence time and efficient heat transfer. These machines create a similar end product to single-stage ice cream production, i.e., when ice cream undergoes dynamic freezing but does not require a secondary static freezing operation. However, the machines produce more than a single serving, so leftover ice cream must unfortunately be put through the static freezing step, affecting the ice crystal size and texture of the ice cream. Additionally, consumer-level machines require thorough cleaning of the mixing bowl after use.

A few consumer-level machines are designed to produce a single serving of ice cream. Generally, these single-serve appliances function by either thoroughly mixing a pre-frozen ice cream base or blending and freezing the ice cream base in a pre-frozen bowl, sometimes with the mixing occurring by hand. Like the multiple-serving units, these machines can produce creamy ice cream with small crystal sizes with a modest production time (5-15 minutes) but require pre-planning and pre-refrigeration to freeze the base and/or the bowl. These systems also require clean-up after making the ice cream. Small crystal size from these single-serve machines is generally achieved by either thoroughly and aggressively mixing a previously frozen base to break up existing ice crystals, or, in the case of the pre-frozen bowls, by keeping mixing times reasonably short.

A New Generation of Single-Serve, On-Demand Ice Cream Makers

Ice crystal size formation is understood well enough to be considered and incorporated into the design and manufacture of many commercial and consumer-level ice cream machines that, in turn, produce creamy, rich ice cream products. However, all existing systems have notable drawbacks. Commercial ice cream production, while having the ability to produce creamy ice creams, is subject to subsequent static freezing processes and cold chain transport, both of which can significantly increase crystal size before the ice cream reaches the consumer, thereby diminishing quality and the user experience. Consumer-level machines require preparation and chilling or freezing of the base mix ingredients, freezing of the mixing bowl, or both. Furthermore, all machines, whether commercial or consumer focused, require clean-up of the machine, the mixing bowl/chamber, or both.

A new generation of single-serve ice cream machines is just beginning to emerge that overcomes the above-noted drawbacks. For instance, ColdSnap, Corp. (Billerica, MA) is developing a single-serve, on-demand ice cream and frozen drink appliance that utilizes shelf stable pods, i.e., pods that do not require refrigeration or freezing prior to use (Figure 2). The system produces ice cream in approximately two minutes and does all of the freezing and mixing within the ColdSnap pod, thus eliminating the need to clean the appliance after use. The Coldsnap system produces very smooth ice cream with extremely fine crystal size that is consumed at the point and time of production.

Figure 2. Picture of the ColdSnap appliance, shown while dispensing.

Residence time in the ColdSnap machine is about two minutes. This short freeze time does not allow for any significant amount of recrystallization, keeping ice crystals close to their original formation size. Additionally, the pod design—which in this case serves as the mixing chamber—is tall and skinny with a high surface-to-volume ratio. The refrigerant material and design of the heat exchanger wall were selected to maintain an optimally low temperature at the chamber wall to rapidly freeze the ice cream mixture without building an ice layer. This process is aided by the mixing paddle, which has been designed to maintain very close contact to the pod wall and rotate at variable speeds depending on the viscosity of the base ingredients and phase of the mixing cycle. At its peak, the paddle rotates at extremely high speeds, more than three to four times other dynamic freezing processes, and helps to break up any larger crystals that might form. The draw temperature is in a similar range to commercial machines and is of less consequence since the product is consumed immediately upon dispense and does not undergo a subsequent static freezing process. Finally, product formulations are carefully created and rigorously evaluated to work in conjunction with machine mixing and freezing parameters to ensure that crystal size is maintained at the smallest possible levels.

Materials and Methods

Crystal size analysis was performed at the Frozen Dessert Center at the University of Wisconsin – Madison, under the direction of Prof. Richard Hartel.[7] All measurements were performed in a refrigerated glove box set to -15°C using a light microscope at 40x magnification (model FX-35DX, Nikon, Inc.). Immediately after freezing in the ColdSnap machine, a small amount of ice cream was taken from the center of each sample and placed on a microscope slide. A drop of chilled 50:50 pentanol/kerosene was added and a cover slip placed on top. The cover slip was gently moved with tweezers to spread the ice crystals underneath.

Ice crystals were traced using Microsoft Softonic Paintbrush for Mac and measured via a specified ice crystal macro in Image Pro Plus software (Media Cybernetics). At least 300 ice crystals were measured per analysis. The mean, standard deviation, min, and max crystal size were determined for each sample.

A total of three samples were frozen in the ColdSnap machine prior to testing: two samples of ColdSnap premium sweet cream mix (sample 1, sample 2) and one sample of a store-bought ice cream, which was thawed before being re-frozen in the ColdSnap machine (sample 3). One sample of the same store-bought ice cream, not frozen in the ColdSnap machine, was used for comparison (sample 4).

