

Cold feat: choosing the right freezing technology for your production line

Abstract of "Review of cryogenic vs.mechanical freezers" by Dr C.J. Kennedy

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1. Introduction

Chilling and freezing are already an essential aspect of many food production and distribution processes. Clear trends in the food industry indicate the rise in demand for frozen and chilled foods will continue, so more and more manufacturers are upgrading or extending their chilling and freezing lines.

But this isn't as straightforward as it used to be. Freezing technology has developed and traditional mechanical freezers, which are still the most widely used systems, are now positioned alongside newer technologies that claim to hold a number of advantages over their predecessors.

So what freezing systems are available to food processors today? What are the pros and cons of them, and how can manufacturers select the best one for their businesses?

2. Comparing freezing technologies

Today's freezers fall into three categories.

- **Mechanical freezers** use a circulating refrigerant to achieve temperature reduction by heat exchange against air to the food.
- **Cryogenic freezers** achieve temperature reduction by the direct application of liquid nitrogen (-196°C) or carbon dioxide onto the food.
- **Impingement freezers** direct high velocity jets of air at the food product.

Within these categories, various freezer designs are available, including tunnel, spiral, IQF and fluidised bed systems. The optimal system will depend on a number of factors, including product type and size, required throughput and factory layout.

The three technologies, and all freezers, have different advantages, drawbacks and limitations. In this paper, we will compare mechanical, cryogenic and mechanical impingement freezing technologies rather than specific systems. The best technology can only be selected when food processors consider their unique circumstances and requirements.

Mechanical freezing

Mechanical freezers were the first to be used in the food industry and are used in the vast majority of freezing / refrigerating lines. The systems are normally dedicated systems, owned and operated by the food processor.

They function by circulating a refrigerant, normally ammonia, around the system, which withdraws heat from the food product. This heat is then transferred to a condenser and dissipated into air or water. The refrigerant itself, now a high pressure, hot liquid, is directed into an evaporator. As it passes through an expansion valve, it is cooled and then vaporises into a gaseous state. Now a low pressure, low temperature gas again, it can be reintroduced into the system.

Cryogenic freezing

Cryogenic freezers are a more recent development, but are used successfully by leading food manufacturers all over the world. These systems are commonly leased, rather than owned by the food manufacturer.

Cryogenic equipment uses very low temperature gases – usually liquid nitrogen or solid carbon dioxide – which are applied directly to the food product.

Impingement freezing

Mechanical impingement freezers have been developed over the past ten years. Product is normally positioned on a belt, through which high pressure air jets can be directed. This air is built up in a plenum above (and sometimes also below) the freezer and channelled through slots, holes or short tubes, towards to food.

This process results in faster freezing than that seen with traditional mechanical freezers, because it breaks up the boundary layer at the surface and improves heat transfer.

A summary of the key differences between the freezing technologies is shown left:

Feature	Mechanical freezers	Cryogenic freezers	Impingement freezers
Ownership	Normally owned by food producer	Normally rented/leased from supplier (which also supplies the coolant)	Normally owned by food producers
Cost structure	High initial capital investment, lower ongoing running costs	Low initial capital investment, higher subsequent variable costs	High initial capital investment, ongoing running costs lower than cryogenic systems but higher than traditional mechanical freezers
Location in factory	Fixed, as usually sited on concrete plinth. Siting limited by space available	Flexible, siting simpler due to smaller footprint than mechanical freezers	More flexible than traditional mechanical freezers
Coolant	Commonly used: Ammonia	Liquid nitrogen (LIN) or solid carbon dioxide (CO ₂)	Commonly used: Ammonia
Heat transfer rate/ speed of freezing	Slower, due to relatively high temperature of refrigerant	Faster, due to high difference in temperature between product surface and refrigerant	Faster, on condition product is flat and no taller than 20mm

3. Factors influencing the choice of freezing technology

Food manufacturers need to consider a number of factors when deciding which technology to install on their production lines. These broadly fall into four categories: product quality and yield requirements, factory management requirements, financial considerations and environmental factors.

3.1 Product quality

Moisture loss/moisture content

All freezing methods cause some degree of moisture loss, during the freezing process itself (evaporative weight loss) and/or during thawing (drip loss).

Evaporative weight loss reduces the weight, and therefore the value of the product, especially in meat, poultry and seafood. At the same time, surface dehydration impacts on product texture, colour and cooking time. The evaporative weight loss reduces the thermal conductivity of the surface layer and therefore prolongs cooking time. This is particularly important in applications where cooking time is limited, such as burgers for fast food outlets.

In most applications, the best way to cut evaporative loss is to reduce temperature as quickly as possible. Rapid temperature reduction lowers the vapour pressure of free water at the surface of the food and so reduces dehydration.

