

## CHILLING AND FREEZING

Freezing is the unit operation in which the temperature of a food is reduced below its freezing point and a proportion of the water undergoes a change in state to form ice crystals. The immobilisation of water to ice and the resulting concentration of dissolved solutes in unfrozen water lower the water activity ( $a_w$ ) of the food ( $a_w$  is described in Chapter 1). Preservation is achieved by a combination of low temperatures, reduced water activity and, in some foods, pre-treatment by blanching. There are only small changes to nutritional or sensory qualities of foods when correct freezing and storage procedures are followed.

The major groups of commercially frozen foods are as follows:

- fruits (strawberries, oranges, raspberries, blackcurrants) either whole or pureed, or as juice concentrates
- vegetables (peas, green beans, sweetcorn, spinach, sprouts and potatoes)
- fish fillets and seafoods (cod, plaice, shrimps and crab meat) including fish fingers, fish cakes or prepared dishes with an accompanying sauce
- meats (beef, lamb, poultry) as carcasses, boxed joints or cubes, and meat products (sausages, beefburgers, reformed steaks)
- baked goods (bread, cakes, fruit and meat pies)
- prepared foods (pizzas, desserts, ice cream, complete meals and cook-freeze dishes).

Rapid increases in sales of frozen foods in recent years are closely associated with increased ownership of domestic freezers and microwave ovens. Frozen foods and chilled

foods (Chapter 19) have an image of high quality and 'freshness' and, particularly in

meat, fruit and vegetable sectors, outsell canned or dried products.

Distribution of frozen foods has a relatively high cost, due to the need to maintain a

constant low temperature. Distribution logistics are discussed further in Chapter 19 in

relation to chilled foods and in Chapter 26. A recent advance in distribution of chilled

and frozen foods is described by Jennings (1999), in which carbon dioxide 'snow' (Section 21.2.4) is added to sealed containers of food, which are then loaded into normal distribution vehicles. The time that a product can be held at the required chilled or frozen storage temperature can be varied from four to 24 hours by adjusting the amount of added snow. Other advantages of the system include greater flexibility in being able to carry mixed loads at different temperatures in the same vehicle, greater control over storage temperature and greater flexibility in use, compared to standard refrigerated vehicles.

### **Calculation of freezing time**

During freezing, heat is conducted from the interior of a food to the surface and is removed by the freezing medium. The factors which influence the rate of heat transfer are:

- the thermal conductivity of the food
- the area of food available for heat transfer
- the distance that the heat must travel through the food (size of the pieces)
- the temperature difference between the food and the freezing medium
- the insulating effect of the boundary film of air surrounding the food (Chapter 1)
- packaging, if present, is an additional barrier to heat flow.

It is difficult to define the freezing time precisely but two approaches are taken.

The

*effective freezing time*<sup>1</sup> measures the time that food spends in a freezer and is used to

calculate the throughput of a manufacturing process whereas the *nominal freezing time*<sup>2</sup>

can be used as an indicator of product damage as it takes no account of the initial conditions or the different rates of cooling at different points on the surface of the food.

The calculation of freezing time is complicated for the following reasons:

- differences in the initial temperature, size and shape of individual pieces of food
- differences in the freezing point and the rate of ice crystal formation within different

regions of a piece of food

- changes in density, thermal conductivity, specific heat and thermal diffusivity with a

reduction in temperature of the food.

Removal of latent heat further complicates the unsteady-state heat transfer calculations (Chapter 1), and a complete mathematical solution of freezing rate is not

possible. For most practical purposes an approximate solution based on formulae developed by Plank (equation (21.1)) is adequate. This involves the following assumptions:

- freezing starts with all water in the food unfrozen but at its freezing point, and loss of sensible heat is ignored.

heat transfer takes place sufficiently slowly for steady-state conditions to operate

- the freezing front maintains a similar shape to that of the food (for example in a rectangular block the freezing front remains rectangular)
- there is a single freezing point
- the density of the food does not change
- the thermal conductivity and specific heat of the food are constant when unfrozen and

then change to a different constant value when the food is frozen.

