REFRIGERATION SYSTEMS

Temperature plays an important role in maintaining the quality of stored food products. Lowering the temperature retards the rates of reactions that cause quality deterioration. It is generally agreed that the reaction rate is reduced by half by lowering the temperature by 10°C.

In earlier days, a lower temperature was obtained by the use of ice. Ice was allowed to melt in an insulated chamber that contained food products. During melting, ice requires latent heat (333.2 kJ/kg) to be converted from the solid phase to liquid water. This heat was extracted from the product that was kept next to ice in an insulated chamber.

Today, the cooling process is achieved by the use of a mechanical refrigeration system. Refrigeration systems allow transfer of heat from the cooling chamber to a location where the heat can easily be discarded. The transfer of heat is accomplished by using a refrigerant, which like water changes state—from liquid to vapor. Unlike water, a refrigerant has a much lower boiling point. For example, ammonia, a commonly used refrigerant in industrial plants, has a boiling point of -33.3°C. This is a much lower temperature compared with 100°C, the boiling point of water at atmospheric pressure. Similar to water, ammonia needs latent heat to change its phase from liquid to gas at its boiling point. The boiling point of a refrigerant can be varied by changing the pressure. Thus, to increase the boiling point of ammonia to 0°C, its pressure must be raised to 430.43 kPa.

A very simple refrigeration system that utilizes a refrigerant is shown in Figure 1. The only drawback in this illustration is the onetime use of the refrigerant. Because refrigerants are expensive, they must be reused. Thus, the system must be modified to allow collection of the refrigerant vapors and their conversion to liquid state so that the same refrigerant can be used repetitively. This is accomplished with the use of a mechanical vapor-compression system.

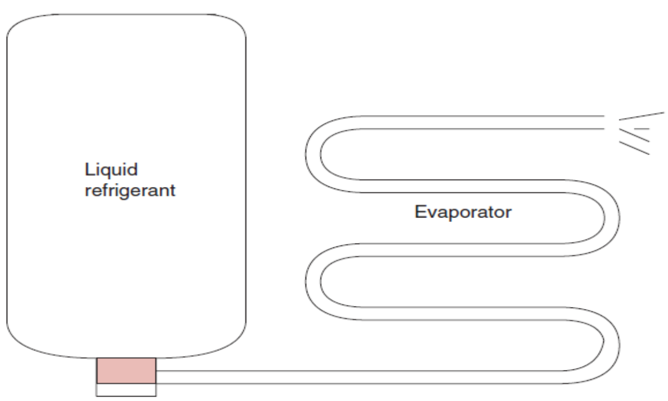

Figure 1. Use of liquid refrigerant to accomplish refrigeration.

COMPONENTS OF A REFRIGERATION SYSTEM

Major components of a simple mechanical vapor compression refrigeration system are shown in Figure 2. As the refrigerant flows through these components its phase changes from liquid to gas and then back to liquid. The flow of refrigerant can be examined by tracing the path of the refrigerant in Figure 2 .

At location D on Figure 2, just prior to the entrance to the expansion valve, the refrigerant is in a saturated liquid state. It is at or below its condensation temperature. The expansion valve separates the high pressure region from the low-pressure region. After passing through the expansion valve, the refrigerant experiences a drop in pressure accompanied by a drop in temperature. Due to the drop in pressure, some of the liquid refrigerant changes to gas. The liquid/gas mixture leaving the expansion valve is termed “flash gas”.

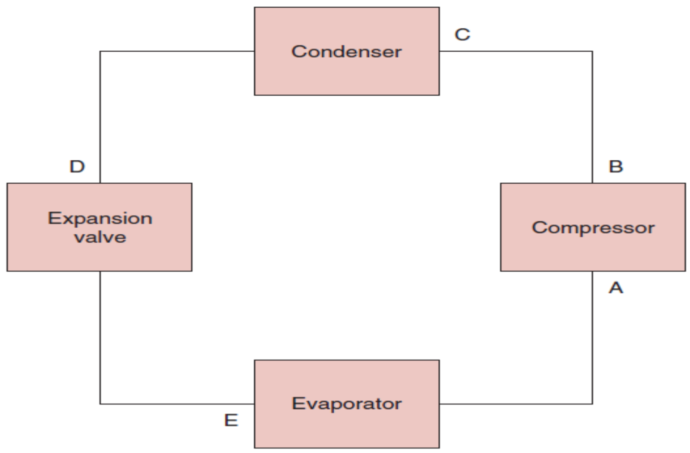

Figure 2. A mechanical vapor-compression refrigeration system.

The liquid/gas mixture enters the evaporator coils at location E. In the evaporator, the refrigerant completely vaporizes to gas by accepting heat from the media surrounding the evaporator coils. The saturated vapors may reach a superheated stage due to gain of additional heat from the surroundings.

The saturated or superheated vapors enter the compressor at location A, where the refrigerant is compressed to a high pressure. This high pressure must be below the critical pressure of the refrigerant and high enough to allow condensation of the refrigerant at a temperature slightly higher than that of commonly available heat sinks, such as ambient air or well water. Inside the compressor, the compression process of the vapors occurs at constant entropy (called an isentropic process). As the pressure of the refrigerant increases, the temperature increases, and the refrigerant becomes superheated as shown by location B.

The superheated vapors are then conveyed to a condenser. Using either an air-cooled or a water-cooled condenser, the refrigerant discharges heat to the surrounding media. The refrigerant condenses back to the liquid state in the condenser as shown by location D. After the entire amount of refrigerant has been converted to saturated liquid, the temperature of the refrigerant may decrease below that of its condensation temperature due to additional heat discharged to the surrounding media; in other words, it may be subcooled. The subcooled or saturated liquid then enters the expansion valve and the cycle continues.

