CHAPTER

17

REFRIGERATION AND FREEZING OF FOODS

Refrigeration and freezing of perishable food products is an important and fascinating application area of heat transfer and thermodynamics. Refrigeration *slows down* the chemical and biological processes in foods and the accompanying deterioration and the loss of quality. The *storage life* of fresh perishable foods such as meats, fish, fruits, and vegetables can be extended by several days by cooling, and by several weeks or months by freezing. There are many considerations in the design and selection of proper refrigeration and heat transfer mechanisms, and this chapter demonstrates the importance of having a broad base and a good understanding of the processes involved when designing heat transfer equipment. For example, fruits and vegetables continue to *respire* and *generate heat* during storage; most foods freeze over a *range of temperatures* instead of a single temperature; the quality of frozen foods is greatly affected by the *rate of freezing*; the *velocity* of refrigerated air affects the rate of moisture loss from the products addition to the rate of heat transfer, and so forth.

We start this chapter with an overview of *microorganisms* that are responsible for the spoilage of foods since the primary function of refrigeration is to retard the growth rate of microorganisms. Then we present the general considerations in the *refrigeration* and *freezing* of foods and describe the different methods of freezing. In the following sections we describe the distinctive features and refrigeration needs of *fresh fruits and vegetables, meats*, and *other food products*. Next we consider the heat transfer mechanisms in *refrigerated storage rooms*, Finally, we discuss the *transportation* of refrigerated foods since most refrigerated foods spend part of their life in transit in refrigerated trucks, railroad cars, ships, and even airplanes.

17–1 ▪ CONTROL OF MICROORGANISMS IN FOODS

Microorganisms such as *bacteria, yeasts, molds*, and *viruses are widely* encountered in air, water, soil, living organisms, and unprocessed food items, and cause *off-flavors* and *odors, slime production, changes* in the texture and appearances, and the eventual *spoilage* of foods. Holding perishable foods at warm temperatures is the primary cause of spoilage, and the prevention of food spoilage and the premature degradation of quality due to microorganisms is the largest application area of refrigeration. The first step in controlling microorganisms is to understand what they are and the factors that affect their transmission, growth, and destruction.

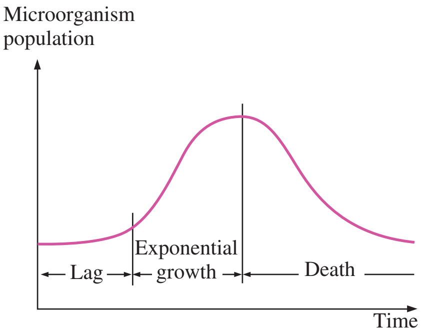


FIGURE 17–1
Typical growth curve of microorganisms.

Of the various kinds of microorganisms, *bacteria* are the prime cause for the spoilage of foods, especially moist foods. Dry and acidic foods create an undesirable environment for the growth of bacteria, but not for the growth of yeasts and molds. *Molds* are also encountered on moist surfaces, cheese, and spoiled foods. Specific *viruses* are encountered in certain animals and humans, and poor sanitation practices such as keeping processed foods in the same area as the uncooked ones and being careless about handwashing can cause the contamination of food products.

When *contamination* occurs, the microorganisms start to adapt to the new environmental conditions. This initial slow or no-growth period is called the **lag phase** and the shelf life of a food item is directly proportional to the length of this phase (Fig. 17–1). The adaptation period is followed by an *exponential growth* period during which the population of microorganisms can double two or more times every hour under favorable conditions unless drastic sanitation measures are taken. The depletion of nutrients and the accumulation of toxins slow down the growth and start the *death* period.

