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Freezers using Cryogens: A Review

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Abstract: Innovative cryogenic freezing technologies can be used to produce high quality frozen foods. The potential for the development of new cryogenic equipment and processes is still enormous. This paper presents the fundamentals of cryogenic freezing and various food freezing technologies, discussing some technical descriptions of representative freezing equipment developed in the past. Product quality issues encountered when using cryogenic systems with inappropriate knowledge of the product or inadequate cold chain after cryogenic freezing -i.e. recrystallization, mechanical damage and others- are also addressed.

Keywords: Liquid nitrogen, Carbon dioxide, Food freezer, Tunnel freezer, Rotary freezer.

Introduction

In the food manufacturing industry, mechanical freezing is seen as a long established form of freezing technology while the cryogenic technology is seen as a new alternative, especially for low production and varying capacity requirements (Kumar, et. al., 2004a).Quality control and food preservation by mechanical freezing is not a recent phenomenon. However, preservation of foods by cryogenic means is a new development in this area. Research on the thermodynamics of food freezing commenced in America in 1865 using ice and salt. However, food-freezing industries on a commercial scale using mechanical refrigeration systems started only in 1890 (Shenoy, 1979). While the principles of mechanical freezing have not changed since it was invented over 100 years ago, the components, materials and operating systems have advanced to the latest design and intelligent system control in order to provide the best food safety, low maintenance and energy efficiency. The modern day high tech mechanical IQF (Individual Quick Freezing) tunnels are proof of this development (Heap et. al., 1983).Cryogenic refrigeration refers to the use of expandable gaseous refrigerants, such as argon, oxygen, hydrogen, nitrogen, carbon dioxide and others, that at atmospheric pressure evaporate or sublime at very low temperatures. In the food industry, the most popular cryogenic substances are nitrogen (N_2) and carbon dioxide (CO_2). Cryogenic systems reduce temperature through the direct application of cryogen, within an enclosure that contains the food product, while mechanical systems use a re-circulating refrigerant within an air cooler that exchanges heat from air circulating within the freezer to reduce food temperature (Kumar, et. al., 2004b).

There are 2 main types of cryogenic systems used as an alternative to the IQF systems: sprayingandimmersion. For the first type, a medium of carbon dioxide or liquid nitrogen is sprayed on the food products that are placed on a belt that goes through the freezer, and it has as an advantage fast freezing result and really low dehydration. Since there is no movement of the food products though, there is a high risk for lump formation and that the products stick to the belt, thus making the belt very difficult to clear. The second type is a highly efficient method. The freezing time is extremely short and dehydration is unbeatable low. Since the products are immersed separately into a bath containing carbon dioxide or liquid nitrogen, there are no weary parts and the freezer is very easy to clean. The disadvantage for the immersion cryogenic method is the very high consumption of refrigerant and dependence on the medium supply (Heap et. al., 1983).Fast freezing rate is often seen as one of the main benefits of a cryogenic system together with the freezers small size, while mechanical freezing is said to be slower due to the difference in refrigerant temperature and the big footprint of the freezers is seen as a drawback. Today's mechanical freezers though, can rival cryogenic systems both in terms of freezing speed and footprint (George, 1993).

The advantage of IQF freezers are the high air velocity impingement systems, capable of extremely quick freezing of small, flat, unpackaged food products such as shrimp, peas, diced meat or diced/sliced fruits and vegetables. The high air velocity is suspending the product in the cold air stream, separately freezing each piece of product without creating lumps.The associated refrigeration plant for a mechanical freezer can be packaged in a weatherproof housing on a moveable frame. Compare to this, a cryogenic system has fixed pipework and requires a large external gas storage tank.Flexibility is important to the customer, therefore equipment manufacturers today are no longer building large, fixed systems, but compact modular formats on mobile frames with a small footprint.

Some Disadvantages with Cryogenic Freezing

In a cryogenic system the product conveyor is a stainless steel belt because of the extreme low temperature of the freezer and thus the belt is always subject to significant maintenance. The advantage of a mechanical system is that the conveyor belt can also be manufactured from food grade low temperature plastic. Plastic provides easier release for wet food products and is easier to clean for improved hygiene. Also, different plastic module belt designs are available for different varieties of food and airflows (Kumar, et. al, 2004b).Cryogenic freezing exponents will generally try to argue that the size and complexity of a IQF freezer requires more manpower to clean the system, but in fact mechanical freezers are often easier to clean due to access for the personal inside and outside the enclosure. Furthermore, automated CIP (Clean in Place) systems have surpassed the need for manual cleaning of the mechanical freezers (Eek, 1991).