1. Evaporator

Inside the evaporator, the liquid refrigerant vaporizes to a gaseous state. The change of state requires latent heat, which is extracted from the surroundings.

Based on their use, evaporators can be classified into two categories. *Direct-expansion* evaporators allow the refrigerant to vaporize inside the evaporator coils; the coils are in direct contact with the object or fluid being refrigerated. *Indirect-expansion* evaporators involve the use of a carrier medium, such as water or brine, which is cooled by the refrigerant vaporizing in the evaporator coils. The cooled carrier medium is then pumped to the object that is being refrigerated. The indirect expansion evaporators require additional equipment. They are useful when cooling is desired at several locations in the system. Water may be used as a carrier medium if the temperature stays above freezing. For lower temperatures, brine (a proper concentration of $CaCl_2$) or glycols, such as ethylene or propylene glycol, are commonly used.

The evaporators are either bare-pipe, finned-tube, or plate type, as shown in Figure 3. Bare-pipe evaporators are most simple, easy to defrost and clean. The fins added to the finned-tube evaporators allow increase in surface area, thus increasing the rate of heat transfer.
The plate evaporators allow an indirect contact between the product (e.g., a liquid food) to be cooled and the refrigerant.

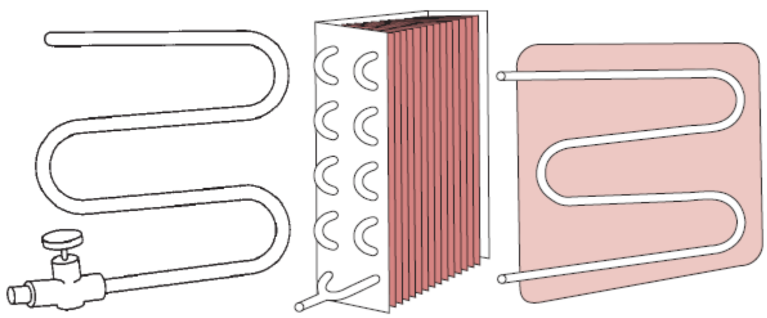

Figure 3. Different types of evaporator coils.

Evaporators can also be classified as direct-expansion and flooded types. In the direct-expansion type of evaporators, there is no recirculation of the refrigerant within the evaporator. The liquid refrigerant changes to gas as it is conveyed through a continuous tube. In contrast, the flooded evaporator allows recirculation of liquid refrigerant. The liquid refrigerant, after going through the metering device, enters a surge chamber. As shown in Figure 4, the liquid refrigerant boils in the evaporator coil and extracts heat from the surroundings. The liquid refrigerant is recirculated through the surge tank and the evaporator coil. The refrigerant gas leaves the surge tank for the compressor.

2. Compressor

The refrigerant enters the compressor in a vapor state at low pressure and temperature. The compressor raises the pressure and temperature of the refrigerant. It is due to this action of the compressor that heat can be discharged by the refrigerant in the condenser. The compression processes raise the temperature of the refrigerant sufficiently above the ambient temperature surrounding the condenser, so that the temperature gradient between the refrigerant and the ambient promotes the heat flow from the refrigerant to the ambient.

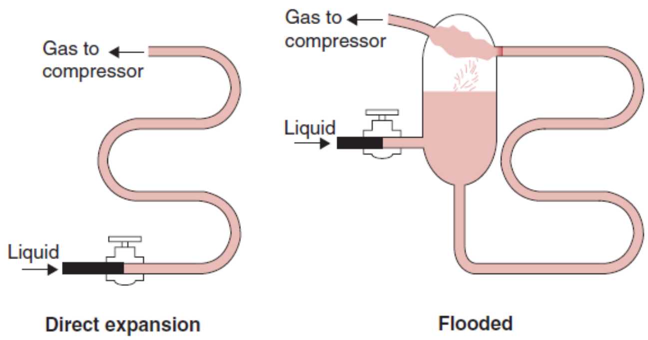

Figure 4. A direct-expansion evaporator and a flooded-type evaporator.

The three common types of compressors are reciprocating, centrifugal, and rotary. As is evident from the name, the reciprocating compressor contains a piston that travels back and forth in a cylinder. Reciprocating compressors are most commonly used and vary in capacity from a fraction of a ton to 100 tons of refrigeration per unit. The centrifugal compressor contains an impeller with several blades that turn at high speed.

The rotary compressor involves a vane that rotates inside a cylinder. The compressor may be operated with an electric motor or an internal combustion engine. Figure 5 shows a typical installation of a reciprocating compressor operated with an electric motor.

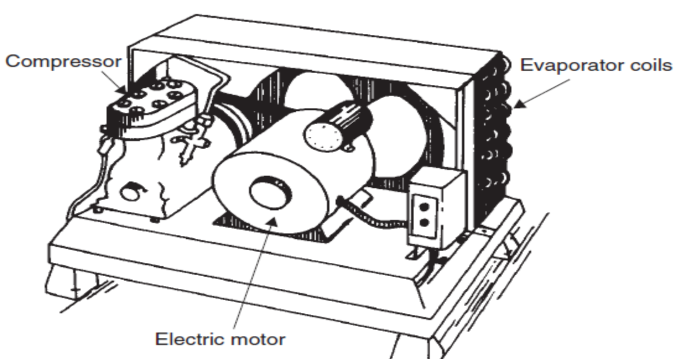

Figure 5. A typical compression refrigeration system of a two-cylinder, air-cooled condenser driven by an electric motor.

An important parameter that influences the performance of a compressor is the compressor capacity. The compressor capacity is affected by several factors. Factors that are inherent to the design of equipment include (a) piston displacement, (b) clearance between the piston head and the end of the cylinder when the piston is at the top of its stroke, and (c) size of the suction and discharge valves. Other factors that influence the compressor capacity are associated with the operating conditions. These factors include (a) revolutions per minute, (b) type of refrigerant, (c) suction pressure, and (d) discharge pressure.