The freezing time for cubes of food is calculated using:

$$t_f = \frac{L^2}{6h} \left[ \frac{1}{k_1} + \frac{L}{24k_2} \right]$$

—  
 $L$

6

—  
1

$h$

—  
 $x$

$k_1$

—  
 $L^2$

$24k_2$

—  
 $21_1$

where  $t_f$  (s) — freezing time,  $L$  (m) — length of the cube,  $h$  ( $\text{Wm}^{-2}\text{K}^{-1}$ ) — surface heat

transfer coefficient,  $_f$  ( $^{\circ}\text{C}$ ) — freezing point of the food,  $_a$  ( $^{\circ}\text{C}$ ) — temperature of the

freezing medium,  $\lambda$  (J kg<sup>-1</sup>) latent heat of crystallisation,  $\rho$  (kg m<sup>-3</sup>) density of the food,  $x$  (m) thickness of the packaging,  $k_1$  (W m<sup>-1</sup>K<sup>-1</sup>) thermal conductivity of the packaging,  $k_2$  (W m<sup>-1</sup>K<sup>-1</sup>) thermal conductivity of the frozen zone,  $\phi$  and  $\alpha$  are factors which represent the shortest distance between the centre and the surface of the food. Other shapes require different factors; these are 2 and 8 for a slab, 4 and 16 for a cylinder and 6 and 24 for a sphere. Derivation of the equation is described by Earle (1983). Equation (21.1) may be rearranged to find the heat transfer coefficient as follows:

$$h = \frac{L}{\phi} \left[ \frac{t_f - t_a}{Lx} + \frac{24k_2}{\alpha} \right]$$

### Equipment

The selection of freezing equipment should take the following factors into consideration:  
 the rate of freezing required; the size, shape and packaging requirements of the food;  
 batch or continuous operation, the scale of production, range of products to be processed  
 and not least the capital and operating costs.

Freezers are broadly categorised into:

- mechanical refrigerators, which evaporate and compress a refrigerant in a continuous cycle (details are given in Chapter 19) and use cooled air, cooled liquid or cooled surfaces to remove heat from foods
- cryogenic freezers, which use solid or liquid carbon dioxide, liquid nitrogen (or until recently, liquid Freon) directly in contact with the food.

An alternative classification, based on the rate of movement of the ice front is:

- *slow freezers* and *sharp freezers* (0.2 cm h<sup>-1</sup>) including still-air freezers and cold

stores

- *quick freezers* (0.5–3 cm h<sup>-1</sup>) including air-blast and plate freezers
- *rapid freezers* (5–10 cm h<sup>-1</sup>) including fluidised-bed freezers
- *ultrarapid freezers* (10–100 cm h<sup>-1</sup>), that is cryogenic freezers.

All freezers are insulated with expanded polystyrene, polyurethane or other materials

which have low thermal conductivity (Chapter 1, Table 1.5). Recent developments in

computer control, described in Chapter 2, are incorporated in most freezing equipment to

monitor process parameters and equipment status, display trends, identify faults and

automatically control processing conditions for different products.

### **Cooled-air freezers**

In *chest freezers* food is frozen in stationary (natural-circulation) air at between  $-20^{\circ}\text{C}$

and  $-30^{\circ}\text{C}$ . Chest freezers are not used for commercial freezing owing to low freezing

rates (3–72 h), which result in poor process economics and loss of product quality (Section 21.3). *Cold stores* are used to freeze carcass meat, to store foods that are frozen

by other methods, and as hardening rooms for ice cream. Air is usually circulated by fans.

to improve the uniformity of temperature distribution, but heat transfer coefficients are

low (Table 21.3).

A major problem with cold stores is ice formation on floors, walls and evaporator coils, caused by moisture from the air or from unpackaged products in the store.

For

example, air at  $10^{\circ}\text{C}$  and 80% relative humidity contains 6 g water per kg of air (see

Section 15.1). If air enters the cold store through loading doors at a rate of 1000 m<sup>3</sup> h<sup>-1</sup>,

173 kg of water vapour enters the store per day (Weller and Mills, 1999). This condenses

to water and freezes on the cold surfaces, which reduces the efficiency of the refrigeration

plant, uses up energy that would otherwise be used to cool the store, creates potential hazards from slippery working conditions and falling blocks of ice, and requires frequent defrosting of evaporator coils. A desiccant dehumidifier, described by Weller and Mills (1999), overcomes these problems by removing moisture from the air as it enters the store and thus reduces ice formation, reduces the size of compressors and fans, and energy needed to maintain the store temperature.