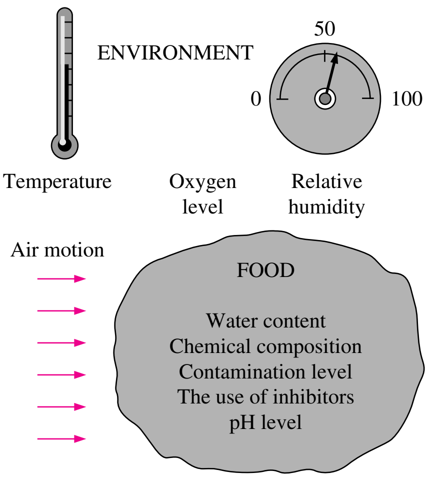


FIGURE 17–2
The factors that affect the rate of growth of microorganisms.

The *rate of growth* of microorganisms in a food item depends on the characteristics of the food itself such as the chemical structure, pH level, presence of in inhibitors and competing microorganisms, and water activity as well as the environmental conditions such as the temperature and relative humidity of the environment and the air motion (Fig. 17–2)

Microorganisms need *food* to grow and multiply, and their nutritional needs are readily provided by the carbohydrates, proteins, minerals, and vitamins in a food. Different types of microorganisms have different nutritional needs, and the types of nutrients in a food determine the types of microorganisms that may dwell on them. The preservatives added to the food may also inhibit the growth of certain microorganisms. Different kinds of microorganisms that exist compete for the same food supply, and thus composition of microorganisms in a food at any time depends on the *initial make-up* of the microorganisms.

All living organisms need *water* to grow, and microorganisms cannot grow in foods that are not sufficiently moist. Microbiological growth in refrigerated foods such as fresh fruits, vegetables, and meats starts at the *exposed surfaces* where contamination is most likely to occur. A fresh meat package left in a room will spoil quickly, as you may have noticed. A meat carcass hung in a controlled environment, on the other hand, will age healthily as a result of *dehydration* on the outer surface, which inhibits microbiological growth there and protects the carcass.

Microorganism growth in a food item is governed by the combined effects effects of the *characteristics of the food* and the *environmental factors*.

We cannot do much about the characteristics of the food, but we certainly can alter the environmental conditions to more desirable levels through *heating, cooling, ventilating, humidification, dehumidification*, and control of the *oxygen* levels. The growth rate of microorganisms in foods is a strong function of temperature, and temperature control is the single most effective mechanism for controlling the growth rate.

Microorganisms grow best at "warm" temperatures, usually between 20 and 60°C. The growth rate *declines* at high temperatures, and *death* occurs at still higher temperatures, usually above 70°C for most microorganisms. *Cooling* is an effective and practical way of reducing the growth rate of microorganisms and thus extending the *shelf life* of perishable foods. A temperature of 4°C or lower is considered to be a safe refrigeration temperature. Sometimes a small increase in refrigeration temperature may cause a large increase in the growth rate, and a considerable decrease in shelf-life of the food (Fig. 17–3). The growth rate of some microorganisms, for example, doubles for each 3°C rise in temperature.

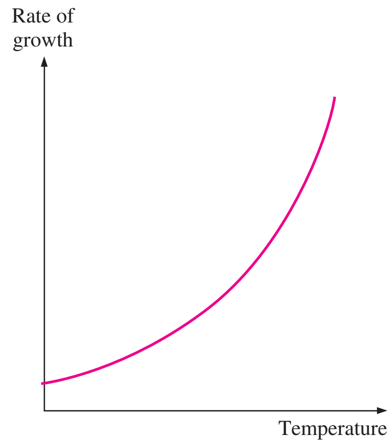


FIGURE 17–3
The rate of growth of microorganisms in a food product increases exponentially with increasing environmental temperature.

Another factor that affects microbiological growth and transmission is the *relative humidity* of the environment, which is a measure of the water content of the air. High humidity in *cold rooms* should be avoided since condensation that forms on the walls and ceiling creates the proper environment for *mold growth* and buildups. The drip of contaminated condensate onto food products in the room poses a potential health hazard.