It is often necessary to control the compressor capacity, since the refrigeration loads are seldom constant. Thus, the compressor is operated mostly at partial loads compared with the refrigeration load used in the design of a compressor. The compressor capacity can be controlled by (a) controlling the speed (revolutions per minute), (b) bypassing gas from the high-pressure side to the low-pressure side of the compressor, and (c) internal bypassing of gas in a compressor, by keeping the suction valve open. The speed can be controlled by the use of a variable-speed electric motor.

3. Condenser

The function of the condenser in a refrigeration system is to transfer heat from the refrigerant to another medium, such as air and/or water. By rejecting heat, the gaseous refrigerant condenses to liquid inside the condenser.

The major types of condensers used are (1) water-cooled, (2) air-cooled, and (3) evaporative. In evaporative condensers, both air and water are used.

Three common types of water-cooled condensers are (1) double pipe, (2) shell and tube (as shown in Fig. 6), and (3) shell and coil.

In a double-pipe condenser, water is pumped in the inner pipe and the refrigerant flows in the outer pipe. Countercurrent flows are maintained to obtain high heat-transfer efficiencies. Although double-pipe condensers commonly have been used in the past, the large number of gaskets and flanges used in these heat exchangers leads to maintenance problems.

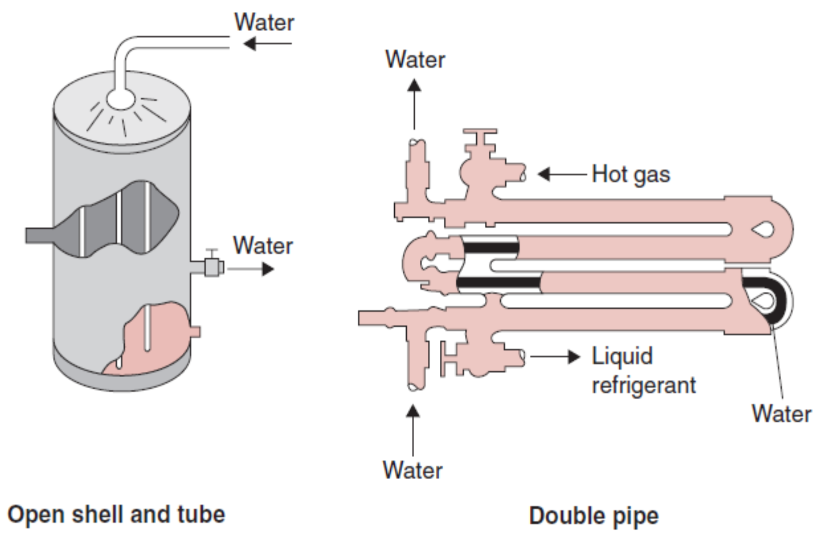

Figure 6. An open shell-and-tube condenser and double-pipe condenser.

In a shell-and-tube condenser, water is pumped through the pipes while refrigerant flows in the shell. Installations of fins in pipes allows better heat transfer. The shell-and-tube condensers are generally low in cost and easy to maintain. In a shell-and-coil condenser, a welded shell contains a coil of finned water tubing. It is generally most compact and low in cost.

Air-cooled condensers can be either tube-and-fin type or plate type, as shown in Figure 7. Fins on tubes allow a large heat transfer area in a compact case. The plate condensers have no fins, so they require considerably larger surface areas. However, they are cheaper to construct and require little maintenance. Both these types of condensers can be found in household refrigerators.

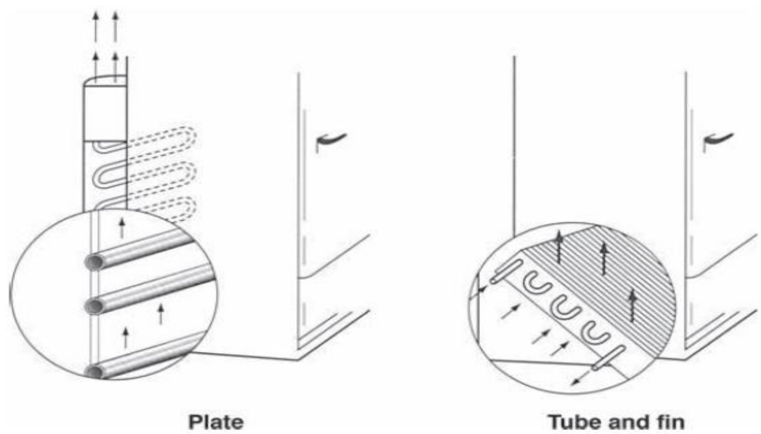

Figure 7. A plate and tube-and-fin condenser.

Air-cooled condensers can also employ artificial movement of air by using a fan. The fan helps in obtaining higher convective heat-transfer coefficients at the surface of the condenser.

In evaporative condensers, a circulating water pump draws water from a pan at the base of the condenser and sprays the water onto the coils. In addition, a large amount of air is drawn over the condenser coils. Evaporation of water requires latent heat, which is extracted from the refrigerant.

4. Expansion Valve

An expansion valve is essentially a metering device that controls the flow of liquid refrigerant to an evaporator. The valve can be operated either manually or by sensing pressure or temperature at another desired location in the refrigeration system.

The common type of metering devices used in the refrigeration system include (1) manually operated expansion valve, (2) automatic low-side fl oat valve, (3) automatic high-side float valve, (4) automatic expansion valve, and (5) thermostatic expansion valve.