In *blast freezers*, air is recirculated over food at between  $-30^{\circ}\text{C}$  and  $-40^{\circ}\text{C}$  at a velocity of  $1.5\text{--}6.0\text{ m s}^{-1}$ . The high air velocity reduces the thickness of boundary films surrounding the food (Chapter 1, Fig. 1.3) and thus increases the surface heat transfer coefficient (Table 21.3). In batch equipment, food is stacked on trays in rooms or cabinets. Continuous equipment consists of trolleys stacked with trays of food or on conveyor belts which carry the food through an insulated tunnel. The trolleys should be fully loaded to prevent air from bypassing the food through spaces between the trays. Multipass tunnels contain a number of belts, and products fall from one to another. This breaks up any clumps of food and allows control over the product depth (for example a  $25\text{--}50\text{ mm}$  bed is initially frozen for  $5\text{--}10\text{ min}$  and then repiled to  $100\text{--}125\text{ mm}$  on a second belt). Air flow is either parallel or perpendicular to the food and is ducted to pass evenly over all food pieces. Blast freezing is relatively economical and highly flexible in that foods of different shapes and sizes can be frozen. The equipment is compact and has a relatively low capital cost and a high throughput ( $200\text{--}1500\text{ kg h}^{-1}$ ). However, moisture from the food is transferred to the air and builds up as ice on the refrigeration coils, and this necessitates frequent defrosting. The large volumes of recycled air can also cause

dehydration losses of up to 5%, freezer burn and oxidative changes to unpackaged or individually quick frozen (IQF) foods. IQF foods freeze more rapidly, enable packaged foods to be partly used and then refrozen, and permit better portion control. However, the low bulk density and high void space causes a higher risk of dehydration and freezer burn (Section 21.3).

*Belt freezers* (spiral freezers) have a continuous flexible mesh belt which is formed into spiral tiers and carries food up through a refrigerated chamber. In some designs each tier rests on the vertical sides of the tier beneath (Fig. 21.3) and the belt is therefore 'selfstacking'.

This eliminates the need for support rails and improves the capacity by up to 50% for a given stack height. Cold air or sprays of liquid nitrogen (Section 21.2.4) are directed down through the belt stack in a countercurrent flow, which reduces weight losses due to evaporation of moisture. Spiral freezers require relatively small floor-space and have high capacity (for example a 50–75 cm wide belt in a 32-tier spiral processes up to 3000 kg h<sup>-1</sup>). Other advantages include automatic loading and unloading, low maintenance costs and flexibility to freeze a wide range of foods including pizzas, cakes, pies, ice cream, whole fish and chicken portions.

*Fluidised-bed freezers* are modified blast freezers in which air at between -25°C and -35°C is passed at a high velocity (2–6 m s<sup>-1</sup>) through a 2–13 cm bed of food, contained on a perforated tray or conveyor belt. In some designs there are two stages; after initial rapid freezing in a shallow bed to produce an ice glaze on the surface of the food, freezing is completed on a second belt in beds 10–15 cm deep. The formation of a glaze is useful for fruit pieces and other products that have a tendency to clump together. The shape and

size of the pieces of food determine the thickness of the fluidised bed and the air velocity needed for fluidisation (a sample calculation of air velocity is given in Chapter 1). Food comes into greater contact with the air than in blast freezers, and all surfaces are frozen simultaneously and uniformly. This produces higher heat transfer coefficients, shorter freezing times (Table 21.3), higher production rates (10 000 kg h<sup>-1</sup>) and less dehydration of unpackaged food than blast freezing does. The equipment therefore needs less frequent defrosting. However, the method is restricted to particulate foods (for example peas, sweetcorn kernels, shrimps, strawberries or French fried potatoes). Similar equipment, named *through-flow freezers*, in which air passes through a bed of food but fluidisation is not achieved, is suitable for larger pieces of food (for example fish fillets). Both types of equipment are compact, have a high capacity and are highly suited to the production of IQF foods.