Different microorganisms react differently to the presence of oxygen in the environment. Some microorganisms such as molds require oxygen for growth, while some others cannot grow in the presence of oxygen. Some grow best in low-oxygen environments, while others grow in environments regardless of the amount of oxygen. Therefore, the growth of certain microorganisms can be controlled by controlling the *amount of oxygen* in the environment. For example, vacuum packaging inhibits the growth of micro-organisms that require oxygen. Also, the storage life of some fruits can be extended by reducing the oxygen level in the storage room.

Microorganisms in food products can be controlled by (1) *preventing* contamination by following strict sanitation practices, (2) *inhibiting* growth by altering the environmental conditions, and (3) *destroying* the organisms by heat treatment or chemicals. The best way to minimize contamination in food processing areas is to use fine air filters in ventilation systems to capture the *dust particles* that transport the bacteria in the air. Of course, the filters must remain dry since microorganisms can grow in wet filters. Also, the ventilation system must maintain a positive pressure in the food processing areas to prevent any airborne contaminants from entering inside by infiltration. The elimination of *condensation* on the walls and the ceiling of the facility and the diversion of *plumbing* condensation drip pans of refrigerators to the drain system are two other preventive measures against contamination. Drip systems must be cleaned regularly to prevent microbiological growth in them. Also, any *contact* between raw and cooked food products should be minimized, and cooked products must be stored in rooms with positive pressures. Frozen foods must be kept at −18°C or below, and utmost care should be exercised when food products are packaged after they are frozen to avoid contamination during packaging.

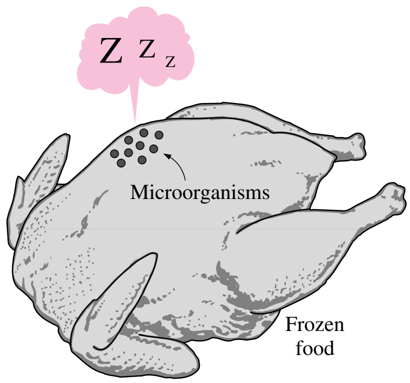


FIGURE 17–4
Freezing may stop the growth of microorganisms, but it may not necessarily kill them.

The growth of microorganisms is best controlled by keeping the *temperature* and *relative humidity* of the environment in the desirable range. Keeping the relative humidity below 60 percent, for example, prevents the growth of all microorganisms on the surfaces. Microorganisms can be destroyed by *heating* the food product to high temperatures (usually above 70°C), by treating them with *chemicals*, or by exposing them to *ultraviolet* light or solar radiation.

Distinction should be made between *survival* and *growth* of microorganisms. A particular microorganism that may not grow at some low temperature may be able to survive at that temperature for a very long time (Fig. 17–4). Therefore, freezing is not an effective way of killing microorganisms. In fact, some microorganism cultures are preserved by freezing them at very low temperatures. The *rate of freezing* is also an important consideration in the refrigeration of foods since some microorganisms adapt to low temperatures and grow at those temperatures when the cooling rate is very low.

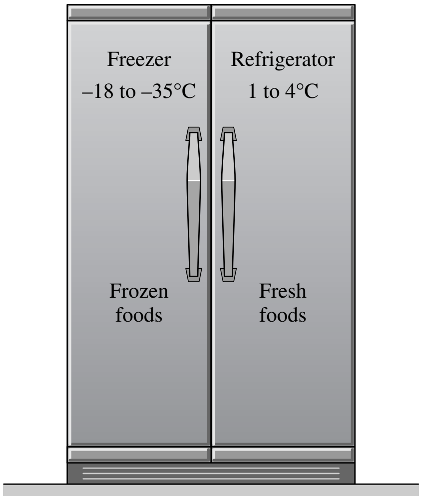


FIGURE 17–5
Recommended refrigeration and freezing temperature for most perishable foods.

