jpht
Review Article

Journal of Postharvest Technology
01 (01): 091-096, October' 2013
www.jpht.info

Effect of Cryogenic Freezing on Food: a Review

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Received : 13 Aug 2013
Revised : 24 Sep 2013
Accepted : 03 Oct 2013

Keywords

Cryogen,
Liquid nitrogen,
Food freezing,
Food quality

Abstract

Food materials are perishable by nature. They require processing or preservation techniques to enhance the storage life. Cryogenics is a branch of engineering wherein production of cryogen and the maintenance of low temperature technologies are studied. Such cryogens have a tremendous potential to be used as a total loss refrigerant. Implementing cryogenic solutions in the field of high-volume/high-quality food processing is important for a number of reasons. Maintaining proper food temperatures throughout the plant is essential for food preservation and food safety. These are fundamental elements for consistent food quality and the hallmark of top quality. At the same time, high-efficiency cryogenic processes using either carbon dioxide (CO_2) or liquid nitrogen (N_2) can boost productivity and streamline operations.

INTRODUCTION

Freezing methods can be divided into two main classes: (1) those involving direct contact between the refrigerant and the food; and (2) those involving the use of a secondary medium, e.g., air, brine, or metal plate, which is cooled by the refrigerant (George, 1993).

Cryogenic food processing technology has made significant advances in the past years. When upgrading from older cryogenic systems or other freezing/chilling methods, the impact is immediate and can be dramatic. Inline and batch cryogenic processing systems can speed production or achieve higher volumes in limited space, often while improving quality. State-of-the-art cryogenic solutions can often save processors hundreds of thousands of dollars a year per line, while preserving the quality of the food product.

Technically the term "cryogenic" pertains to temperatures below -238 ºF (-150 ºC), though it is generally used in the food industry to refer to any cold processing that uses either CO_2 or liquid N_2. At atmospheric pressure, N_2 is a liquid at -320 ºF (-196 ºC), and CO_2 is a solid at -108 ºF. The gases are stored as liquids and conveyed through insulated piping systems to the cryogenic process on the plant floor. The liquid cryogen is then injected into the freezer in order to remove the required heat from the food.

In the meat, poultry and seafood industries, cryogenic processing can efficiently bring protein products to the desired equilibration temperature, and can reduce the need for holding freezers to reduce overall freezing costs at a plant. Cryogenic solutions are also used for freezing entrees and marinated products, and to individually quick freeze (IQF) small items, such as diced products.

In the baking and snack food industry, cryogenic gas processes can be used before, during or after the mixing process which creates dough or batter. Tightly controlled freezing processes can protect the shape, texture and quality of foods

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such as frozen dough products and par-baked breads. For fully baked products, cryogenic technology can help extend shelf-life and maintain product quality all the way to the table.

In both protein and baking operations, cryogenic chilling can improve the quality of downstream operations. Cryogenic systems can also supplement or boost the performance of traditional mechanical chillers and freezers. It should be noted and understood that cryogenic freezing solutions offer substantial operational benefits to the food manufacturer. Cryogenic gases freeze/chill food products quicker than traditional methods. This can equate to higher throughput, quicker changeover rates, and a reduction in floorspace needed for the equipment.

Cryogenic freezing uses refrigerants, such as liquid nitrogen or solid carbon dioxide, directly. Boiling-off of the refrigerant when it comes in contact with the product brings about cooling (Fennema, 1973) as well as using the latent heat absorbed by the boiling liquid, sensible heat is absorbed by the resulting cold gas.

Most cryogenic systems use total loss refrigerants, i.e., the refrigerant is released to the atmosphere and not recovered (Thevenot, 1979). Due to environmental and economic factors, total loss refrigerants must be both readily available and harmless, which limits the choice to atmospheric air and its components (Kumar et al., 2004).