### **21.2.2 Cooled-liquid freezers**

In *immersion freezers*, packaged food is passed through a bath of refrigerated propylene glycol, brine, glycerol or calcium chloride solution on a submerged mesh conveyor. In contrast with cryogenic freezing (Section 21.2.4), the liquid remains fluid throughout the freezing operation and a change of state does not occur. The method has high rates of heat transfer (Table 21.3) and capital costs are relatively low. It is used commercially for concentrated orange juice in laminated card–polyethylene cans, and to pre-freeze filmwrapped poultry before blast freezing.

### **Cryogenic freezers**

Freezers of this type are characterised by a change of state in the refrigerant (or cryogen)

as heat is absorbed from the freezing food. The heat from the food therefore provides the

latent heat of vaporisation or sublimation of the cryogen. The cryogen is in intimate

contact with the food and rapidly removes heat from all surfaces of the food to produce

high heat transfer coefficients and rapid freezing. The two most common refrigerants are

liquid nitrogen and solid or liquid carbon dioxide. Dichlorodifluoromethane (refrigerant

12 or Freon 12) was also previously used for sticky or fragile foods that stuck together in

clumps (for example meat paste, shrimps, tomato slices), but its use has now been phased

out under the Montreal Protocol, due to its effects on the earth's ozone layer (further

details are given in Chapter 19).

The choice of refrigerant is determined by its technical performance for a particular product, its cost and availability, environmental impact and safety (Heap, 1997).

The

market for frozen foods is increasingly characterised by shorter product life cycles and

hence more rapid changes to the number and type of new products. There is a significant

commercial risk if the payback period on capital investment exceeds the product life

cycle, unless the equipment is sufficiently flexible to accommodate new products (Summers, 1998). Two advantages of cryogenic freezers, compared to mechanical systems, are the lower capital cost and flexibility to process a number of different products without major changes to the system (Miller, 1998).

Both liquid-nitrogen and carbon dioxide refrigerants are colourless, odourless and inert. When liquid nitrogen is sprayed onto food, 48% of the total freezing capacity (enthalpy) is taken up by the latent heat of vaporisation needed to form the gas (Table

21.4). The remaining 52% of the enthalpy is available in the cold gas, and gas is therefore

recirculated to achieve optimum use of the freezing capacity. Carbon dioxide has a lower

enthalpy than liquid nitrogen (Table 21.4) but most of the freezing capacity (85%) is available from the subliming solid and the lower boiling point produces a less severe thermal shock. In addition, solid carbon dioxide in the form of a fine snow sublimates on contact with the food, and gas is not recirculated. Carbon dioxide is a bacteriostat but is also toxic, and gas should be vented from the factory to avoid injury to operators. Carbon dioxide consumption is higher than liquid-nitrogen consumption, but storage losses are lower.

In liquid-nitrogen freezers, packaged or unpackaged food travels on a perforated belt through a tunnel (Fig. 21.5), where it is frozen by liquid-nitrogen sprays and by gaseous nitrogen. Production rates are 45–1550 kg h<sup>-1</sup>. The temperature is either allowed to equilibrate at the required storage temperature (between -18°C and -30°C) before the food is removed from the freezer, or alternatively food is passed to a mechanical freezer to complete the freezing process. The use of gaseous nitrogen reduces the thermal shock to the food, and recirculation fans increase the rates of heat transfer. A newer design of tunnel, with fans located beneath the conveyor to produce gas vortices is described by Summers (1998). This design is said to double the output of conventional freezers of the same length, reduce nitrogen consumption by 20% and reduce already low levels of dehydration by 60%. The temperature and belt speed are controlled by microprocessors to maintain the product at a pre-set exit temperature, regardless of the heat load of incoming food. The equipment therefore has the same efficiency at or below its rated capacity. This

results in greater flexibility and economy than mechanical systems, which have a fixed rate of heat extraction (Tomlins, 1995).

Other advantages include:

- simple continuous operation with relatively low capital costs (approximately 30% of the capital cost of mechanical systems)
- smaller weight losses from dehydration of the product (0.5% compared with 1.0–8.0% in mechanical air-blast systems)
- rapid freezing (Table 21.3) which results in smaller changes to the sensory and nutritional characteristics of the product
- the exclusion of oxygen during freezing
- rapid startup and no defrost time
- low power consumption (Leeson, 1987).