A simple, manually operated expansion valve is shown in Figure 8. The valve, manually adjusted, allows a desired amount of flow of refrigerant from the high-pressure liquid side to the low-pressure gas/liquid side. The refrigerant cools as it passes through the valve. The heat given up by the liquid refrigerant is absorbed to convert some of the liquid into vapor. This partial conversion of the liquid refrigerant to gas as it passes through the expansion valve is called *flashing* .

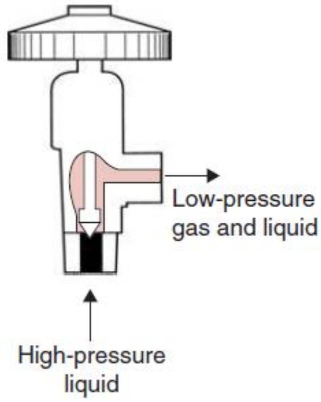

Figure 8. A manually operated expansion valve.

The automatic low-pressure fl oat valve is used in a flooded evaporator. The float ball is located on the low-pressure side of the system, as shown in Figure 6.13. As more liquid is boiled away in the evaporator, the fl oat ball drops and opens the orifice to admit more liquid from the high-pressure side. The orifice closes as the fl oat rises. This type of expansion valve is simple, almost trouble-free, and provides excellent control.

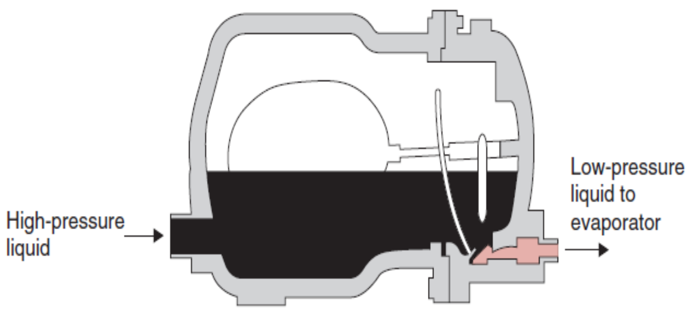

Figure 9. A high-pressure float valve.

In an automatic high-pressure float valve, the float is immersed in high-pressure liquid (Fig. 9). As the heated gas is condensed in the condenser, the liquid-refrigerant level rises inside the chamber. The float consequently rises and opens the orifice, allowing the refrigerant to flow to the evaporator.

The automatic expansion valve maintains a constant pressure in the evaporator. As shown in Figure 10, an increase in evaporator pressure causes the diaphragm to rise against the spring pressure, which results in the valve closing. The valve opens when the evaporator pressure decreases. This valve is used in applications that require a constant refrigeration load and constant evaporator temperature—for example, in a household refrigerator.

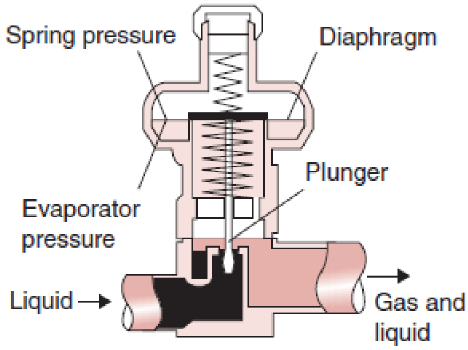

Figure 10. An automatic expansion valve.

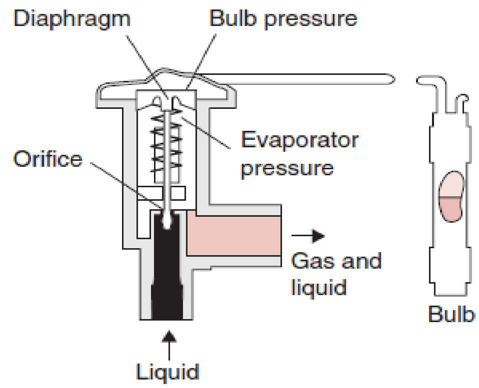

Figure 11. A thermostatic expansion valve.

Thermal expansion valves contain a thermostatic bulb clamped to the side of the suction pipe to the compressor (Fig. 11). The thermostatic bulb senses the temperature of the superheated gas leaving the evaporator. The relatively high temperature of the thermostatic bulb causes the fluid in the bulb (usually the same refrigerant) to increase in pressure. The increased pressure is transmitted via the thermostatic tube to the bellows and the diaphragm chamber. The valve consequently opens to allow more liquid refrigerant to flow through. Thermostatic valves are the most widely used of all metering devices in the refrigeration industry.

SELECTION OF A REFRIGERANT

A wide variety of refrigerants are commercially available for use in vapor-compression systems. Selection of a refrigerant is based on several performance characteristics that assist in determining the refrigerant's suitability for a given system. The following is a list of important characteristics that are usually considered:

1. *Latent heat of vaporization*. A high latent heat of vaporization is preferred. For a given capacity, a high value of latent heat of vaporization indicates that a smaller amount of refrigerant will be circulated per unit of time.
2. *Condensing pressure*. Excessively high condensing pressure requires considerable expenditure on heavy construction of condenser and piping.
3. *Freezing temperature*. The freezing temperature of the refrigerant should be below the evaporator temperature.
4. *Critical temperature*. The refrigerant should have sufficiently high critical temperature. At temperatures above the critical temperature, the refrigerant vapor cannot be liquefied. Particularly in the case of air-cooled condensers, the critical temperature should be above the highest ambient temperature expected.
5. *Toxicity*. In many applications, including air conditioning systems, the refrigerant must be nontoxic.
6. *Flammability*. The refrigerant should be nonflammable.
7. *Corrosiveness*. The refrigerant should not be corrosive to the materials used in the construction of the refrigeration system.