17–2 ▪ REFRIGERATION AND FREEZING OF FOODS

The *storage life* of fresh perishable foods such as meats, fish, vegetables, and fruits can be extended by several days by storing them at temperatures just above freezing, usually between 1 and 4°C. The storage life of foods can be extended by several months by freezing and storing them at subfreezing temperatures, usually between −18 and −35°C, depending on the particular food (Fig. 17–5).

Refrigeration *slows down* the chemical and biological processes in foods, and the accompanying deterioration and loss of quality and nutrients. Sweet corn, for example, may lose half of its initial sugar content in one day at 21°C, but only 5 percent of it at 0°C. Fresh asparagus may lose 50 percent of its vitamin C content in one day at 20°C, but in 12 days at 0°C. Refrigeration also extends the shelf life of products. The first appearance of unsightly yellowing of broccoli, for example, may be delayed by three or more days by refrigeration.

Early attempts to freeze food items resulted in poor-quality products because of the large ice crystals that formed. It was determined that the *rate of freezing* has a major effect on the size of ice crystals and the quality, texture, and nutritional and sensory properties of many foods. During *slow freezing*, ice crystals can grow to a large size, where as during *fast freezing* a large number of ice crystals start forming at once and are much smaller in size. Large ice crystals are not desirable since they can *puncture* the walls the cells, causing a degradation of texture and a loss of natural juices during thawing. A *crust* forms rapidly on the outer layer of the product and seals in the juices, aromatics, and flavoring agents. The product quality is also affected adversely by temperature fluctuations of the storage room.

The ordinary refrigeration of foods involves *cooling* only without any phase change. The *freezing* of foods, on the other hand, involves three stages: *cooling* to the freezing point (removing the sensible heat), *freezing* (removing the latent heat), and *further cooling* to the desired subfreezing temperature (removing the sensible heat of frozen food), as shown in Figure 17–6.

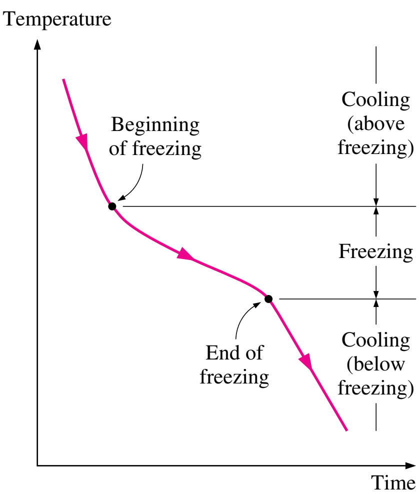


FIGURE 17–6
Typical freezing curve of a food item.

Fresh fruits and vegetables are *live products*, and thus they continue giving off heat that adds to the refrigeration load of the cold storage room. The storage life of fruits and vegetables can be extended greatly by removing the field heat and cooling as soon after harvesting as possible. The optimum storage temperature of most fruits and vegetables is about 0.5 to 1°C above their freezing point. But this is not the case for some fruits and vegetables such as bananas and cucumbers that experience undesirable *physiological changes*, when exposed to low (but still above-freezing) temperatures, usually between 0 and 10°C. The resulting tissue damage is called the **chilling injury** and is characterized by internal discoloration, soft scald, skin blemishes, soggy breakdown, and failure to ripen. The severeness of the chilling injury depends on both the temperature and the length of storage at that temperature. The lower the temperature, the greater the damage in a given time. Therefore, products susceptible to chilling injury must be stored at higher temperatures. A list of vegetables susceptible to chilling injury and the lowest safe storage temperature are given in Table 17–1.