The high production cost of the liquid gas has a direct impact on the purchase cost of gas for the food manufacturer. The ongoing running costs of a cryogenic freezer can be considerably higher than IQF freezer and often food manufacturers have no alternative to their gas supplier. Cryogenic freezers have low running costs in terms of energy consumption but the cost of the liquid gas is high and variable. Also, the carbon emissions for liquid gas production is something to consider in terms of environmental cost (Bald, 1991).IQF freezing systems have more advantages over a cryogenic system in terms of environmental impact, energy efficiency and running costs. IQF freezers can use natural gases such as ammonia, which is an environmental friendly refrigerant with zero potential for ozone depletion and global warming. In addition, energy consumption can be reduced by fitting optimization technology and special software for controlling the compressor and condenser unit operation(Eek, 1991).

The major problem with most cryogenic materials is that they are extremely cold (Table 1). Direct immersion is inadvisable since an extremely high temperature gradient can be imposed on the food, which may disintegrate. Research studies have concluded that the ideal cryogen would have a boiling point of −50°C and a latent heat of evaporation as high as possible (Kennedy, 2000).

Table 1 Properties of Cryogenic Materials

Material	Boiling point °C at 1atm	Latent heat of vaporization (kJ kg^{-1})
Helium	−268.8	454.8
Nitrogen	−195.8	197.7
Carbon monoxide	−190.6	223.6
Argon	−184.4	154.7
Methane	−161.1	568.5
Ethane	−88.9	455.6
Propane	−42.2	420.5
Carbon dioxide	−57.6 (5atm)	313.5
Carbon dioxide (solid)	−79 (sublimation point)	566.0

Advantages with Cryogenic Freezing

The investment cost for a cryogenic system is low since the suppliers supply and rent their equipment for free, but this comes with a monthly cost for the gas tank, thus the food manufacturer is dependent on the gas supply. If the food manufacturer is looking for a short-term, low capacity freezing solution with low capital, then the rental of a cryogenic system is justified. The total cost of the actual gas charge to freeze each kg. of the product should be taken into consideration though. Also, depending on the geography of the food processor, the gas supply might not always be available on a regular basis due to transportation and other logistic factors.

Making an investment in a IQF freezing system makes more sense for companies that are looking for mid to long-term solutions. The flexibility of a IQF mechanical system offers the possibility that in time the freezer can be adapted to suit a wide range of products with adjustments to temperature, airflow, belt mesh and flow configuration. The length of a cryogenic freezing system can be extended to increase capacity but a mechanical system has more manufacturing flexibility.

A strong argument for cryogenic freezing is low dehydration. Cryogenic freezing refers to very rapid freezing achieved by exposing the food products to an extremely cold medium undergoing a change of state. The rate of freezing obtained with cryogenic methods is much greater than that obtained with air-blast or plate freezing but is only moderately greater than that obtained with fluidized bed. Dehydration loss from the product is usually much less than 1%.

Heat Transfer Mechanisms During Cryogenic Freezing

The rate of heat transfer during freezing is influenced by several factors. Some of these are the thermal properties of the food, the surface area of the product available for heat transfer, the size and shape of the product, the temperature difference between the food and the freezing medium, the insulating effect of air surrounding the food and the presence of packaging materials. These factors are significant for mechanical and cryogenic freezing alike. However, the heat transfer phenomena occurring in cryogenic freezing differs from that observed in mechanical systems in several aspects.

Kennedy (1998) reported that the most common process in cryogenic freezing is spraying the surface of the product with either N_2 or CO_2. Though the method of application for both substances is similar, the behaviour of these is quite different: when liquid CO_2 is fed into a spay nozzle, the CO_2 expands and changes to approximately equal parts (by weight) of solid and vapour. The flow of the "snow" (e.g. a mixture of solid particles and vapour), the CO_2 distribution system and internal convective mechanisms create air/CO_2 currents within the freezer. As solid CO_2 particles contact the food surface, the solid almost instantly sublimes to vapour, which draws heat out of the product. This system provides approximately 85% of the refrigeration effect from the sublimation of the solid carbon dioxide. The remaining 15% of the cooling is a result of the contact of the product with air/CO_2 mixture. To obtain the maximum refrigeration benefit, a typical CO_2 system will inject CO_2 throughout the length of the freezer.