8. *Chemical stability*. The refrigerant must be chemically stable.
9. *Detection of leaks*. If a leak develops in the refrigeration system, the detection of such a leak should be easy.
10. *Cost*. Low-cost refrigerant is preferred in industrial applications.
11. *Environmental impact*. The refrigerant released from the refrigeration systems due to leaks should not cause environmental damage.

FREEZING SYSTEMS

To achieve freezing of a food product, the product must be exposed to a low-temperature medium for sufficient time to remove sensible heat and latent heat of fusion from the product. Removal of the sensible and latent heat results in a reduction in the product temperature as well as a conversion of the water from liquid to solid state (ice). In most cases, approximately 10% of the water remains in the liquid state at the storage temperature of the frozen food. To accomplish the freezing process in desired short times, the low-temperature medium is at much lower temperature than the desired final temperature of the product, and large convective heat-transfer coefficients are created.

The freezing process can be accomplished by using either indirect or direct contact systems. Most often, the type of system used will depend on the product characteristics, both before and after freezing is completed. There are a variety of circumstances where direct contact between the product and refrigerant is not possible.

1. Indirect Contact Systems

In numerous food-product freezing systems, the product and refrigerant are separated by a barrier throughout the freezing process. This type of system is illustrated schematically in Figure 12. Although many systems use a non-permeable barrier between product and refrigerant, indirect freezing systems include any system without direct contact, including those where the package material becomes the barrier.

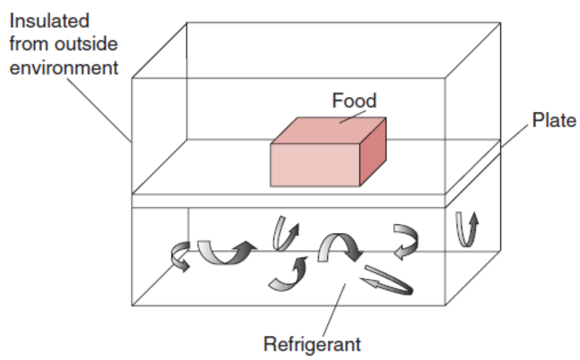

Figure 12. Schematic diagram of an indirect-contact freezing system.

1.1. Plate Freezers

The most easily recognized type of indirect freezing system is the plate freezer, illustrated in Figure 13. As indicated, the product is frozen while held between two refrigerated plates. In most cases, the barrier between product and refrigerant will include both the plate and package material. The heat transfer through the barrier (plate and package) can be enhanced by using pressure to reduce resistance to heat transfer across the barrier as illustrated (Fig. 13). In some cases, plate systems may use single plates in contact with the product and accomplish freezing with heat transfer across a single package surface. As would be expected, these systems are less efficient, and they are costly to acquire and operate.

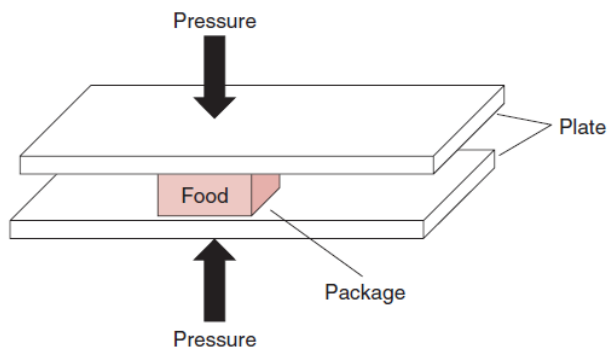

Figure 13. Schematic illustration of a plate freezing system.

Plate-freezing systems can be operated as a batch system with the product placed on the plates for a specified residence time before being removed. In this situation, the freezing time is the residence time and represents the total time required to reduce the product from the initial temperature to some desired final temperature. In general, the batch plate-freezing system has significant flexibility in terms of handling diverse product types and product sizes.

The plate-freezing system operates in a continuous mode by moving the plates holding the product through an enclosure in some prescribed manner. The product is held between two refrigerated plates throughout the freezing process. The movement of plates (and product) occurs as the plates index upward or across within the compartment. At the entrance and exit to the freezing system, the plates are opened to allow the product to be conveyed to or from the system. In a continuous plate-freezing system, the freezing time is the total time required for the product to move from entrance to exit. During the residence time, the desired amounts of sensible and latent heat are removed to achieve the desired frozen product temperature.

1.2. Air-Blast Freezers

In many situations, the product size and/or shape may not accommodate plate freezing. For these situations, air-blast freezing systems become the best alternative. In some cases, the package film is the barrier for the indirect freezing, with cold air being the source of refrigeration.

Air-blast freezers can be a simple design, as in the case of a refrigerated room. In this situation, the product is placed in the room, and the low-temperature air is allowed to circulate around the product for the desire residence of freezing time. This approach represents a batch mode, and the refrigerated room may act as a storage space in addition to the freezing compartment. In most cases, freezing times will be long because of lower air speeds over the product, inability to achieve intimate contact between product and cold air, and the smaller temperature gradients between product and air.

Most air-blast freezers are continuous, such as those illustrated in Figure 14. In these systems, the product is carried on a conveyor that moves through a stream of high-velocity air. The length and speed of the conveyor establish the residence of freezing time. These times can be relatively small based on the use of very low-temperature air, high air velocities, and good contact between individual product packages and the cold air.

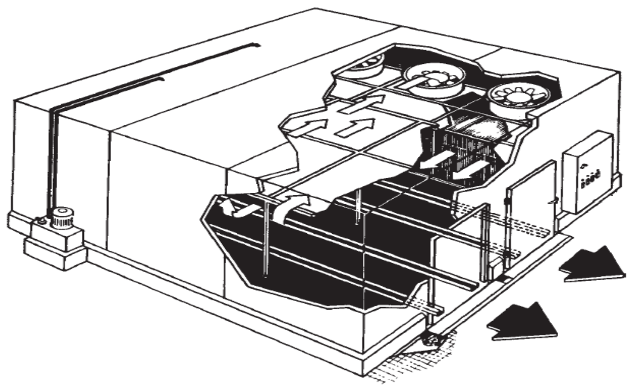

Figure 14. Continuous air-blast freezing system.