Results

Mean ice crystal size for samples one through three ranged from 19.1 µm to 21.7 µm, while sample four had a mean of 31.9 µm, as shown in Figure 3. Ice crystal images of the four samples are shown in Figure 4. Ice crystal size distribution of product frozen in the ColdSnap machine has similar characteristics to dynamically frozen product with a peak crystal size of 15-20 µm, shown overlayed in Figure 5.

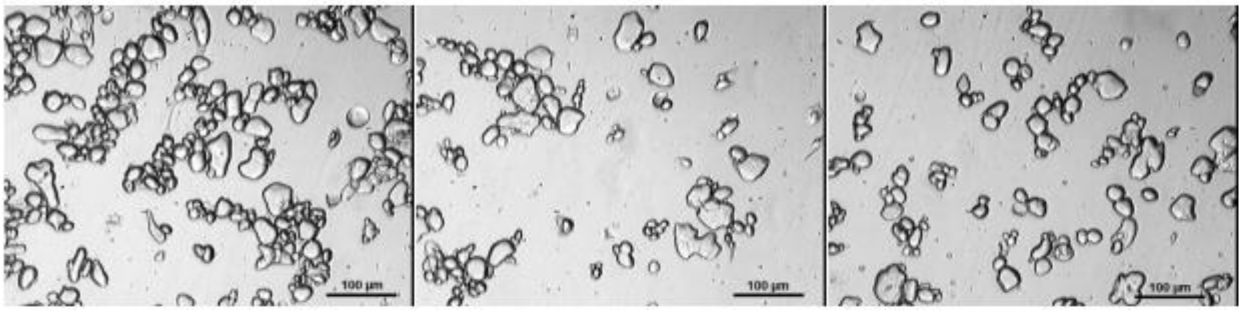
[7] Hartel RW. Ice Crystal Size Distribution Analysis, University of Wisconsin-Madison. (2020)

Ice Crystal Size Analysis

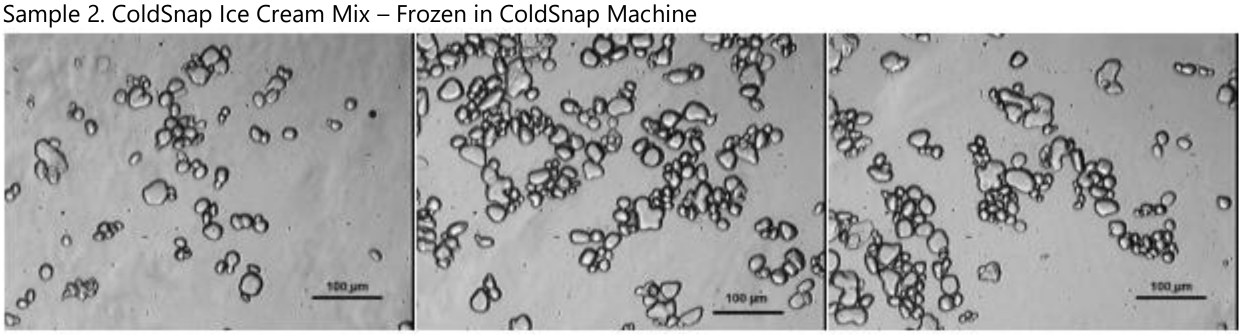
Sample	Method	Mean (µm)	Std. Dev. (µm)	Min. (µm)	Max. (µm)
1. ColdSnap Ice Cream Mix	Frozen in CS machine	21.7	7.7	6.0	51.9
2. ColdSnap Ice Cream Mix	Frozen in CS machine	19.5	7.1	5.3	43.1
3. Store Bought Brand Name Ice Cream	Thawed & frozen in CS machine	19.1	6.2	6.7	38.3
4. Store Bought Brand Name Ice Cream	Not frozen in CS machine	31.9	13.8	6.9	84.9