Cryogenic freezing was first carried out commercially using liquid air, in the 1930s (Bald, 1991). However, liquid air contains a high proportion of liquid oxygen, which is a powerful oxidizing agent. Theoretically it can be produced on site, eliminating the need to purchase and store the ‘gas.’ Although companies have promoted the use of liquid air, in practice, it has been superseded by less harmful liquid nitrogen and the liquid or solid carbon dioxide.

Most food freezing systems rely on convection as the principal means of heat removal. The rate of heat removal from the product depends on the surface area available for heat flow; the temperature difference between the surface and the medium; and the surface heat transfer coefficient (SHTC) . Much higher coefficients are achieved in cryogenic systems than in most conventional refrigeration (Table 1).

Table 1. Published SHTC for different Cooling Processes (George, 1993)

Method	Heat transfer coefficient (Wm^{-2} $^{0}C^{-1}$)
Still air	5–10
Air blast, slow	15-20
Air blast, fast	40–50
Fluidized bed	100–4000
Contact, plate	500
Immersion, still	50–200
Immersion, agitated	<1000
Cryogenic, R 12	1000
Cryogenic, liquid nitrogen	1500

The rate at which heat can be conducted away from the surface is not the sole criterion that governs the time taken to freeze a product. Heat must also be conducted from within the product to its surface before it can be removed. Most foodstuffs are poor conductors of heat and this imposes a severe limitation on attainable freezing times for either large individual items or small items frozen in bulk.

Cryogens are particularly suited to food products that have a high surface-area-to-volume ratio and in which thermal diffusivity of the food does not restrict the transfer of heat from the product to the freezing medium. Typical examples are fish fillets, shellfish, pastries, burgers, meat slices, sausages, pizzas, and extruded products. Typical product freezing times in liquid nitrogen systems are shown in Table 2.

Table 2. Freezing Times of Nitrogen Freezers (George, 1993)

Product	Freezing time (min)
Fruit and vegetables	0.5–6
Meat and meat products	3–20 [a]
Meat patties, hamburgers	3–5
Pastry products	4–8
Precooked foods (warm)	4–8

[a] Large, bulky meat products.

Rapid freezing has been claimed to improve taste, texture, aroma, nutritive value and appearance. It also reduces the bacteriological, enzymatic, oxidative and chemical degradation and the drip loss upon thawing.

The most apparent influence of the freezing rate on product quality is related to the size of the ice crystals, which are formed during the freezing process (Jul, 1984). It has long been shown by photomicrographs that the faster the meat and fish are frozen, the smaller the ice crystals are produced, and that above a certain rate these are predominantly intracellular, when by implication the damage to cell walls should be minimal. However, extracellular ice crystal formation is not necessarily disruptive because muscle cell wall membranes are elastic, unlike those of vegetable tissue (Karel, 1975). Nevertheless, largely on the strength of photomicrographs, plausible advocacy of rapid freezing equipment throughout the 1930s and 1940s resulted, and these views still remain.

Freezing rate does affect the appearance of many food products. For example, fast freezing of poultry tends to produce a lighter-colored product as the small ice crystals scatter the light more than larger crystals. This lighter color is preferred by many consumers (Jeremiah, 1996). In fish, rapidly frozen fillets have a dense white and opaque appearance in comparison with the dark, translucent, vitreous product produced by very slow freezing.

When ice crystals grow they may puncture the cell walls so the juice bleeds out. This causes ‘drip loss’ when the product thaws. The larger the average crystal size is, the greater the number of punctured cells and the greater the drip loss. The loss of juice can result in a loss of firmness and flavor. The drip loss from some food (i.e., strawberries) can be clearly related to freezing rate. Slow freezing can produce drip losses to the tune of 20%. Fast freezing without surface cracking can reduce losses to approximately 5% (Kennedy, 2000). With meat and meat products freezing considerably increase the loss. However, other factors inherent in the animal and its processing before freezing have more effect on the magnitude of drip loss than the difference in freezing rate.

Lower weight loss, during the freezing of unwrapped food, is one of the main advantages of cryogenic freezing. Weight loss during freezing of beef burgers can be as high at 3% in a poorly designed air blast freezing system compared with 0.4% in liquid nitrogen tunnel (Robinson, 1985).