Continuous air-blast freezing systems use a variety of different conveying arrangements for movement of product through the refrigerated air. Alternate arrangements to Figure 14 include tray conveyors, spiral conveyors, and roller conveyors. Most often, the system used will depend on product characteristics.

1.3. Freezers for Liquid Foods

The third general type of indirect freezing systems includes those designed primarily for liquid foods. In many situations, the most efficient removal of thermal energy from a liquid food can be accomplished before the product is placed in a package. Although any indirect heat exchanger designed for a liquid food would be acceptable, the most common type is a scraped-surface system. The heat exchangers for freezing liquid foods are designed specifically for freezing, with the heat-exchange shell surrounding the product compartment becoming an evaporator for a vapor-compression refrigeration system. This approach provides precise control of the heat-exchange surface by adjustment of pressure on the low-pressure side of the refrigeration system.

For freezing liquid foods, the residence time in the freezing compartment is sufficient to decrease the product temperature by several degrees below the temperature of initial ice-crystal formation. At these temperatures, between 60 and 80% of the latent heat has been removed from the product, and the product is in the form of a frozen slurry. In this condition, the product flows quite readily and can be placed in a package for final freezing in a low-temperature refrigerated space. The scraped-surface heat exchanger ensures efficient heat exchange between the slurry and the cold surface.

Freezing systems for liquid foods can be batch or continuous. The batch system places a given amount of unfrozen liquid in the compartment and allows the freezing process to continue until the desired final temperature is reached. The product compartment is a scraped-surface heat exchanger but is operated as a batch system. In the case of ice-cream freezing, the system is designed with facility for injection of air into the frozen slurry to achieve the desired product consistency.

2. Direct-Contact Systems

Several freezing systems for food operate with direct contact between the refrigerant and the product, as illustrated in Figure 15. In most situations, these systems will operate more efficiently since there are no barriers to heat transfer between the refrigerant and the product. The refrigerants used in these systems may be low-temperature air at high speeds or liquid refrigerants with phase change while in contact with the product surface. In all cases, the systems are designed to achieve rapid freezing, and the term *individual quick freezing* (IQF) will apply.

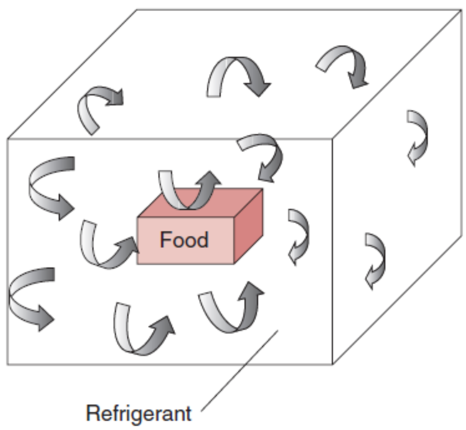

Figure 15. Schematic diagram of a direct-contact freezing system.

2.1. Air Blast

The use of low-temperature air at high speeds in direct contact with small product objects is a form of IQF. The combination of low temperature air, high convective heat-transfer coefficient (high air speed), and small product shape leads to short freezing time or rapid freezing. In these systems, the product is moved through the high-speed-air region on a conveyor in a manner that controls the residence time. The types of product that can be frozen in these systems are limited to those that have the appropriate geometries and that require rapid freezing for maximum quality.

A modification of the regular air-blast IQF system is the fluidized-bed IQF freezing system, as illustrated in Figure 16. In these systems, the high-speed air is directed vertically upward through the mesh conveyor carrying product through the system. By careful adjustment of the air speed in relation to the product size, the product is lifted from the conveyor surface and remains suspended in the low-temperature air. Although the air flow is not sufficient to maintain the product in suspension at all times, the fluidized action results in the highest possible convective heat-transfer coefficients for the freezing process. This type of freezing process results in rapid freezing of product shapes and sizes that can be fluidized in the manner described. The use of the process is limited by the size of product that can be fluidized at air speeds of reasonable magnitude.

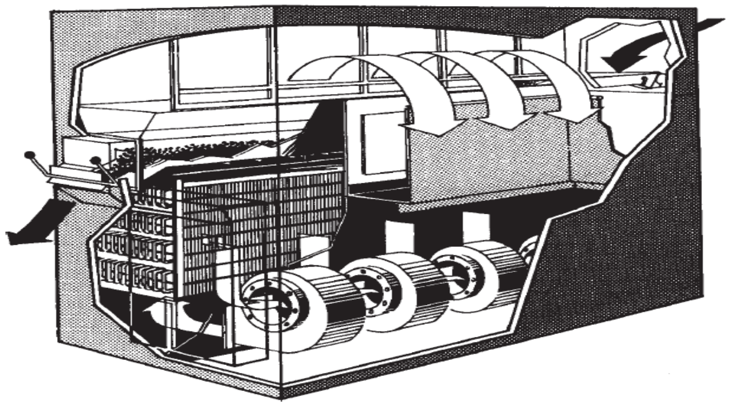

Figure 16. A fluidized-bed freezing system.

2.2. Immersion

By immersion of the food product in liquid refrigerant, the product surface is reduced to a very low temperature. Assuming the product objects are relatively small, the freezing process is accomplished very rapidly or under IQF conditions. For typical products, the freezing time is shorter than for the air-blast or fluidized-bed systems. As illustrated in Figure 17, the product is carried into a bath of liquid refrigerant and is conveyed through the liquid while the refrigerant changes from liquid to vapor and absorbs heat from the product. The most common refrigerants for this purpose are nitrogen and carbon dioxide.