Drip loss occurs during thawing if a food product suffers from cellular damage, caused by the growth of large ice crystals, during a slow freezing process. This loss of moisture affects the colour, flavour and nutritional quality of the thawed product as nutrients and pigments are contained in the lost moisture. Structure damage can also cause textural degradation, or a reduction in firmness, particularly in vegetables and fruits. This was demonstrated in Agnelli and Macscheroni's 2002 study, which showed the effects of freezing damage when they measured the texture of frozen strawberries using a compression test. They showed that the strawberries maintained their firmness to a greater degree when rapidly frozen using cryogenic freezing.

Colour

Thawed food colour is affected by freezing in two ways. The first, pigment loss due to drip loss, is explained above. Secondly, as ice crystals grow during freezing, there is a concentration of the solutes in the remaining unfrozen fraction. This increase in concentration speeds up processes such as oxidation and enzymic browning. The longer the product remains at a temperature close to the freezing plateau (ie, the slower the freezing process), the greater these effects will be.

Agnelli and Macscheroni's research showed the results of colour measurements on frozen thawed hamburgers. It demonstrates the importance of the rate of freezing and the benefits of a faster freezing rate:

- Drip loss and pigment drainage are both reduced.
- Meat browning is minimised: the colour of cryo-mechanically frozen burgers is more like the original meat colour than those frozen using purely mechanical methods.

Delicate products

As a result of their system design and product handling characteristics, cryogenic freezers are deemed the most suitable for handling fragile or delicate products, including many types of soft fruits.

Product quality: conclusions

Research and experience show that fast freezing reduces moisture and yield loss, and minimises changes in product texture, colour and flavour. So which technology will achieve the quickest temperature reduction?

The rate at which freezers reduce temperature is described as the mean heat transfer rate (per unit area), or $h \times \Delta T$. The higher the mean heat transfer rate, the faster temperature is lowered.

Let us assume a mean product surface temperature during the freezing process of -10°C. A conventional mechanical spiral freezer with an air temperature of -30°C and a heat transfer coefficient of 25 W/Km² has an equivalent mean specific heat transfer rate of $25 \times 20 = 500 \text{ W/Km}^2$.

A conventional cryogenic tunnel freezer with a mean temperature of -80°C and a heat transfer coefficient of 60 W/Km² has a mean specific heat transfer rate, of $60 \times 70 = 4,200 \text{ W/m}^2$.

Due to their higher freezing rate, mechanical impingement or cryogenic freezers are therefore the better technologies for optimum product quality. However, it is only in limited applications, namely thin foods with flat, perpendicular surfaces like burgers, that mechanical impingement freezers have been shown to achieve similar heat transfer to cryogenic systems. Heat transfer is highly dependent on the direction of air flow, so for bulkier or uneven products, impingement freezing may be considerably less desirable.

3.2 Factory management

Every food processing factory is unique and must be considered when choosing a freezing technology. Factors to look at include the space available, the level of flexibility required and hygiene, cleaning and maintenance.

Footprint/available space

In almost all cases, cryogenic freezers have smaller footprints than their traditional mechanical counterparts, assuming similar throughput levels. Some mechanical impingement systems are now also supplied in modular form, and also occupy a small footprint. This can be demonstrated by comparing values for two typical freezers used for freezing burgers.

Throughput	Mechanical freezer	Cryogenic freezer
2,000kg / hour	9.5 x 6.5m footprint, min height required: 3.7m.	12 x 1.6m footprint, max. height 1.75m.
	Total footprint: 62m ²	Total footprint: 19m ²

Turnover

Fluctuating consumer demand can cause sudden and often unexpected increases or decreases in turnover. Factory managers are dependent on many variables outside their control, including consumer acceptance of the product and its life cycle.

It is therefore imperative to forecast as accurately as possible, likely maximum turnover during the freezing equipment's payback period. In the case of mechanical freezers, this can be several years. Overoptimistic forecasting will reduce efficiency, while pessimistic planning could result in insufficient freezing capacity.

Whereas mechanical freezers have a fixed maximum throughput for any specific product, modular cryogenic and mechanical impingement freezers can be adapted (by increasing tunnel length, for example) to respond quickly to changes in turnover. Importantly, because cryogenic freezers are usually rented, such changes do not require significant additional capital outlay by the manufacturer.

It should be noted that mechanical impingement freezing technology has overcome many of the flexibility issues of traditional mechanical systems, particularly in terms of weight and footprint. On the other hand, mechanical impingement freezing is less flexible than traditional mechanical processes because of its value only in flat products no higher than 20mm. Both cryogenic and traditional mechanical systems are better suited to production lines which sometimes, or always, handle taller, or uneven, products.

Production line configuration

In today's fast-moving food industry, manufacturers often need to change the layout of their facilities. This is especially true in contract manufacturing. Large mechanical spiral freezers are very large pieces of equipment whose weight often needs to be supported by a concrete plinth. Reconfiguring the positioning of a cryogenic or mechanical impingement tunnel freezer is not always simple, but rarely requires changes to the building's structure.