Figure 3. Results of Ice Crystal Size Analysis

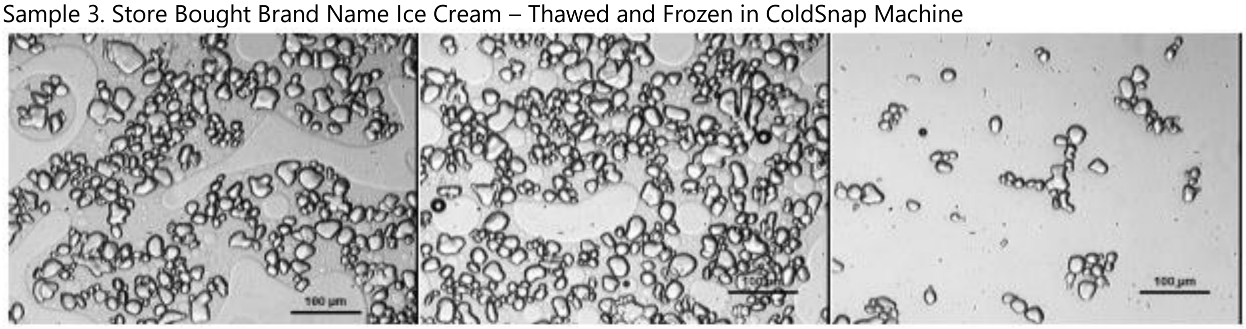
Sample 1. ColdSnap Ice Cream Mix – Frozen in ColdSnap Machine



Sample 2. ColdSnap Ice Cream Mix – Frozen in ColdSnap Machine



Sample 3. Store Bought Brand Name Ice Cream – Thawed and Frozen in ColdSnap Machine



Sample 4. Store Bought Brand Name Ice Cream – Not Frozen in ColdSnap Machine

Figure 4. Images of Ice Crystals in Samples 1-4.

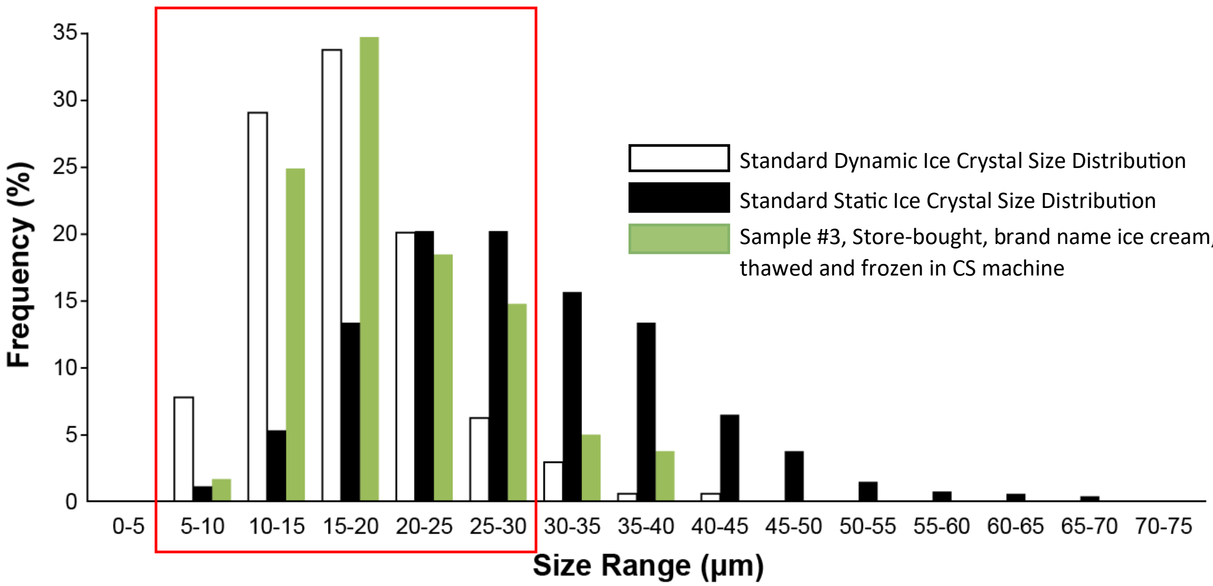


Figure 5. Ice crystal size distribution graph (from Figure 1), overlayed with ice crystal size distribution of sample 3 (Store bought brand name ice cream, thawed and frozen in the ColdSnap machine, from Figure 3). The red box surrounds the ice crystal size distribution of the dynamic freeze (white bars) and of sample 3 (green bars), showing that the ColdSnap machine performs a typical dynamic freeze cycle.

Conclusion

Ice crystal size greatly impacts consumer enjoyment of ice cream. Thus, discovering a way to consistently deliver ice cream with the smallest possible ice crystal size is a common goal amongst ice cream manufacturers. Standard store-bought ice cream undergoes both dynamic and static freezing steps, followed by transportation and storage, which can result in a product with larger ice crystals than ideal for the optimal eating experience. Current on-demand systems require pre-planning, pre-refrigeration/freezing, and/or post-process cleaning. Single serve, shelf stable, individualized pod-based systems offer a solution to these problems by achieving fast dynamic freeze times and eliminating the need for static freezing. This ensures that the ice cream consistently reaches the consumer in an optimal state with the smallest crystals possible, which imparts a smooth, creamy texture to the product every single time.