In N_2 systems, the N_2 is sprayed into the freezer and separates as liquid and vapour. As droplets touch the product surface, the liquid changes to vapour, extracting latent heat from the food surface in the process. The vapour distribution through the freezer creates convective currents that increase the freezing rate. In this case, about 50% of the refrigeration effect is supplied by the N_2 phase change from liquid to vapour. The remaining heat is removed by the N_2 vapour flowing through the freezer (Khadatkar, et.al., 2004).

It should be noted that heat removal would not induce phase change by itself: additional factors such as the rate of formation of ice crystals and the propagation of these in the food structure are involved.

Liquid nitrogen is produced by liquefaction of air, either as a principal product or as a byproduct of liquid oxygen. Nitrogen is the main constituent of atmospheric air and at atmospheric pressure it liquefies at −196°C. It is usually supplied and stored at a pressure of 3–6 bar, with corresponding boiling points of −185°C to −177°C. A useful rule of thumb is that 1 ton per hour of liquid nitrogen is approximately equivalent to 100kW of mechanical refrigeration (Mermelstein, 2000). Energy required to produce 1 kg of liquid nitrogen is around 3000kJ, or eight times the consequent stored refrigerating effect (Kennedy, 2000).
Carbon dioxide does not exist in liquid form at atmospheric pressure. It sublimes directly into gas without going through a liquid phase. Liquid carbon dioxide is generally supplied either at ambient temperature (e.g., 25°C and 65 bar), giving a refrigerating capacity of 199 $kJ.kg^{-1}$, or at −16°C and 22 bar, giving a refrigerating capacity of 311 $kJ.kg^{-1}$ (Heap and Mansfield, 1983). The majority of the 'refrigeration effect' stored in solid CO_2 is latent, whereas in liquid nitrogen almost half of the effect is due to sensible heat transfer to the cold gas.Cryogens are typically employed as sprays in tunnel or batch cabinet systems, or direct immersion tunnels (Khadatkar et al., 2004a). Operation of cryogenic systems is relatively straightforward. The two basic functions to regulate are: (1) conveyor speed to give the required retention time, and (2) refrigerant flow rate to give the desired product temperature (Singh, 1986).

Tunnel Freezers: Essentially a tunnel freezer is a countercurrent heat exchanger. The cryogen is sprayed at one end and the gas passed countercurrent to product traveling on a belt in the opposite direction. This enables the exit temperature of cryogen to be only 20°C below the product inlet temperature. Thus product can be pre-cooled before being subjected to the full force of the refrigeration effect. Approximately 50% of the product's heat can be extracted before it reaches the cryogen spray. Straight or spiral tunnels are utilized. As a rule, carbon dioxide tunnels tend to be longer than liquid nitrogen tunnels for the same capacity.

A tunnel freezer operates by conveying the product through an enclosed space within which the cryogen is discharged. Cryogen consumption is improved by insulation and isolation of the freezing tunnel, and by the control of cold gas within the tunnel. The product passes through three distinct zones in the tunnel: the precool zone, the freezing zone, and the post-cool zone. In the precool zone, the product is cooled using gas and fans force the gas vertically past the product. In the freezing zone, sprays discharge cryogen directly on product and belt, while in the post-cool zone, which is a gas-cooled section, with more fan circulation, some temperature stabilization takes place (Khadatkar, et.al., 2004).

The objective of all cryogenic tunnel freezers is to quickly freeze or cool products in an efficient manner using a cryogenic liquid. Suited for processing large quantities of products in a small footprint, cryogenic tunnel freezers can increase product yield compared to alternative technologies. Cryogenic tunnel freezers also result in less product dehydration while retaining product textures.Although these are significant advantages over mechanical freezing systems, the most important concern for many food processors remains product freezing cost. It is critical, therefore, to design a cryogenic tunnel freezer to operate as efficiently as possible while incorporating the processor’s layout and required production capacities. In its basic form, a cryogenic tunnel freezer consists of four primary parts:

- An insulated enclosure that houses a conveyor belt to carry the products.
- An injection system to inject the cryogenic liquid.
- Circulation fans to improve heat transfer with the products.
- An exhaust system to evacuate excess gases.