Product changes

For smaller food processors in particular, the ability to freeze a range of different products is important. Both freezing time and downtime influence a manufacturer's capacity to change products. When changing products, ideally all of the first product should exit the freezer before the second product enters. This is because differences in freezing times determine the "residence time" and the belt speed required for a given product. The longer the residence time, the longer the downtime will be between the two products.

If cleaning is required at the time of product changeover, as is often the case with coated products, or switches between raw and cooked foods, manufacturers also need to take account of hygiene and cleaning features, as detailed below.

If a manufacturer runs only one type of product, at very high speeds, on a daily basis for a long period of time, mechanical freezing may be the more suitable technology. This is dependent, of course, on sufficient floor space, capital availability, the recruitment of skilled personnel etc.

Maintenance, hygiene and cleaning

These processes should be as quick and simple as possible to maximise uptime and optimise line efficiency. The build-up of moisture or snow across evaporators in mechanical freezers, for instance, can prolong production times and lower output.

Thorough, regular hygiene and cleaning are, of course, essential in the food industry but must also have minimum impact on productivity. Smaller and simply-designed freezers are clearly quicker and cheaper to clean. Fewer complex internal parts, reduced height and optimal accessibility all cut the time needed for cleaning processes and make them more effective.

Mechanical impingement freezers often feature smaller design and easier access, similar to cryogenic systems. However, their structures remain complex and are difficult to drain, so cleaning is awkward and there are more potential hygiene issues.

Factory management: conclusions

Taking into account the issues factory managers are concerned with, it can be concluded that cryogenic freezers are often the preferable technology for many food processors, due to their:

- Smaller footprint
- Adaptability to changes in turnover
- Flexibility in handling different products
- Simpler and more accessible design
- Lower initial capital cost.



3.3 Financial considerations

Installing or augmenting freezing equipment incurs cost in a number of areas, including capital investment, running costs and labour costs during operation and maintenance.

Capital outlay and running costs

There is a distinct difference between cryogenic and mechanical freezing when it comes to costs. Whereas mechanical freezing requires a much larger initial capital outlay, running costs are higher with cryogenic equipment. The extent of this difference depends on a large number of factors, but on any given product line, there will be a point in time at which the cumulative cost of cryogenic freezing begins to exceed the cost of mechanical freezing.

It should be noted, however, that the current economic climate is making financing arrangements more difficult. Manufacturers unable or unwilling to make a significant capital outlay may therefore benefit from cryogenic freezing systems.

Labour costs

Due to their size and complexity, mechanical freezers tend to require more manpower for cleaning. Maintenance demands are also higher for mechanical systems, as is the necessary skill level of maintenance operatives. The relative importance of these factors will depend on the freezer model and the local cost of labour.

Product quality

As mentioned earlier, minimising moisture loss is key to maximising product quality and value, particularly in high-value products. The choice of freezer system therefore has financial, as well as qualitative, implications for manufacturers.

Financial considerations: conclusions

It is imperative that all financial factors are taken into account when choosing between cryogenic and mechanical freezing. Manufacturers should look at costs over a specified period and define the total cost of ownership of each technology. Freezer suppliers are able to assist with this, but mechanical impingement technology is almost always more expensive than traditional mechanical freezing due to the cost of generating the high air velocity. Decisions may be influenced heavily by the availability of investment capital.

3.4 Environmental factors

With increasing awareness of energy use / waste, and the impact of manufacturing on carbon emissions and developments in legislation, food producers need to consider the environmental impact of their freezing technology.

The Food and Drink Federation and the Carbon Trust estimate that food manufacturing accounts for only 10% of energy related emissions in the food chain. Most of this – around 60% – is due to refrigeration and freezing by large frozen food processors. Mechanical freezers require less energy than is needed for the production of liquid nitrogen, but in the total food production system, both technologies contribute only a small percentage of emissions.

4. Conclusions

What does the analysis tell us? It is obvious that selecting a freezing technology is not simple and no single technology is the perfect choice for all manufacturers.

Before choosing a specific freezer, users have to consider available financing, the product(s) being handled, factory layout and management and the requirement for flexibility.

Cryogenic freezing systems afford widespread benefits in terms of freezing rate across a range of foods, resulting in higher quality products. The low capital outlay, flexibility and ease of cleaning are also appealing to many food manufacturers today. Mechanical systems have a higher capital outlay, but can provide financial benefits in the longer term. Advances in impingement freezing technology are narrowing the gap between mechanical and cryogenic systems to a certain extent, but the benefits are limited to a specific type of product. Manufacturers are advised to work with leading freezer suppliers to identify the technology best suited to their needs, and then the most appropriate equipment for their production lines.

5. Tell me more

About the author:

Dr Chris Kennedy is a respected independent consultant in the food industry.

In 2009, he analysed the key considerations for choosing new freezing equipment. He validated or challenged opinions on the benefits of different freezing technologies, referencing published data where possible. This white paper summarises the key points from the research.

Dr Kennedy is a member of the Institute of Refrigeration, The Institute of Food Science and Technology and the Institute of Physics. He has 15 years' experience providing consultancy services to the food industry.

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