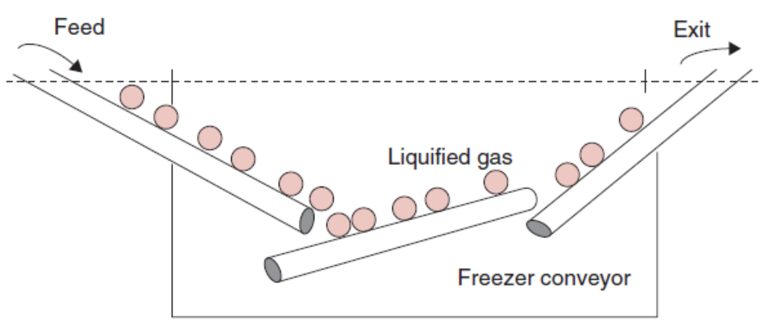

Figure 17. Schematic illustration of an immersion freezing system.

One of the major disadvantages of immersion-type freezing systems is the cost of the refrigerant. Since the refrigerant changes from liquid to vapor while the product freezes, it becomes difficult to recover the vapors leaving the freezing compartment. These refrigerants are expensive, and the overall efficiency of the freezing system is a function of the ability to recover and reuse the vapors produced in the freezing compartments.

FREEZING TIME

A key calculation in the design of a freezing process is the determination of freezing time. Three distinct periods are noticeable at any location within a food undergoing freezing: prefreezing, phase change, and postfreezing. Consider a simple experiment that illustrates these three periods. First, we measure temperature change in freezing pure water into ice by placing an ice-cube tray filled with water in the freezer section of a home freezer, with a thermocouple located inside the tray. In the second part of the experiment, we measure temperature in a small stick of potato (e.g., a french fry) placed in a freezer with a thermocouple embedded inside the potato stick. The temperature–time plots for water and potato obtained in these experiments will be similar to those shown in Figure 18. During the precooling period, the temperature of water decreases to the freezing point as sensible heat is removed. The temperature plot shows a small amount of supercooling (below 0°C); once nucleation occurs and ice crystals begin to form, the freezing point increases to 0°C. The temperature remains at the freezing point until a complete phase change occurs as latent heat of fusion is removed from liquid water to convert it into solid ice. When all the liquid water has changed into solid ice, the temperature of the ice decreases rapidly as sensible heat is removed during the postfreezing period.

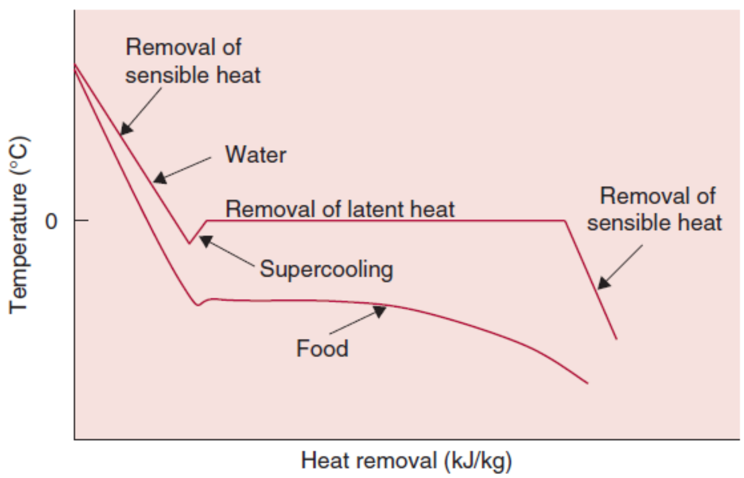

Figure 18. Freezing diagram of water and a food material.

For the potato, the temperature plot obtained during freezing is similar to that of water but with important differences. Like water, the temperature decreases during precooling as sensible heat is removed. However, the temperature at which initial nucleation occurs and ice crystals begin to form is lower than that of water due to the presence of solutes in the food. After a brief period of supercooling, latent heat is gradually removed with decreasing temperature.

This deviation in temperature profile from that of pure water is the result of the concentration effect during freezing of foods. As water in the food converts into ice, the remaining water becomes more concentrated with solutes and depresses the freezing point. This gradual change in temperature with the additional removal of latent heat continues until the food is largely a mix of the initial solid food components and ice. After this time, mostly sensible heat is removed until some final, preselected, endpoint temperature is reached. Typically, fruits and vegetables are frozen to a temperature of -18°C, and foods with higher fat content such as ice cream and fatty fish are frozen to lower temperatures of around -25°C. We can draw several conclusions from these simple freezing experiments:

1. Freezing involves removal of both sensible and latent heat.
2. Freezing of pure water exhibits sharp transitions between the different freezing periods, whereas with foods, the transitions are more gradual.
3. At the endpoint temperature for freezing foods, the frozen food may still have some water present as a liquid; in fact, up to 10 percent water may be in liquid state for foods frozen to -18°C.

This highly concentrated unfrozen water may play an important role in determining the storage of frozen foods.

As indicated earlier, freezing time is the most critical factor associated with the selection of a freezing system to ensure optimum product quality. Freezing-time requirements help establish the system capacity. We will review two methods used in predicting freezing time for foods. The first method using Plank's equation is relatively simple, but it has some notable limitations. The second method—Pham's method—relies more completely on the physical aspects of the process and provides more accurate results. Pham's method can be programmed into a spreadsheet for ease of calculation.

1. Plank's Equation

The first and most popular equation for predicting freezing time was proposed by Plank (1913) and adapted to food by Ede (1949). This equation describes only the phase change period of the freezing process.