To get the most efficient cryogenic freezing system, it is necessary to use as much of the available energy as possible from each pound of cryogen. The energy available in the cryogen will depend on a variety of factors; however, the most important variables are the cryogen’s storage pressure and the exhaust vapor temperature of the freezer.For carbon dioxide (CO_2), about 85 percent of the refrigeration capacity will be obtained during the sublimation of the solid CO_2 (latent heat) and 15 percent in the cold vapors (sensible heat). For a nitrogen system, about 50 percent of the refrigeration capacity is obtained during the vaporization of the liquid (latent heat) and 50 percent from the cold vapors (sensible heat). Once it is understood where the refrigeration capacity of the cryogen being used is found, it is possible to begin to choose a type of freezing tunnel that will best and most efficiently utilize the cryogen (Abramov, et. al., 1969).

A good distribution of CO_2 throughout the tunnel freezer is important to efficiently use the refrigeration capacity available in the CO_2.For a nitrogen system, it will be necessary to strategically place the injection header to allow for a spray of liquid and, at the same time, obtain a good recirculation of the nitrogen gases. The efficiency of a nitrogen system primarily is reflected in the exhaust gas temperature. If the exhaust gas temperature is too low, there will be a reduction in the sensible heat of the nitrogen gases available to freeze the products. This results in higher nitrogen consumption and a less-efficient freezing process.

Rotary Freezers: Rotary freezers have also been developed for individually quick frozen products such as shrimps, cubed chicken meat, or meatballs. A fine mist of cryogen is used to freeze the surface of the product and prevent individual pieces sticking to one another before they enter a rotating drum, which keeps them separated during the freezing process (Khadatkar, et.al., 2004).

Immersion Freezers: Immersion freezers are the simplest and most inexpensive way of using cryogens to freeze foodstuffs. Immersion freezers are best suited to high volumes of product where crust freezing is required or where the product is sufficiently robust to withstand the thermal shock of a high temperature differential. Very fast heat transfers are possible, but the system is wasteful in that only the latent heat of the liquid is used and cold vapor is lost (Khadatkar, et.al., 2004).

Cabinet Freezers: Batch cabinet freezers utilizing cryogens have been developed for freezing prepared and precooked food, particularly for airline meals. Liquid cryogen is injected at time intervals into a cabinet containing the food on racks; circulation fans are usually utilized to provide even and efficient freezing. Freezing times vary from 5 min to 1h, depending on the product and its temperature (Khadatkar, et.al., 2004).

Pellet Freezers: Liquids and semi solids are often frozen into pellets. This can be carried out using contact freezing between belts or in molds, or cryogenic freezing using liquid nitrogen and a forming device. Belt freezers employ a similar contact method of freezing to plate freezers. Single-band and double-band freezers are designed to freeze thin layers, usually of liquid or semi liquid products such as vegetable purées, fruit pulps, egg yolk, sauces, soup, etc. In double-band systems, product is frozen between two endless belts, of which the top is flat and the lower belt corrugated. The product is spread into the corrugations; the top belt encloses the exposed surface, thus freezing the product as IQF pellets (Khadatkar, et.al., 2004).

Combined Freezers: A cost-effective alternative to 100% cryogenic freezing is a combined freezer. The principle is to use a cryogenic freezing unit for initial freezing of the outer surface of the product, followed immediately by mechanical freezing to reduce the temperature of the bulk of the product. One advantage of this approach is that the cryogenic stage can often be retrofitted (Khadatkar, et.al., 2004).

Conclusion

In cryogenic freezing, liquefied gases are placed in direct contact with the foods. Food is exposed toan atmosphere below -60°C through direct contact with liquid nitrogen or liquid carbon dioxide or their vapor. This is a very fast method of freezing; thus, adequate control is necessary for achieving quality products. It also provides flexibility by being compatible with various types of food products and having low capital cost. The rapid formation of small ice crystals greatly reduces thedamage caused by cell rupture, preserving color, texture, flavor, and nutritional value. The rapid freezing also reduces the evaporative weight loss from the products, provides high product throughput, andhas low floor space requirements.Equipment for cryogenic freezing usually takes the form of an insulated open-ended tunnel through which passes a variable-speed conveyor belt. The unpackaged product is placed on the belt and freezing is achieved by spraying or permitting liquid refrigerant to drip on the product or by exposing the product to very cold air or cold vapors from the boiling refrigerant. In spite of increase in usage of cryogenic food freezing, considerable controversy still exists with regard to the relative merits vs. more traditional methods of freezing.

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