However, technological advances in conventional freezing systems can substantially reduce – if not completely remove this saving. In a modern spiral freezer operating at −30°C air temperature, weight loss will be approximately 1.2%. In an air impingement freezer operating at a −46°C, the weight loss from a burger can be less than 0.4% (Kennedy, 2000).

Some products, such as delicate soft fruits and light pastry products may crack when they are submitted to very high freezing rates or very low temperatures. Research suggests that crust freezing produces a shell that prevents further volume expansion, when the internal portion of the unfrozen material undergoes phase transition. If the internal stress is higher than the frozen material strength, product will crack during freezing. Products with high void spaces, which allow internal stresses to dissipate, show a lessened chance of freeze-cracking (Jul, 1984). Precooling prevents freeze-cracking because it reduces the differences in temperature between the product and the freezing medium, and reduces the difference between freezing time at the center and at the surface. When the phase change of the core region occurs before the surface becomes brittle, food products can support the internal pressure and freeze-cracking does not occur.

Effect of Cryogenic freezing on quality of food products:

Freezing and frozen storage can be utilized for the long-term preservation of some fruits and vegetables. Freezing decreases the water activity, inhibits microorganism growth and reduces enzymatic activity resulting in extending the shelf life of the product (Fellows, 2000, Heldman, 1992). Many published research works have confirmed the close relationship between quick freezing and high quality frozen products and the resulting increase shelf life with maximum preservation of initial quality (Sanz et al., 1999, Sun and Li, 2003, Zhang et al., 2004).

Color plays a fundamental part in the consumers' evaluation of the food quality. Color changes are considered as the major quality attribute that affects consumers' selection (Zhang et al., 2004). Enzymatic oxidation of phenolic substances is the main reason that induces color changing (browning). Ice crystals formed during freezing will enhance enzymatic oxidation due to the destruction of the cells and tissues of the product and therefore increased contact between phenolics, oxygen and enzymes (Ruenroengklin et al., 2008).

Textural parameters of frozen foods play an essential part in determining the acceptability of these products by consumers. Higher values of hardness, chewiness and resilience of the pulp indicate better quality products (Zhang et al., 2007, Krause et al., 2008). Several researchers have studied the effects of freezing on textural quality of fruits (Delgado and Rubiolo, 2005, Van Buggenhout et al., 2006, Sousa et al., 2007).

Enzymatic activity is responsible for the quality deterioration in most of the frozen fruits. The enzyme activity decreases as the temperature decrease; however as a result of freezing, the chemical reactions catalyzed by the enzymes occur due to the increase in concentration of salts (Maier et al., 1964, Whitaker, 1972, Marin and Cano, 1992).

Dates, irrespective of the cultivars, contain more than 75% sugars on a dry-weight basis (Kanner et al., 1978). Al-Mashhadi et al. (1993) found that the reducing sugars (fructose and glucose) in date fruits increased while the sucrose sugar decreased at the end of twelve months of frozen storage. In another study a decrease in the reducing sugars of date fruits was reported at the end of six months of frozen storage (Mikki and Al-Taisan, 1993).

CONCLUSION

Freezing protects the quality of food, and the quality of freezing method used impacts the organoleptic properties of food after thawing. Organoleptic properties are characteristics experienced through the senses, such as appearance, texture, taste and smell. Abundant research has shown that the key to high-quality frozen food is freezing rate: the faster the freezing rate, the higher the quality of food product. This article explains how rapid freezing with cryogenic-based systems helps in minimizing organoleptic deterioration, particularly in sensitive foods like seafood, fruit, vegetables and meat. Cryogenic systems can be used effectively to freeze, transport, and store a wide range of foodstuffs, and a wide range of equipment and techniques is available using either nitrogen or carbon dioxide. While there are many practical, as well as economic, disadvantages to cryogenic refrigeration systems, there are many situations in which low capital or maintenance cost and/or rapid freezing rates make these techniques worthwhile.

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