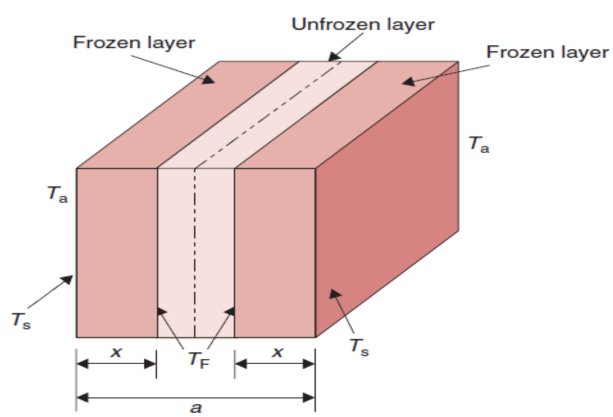

Figure 19. Use of Plank's equation in determining freezing time.

Consider an infinite slab (Fig 19) of thickness *a*. We assume that the material constituting the slab is pure water. Because this method ignores the prefreezing step, the initial temperature of the slab is the same as the initial freezing point of the material, T_F. With water, the initial freezing point is 0°C. The slab is exposed to a freezing medium (e.g., low-temperature air in a blast freezer) at temperature T_a. The heat transfer is one-dimensional. After some duration of time, there will be three layers: two frozen layers each of thickness *x* and a middle unfrozen layer. Consider the right half of the slab. A moving front inside the slab separates the frozen from the unfrozen region. As water is converted into ice at the moving front, latent heat of fusion, L, is generated. This latent heat of fusion from the moving front must be transferred through the frozen layer to the outside freezing medium. The convective heat transfer coefficient at the surface of the slab is *h*. The temperature of the unfrozen region remains at T_F until the freezing front moves all the way to the center plane of the slab. Next, we consider the rate of heat transfer, *q*, from the moving front to the surrounding freezing medium. There are two layers, a conductive frozen layer and a convective boundary layer. Thus, we can write the following expression:

$$q = \frac{A(T_F - T_a)}{\frac{1}{h} + \frac{x}{k_f}} \qquad \text{-------- Eq. 1}$$

where the denominator is the sum of thermal resistances for the outer convective and internal conductive frozen layer. The moving front advances with a velocity of d*x* /d*t*, and the heat generated is the latent heat of fusion, *L*. Thus,

$$q = AL\rho_f \frac{dx}{dt} \qquad \text{-------- Eq. 2}$$

Since all the heat generated at the freezing front must be transferred out to the surrounding medium, equating Equations (1) and (2), we obtain

$$L\rho_f \frac{dx}{dt} = \frac{(T_F - T_a)}{\frac{1}{h} + \frac{x}{k_f}} \qquad \text{-------- Eq. 3}$$

Separating variables, rearranging the terms and setting up integrals, noting that the freezing process is completed when the moving front advances to the center of the slab, *a*/2, we get,

$$\int_0^{t_f} dt = \frac{L\rho_f}{(T_F - T_a)} \int_0^{a/2} \left[\frac{1}{h} + \frac{x}{k_f}\right] dx \qquad \text{-------- Eq. 4}$$

Integrating, we obtain the freezing time, t_f,

$$t_f = \frac{L\rho_f}{(T_F - T_a)} \left[\frac{a}{2h} + \frac{a^2}{8k_f}\right] \qquad \text{-------- Eq. 5}$$

Equation (5) is derived for an infinite slab. However, using the same steps we can obtain similar expressions for either an infinite cylinder or a sphere, but with different geometrical constants. Furthermore, to apply Equation (5) to a food material with a moisture content, m_m, we must replace latent heat of fusion of water, L, with L_f,the latent heat of fusion for the food material, or,

$$L_f = m_m L \qquad \text{-------- Eq. 6}$$

where m_m is the moisture content of the food (fraction) and L is the latent heat of fusion of water, 333.3 kJ/(kg K).

Therefore, a general expression appropriate for a food material for calculating freezing time, known as Plank's equation, is

$$t_F = \frac{\rho_f L_f}{T_F - T_a}\left(\frac{P'a}{h} + \frac{R'a^2}{k_f}\right) \qquad \text{-------- Eq. 7}$$

where ρ_f is the density of the frozen material, L f is the change in the latent heat of the food (kJ/kg), TF is the freezing temperature (°C), T_a is the freezing air temperature (°C), h is the convective heat transfer coefficient at the surface of the material (W/[m 2°C]), a is the thickness/diameter of the object (m), k is the thermal conductivity of the frozen material (W/[m°C]), and the constants P′ and R′ are used to account for the influence of product shape, with P′ = 1/2 , R′ = 1/8 for infinite plate; P′ = 1/4 , R′ =1/16 for infinite cylinder; and P′ = 1/6 , R′ = 1/24 for sphere.

From Equation (7) it is evident that the freezing time *t* F will increase with increasing density ρ_f, the latent heat of freezing L_f, and increasing size *a*. With an increase in the temperature gradient, the convective heat-transfer coefficient *h*, and the thermal conductivity *k* of frozen product, the freezing time will decrease. The dimension *a* is the product thickness for an infinite slab, and the diameter for an infinite cylinder or a sphere.

The limitations to Plank's equation are related primarily to assignment of quantitative values to the components of the equation. Density values for frozen foods are difficult to locate or measure. Although the initial freezing temperature is tabulated for many foods, the initial and final product temperatures are not accounted for in the equation for computation of freezing time. The thermal conductivity *k* should be for the frozen product, and accurate values are not readily available for most foods.

Even with these limitations, the ease of using Plank's equation has made it the most popular method for predicting freezing time. Most other available analytical methods are modifications of Plank's equation, with an emphasis on developments to overcome limitations to the original equation.