Chilling injury differs from **freezing injury**, which is caused by prolonged exposure of the fruits and vegetables to subfreezing temperatures and thus the actual *freezing* at the affected areas. The freezing injury is characterized by rubbery texture, browning, bruising, and drying due to rapid moisture loss. The freezing points of fruits and vegetables do not differ by much, but their susceptibility to freezing injury differs greatly. Some vegetables are frozen and thawed several times with no significant damage, but others such as tomatoes suffer severe tissue injury and are ruined after one freezing. Products near the refrigerator coils or at the bottom layers of refrigerator cars and trucks are most susceptible to freezing injury. To avoid freezing injury, the rail cars or trucks should be *heated* during transportation in sub-freezing weather, and adequate air circulation must be provided in cold storage rooms. Damage also occurs during *thawing* if it is done too fast. It is recommended that thawing be done at 4°C.

Dehydration, or *moisture loss*, causes a product to shrivel or wrinkle and lose quality. Therefore, proper measures must be taken during cold storage of food items to minimize moisture loss, which also represents a direct loss of the salable amount. A fruit or vegetable that loses 5 percent moisture, for example, will weigh 5 percent less and will probably be sold at a lower unit price because of loss of quality.

The loss of moisture from fresh fruits and vegetables is also called **transpiration**. The amount of moisture lost from a fruit or vegetable per unit mass of the fruit or vegetable per unit time is called the *transpiration rate*. The transpiration rate varies with the environmental conditions such as the temperature, relative humidity, and air motion. Also, the transpiration rate is different for different fruits and vegetables. The tendency of a fruit or vegetable to transpire is characterized by the *transpiration coefficient*, which is the rate of transpiration per unit environmental vapor pressure deficit. The transpiration coefficient of apples, for example, is 58 ng/s · Pa · kg, whereas it is 1648 ng/s · Pa · kg for carrots and 8750 ng/s · Pa · kg for lettuce. This explains why the lettuce dehydrates quickly while the apples in the same environment maintain their fresh appearance for days.

Moisture loss can be minimized by (1) keeping the *storage temperature* of food as low as possible, (2) keeping the *relative humidity* of the storage room as high as possible, and (3) avoiding *high air velocities* (Fig. 17–7). However, air must be circulated continuously throughout the refrigerated storage room to keep it at a uniform temperature. To maintain high quality and product consistency, *temperature swings* of more than 1°C above or below the desired temperature in the storage room must be avoided. Air motion also minimizes the growth of molds on the surfaces of the wrapped or unwrapped food items and on the walls and ceiling of the storage room.

TABLE 17–1

Some vegetables susceptible to chilling injury and the lowest safe storage temperature (from ASHRAE *Handbook: Refrigeration*, Chap. 17, Table 3)

Vegetable	Lowest safe temperature, °C
Cucumbers	10
Eggplants	7
Casaba melons	7 to 10
Watermelons	4
Okra	7
Sweet peppers	7
Potatoes	3 to 4
Pumpkins	10
Hard-shell squash	10
Sweet potatoes	13
Ripe tomatoes	7 to 10
Mature green tomatoes	13

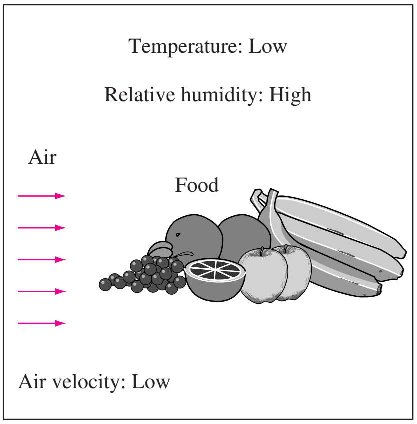


FIGURE 17–7
The proper environment for food storage to minimize moisture loss.

Waxing reduces moisture loss and thus slows down shriveling and maintains crispness in some products such as cucumbers, mature green tomatoes, peppers, and turnips. Waxing also gives the products an attractive glossy appearance. But a wax coating that is too thick may actually increase decay, especially when no fungicides are used.

Refrigeration is not necessary for all food items. For example, *canned foods* that are heat processed can be stored at room temperature for a few months without any noticeable change in flavor, color, texture, and nutritional value. Refrigeration should be considered for the storage of canned foods longer than two or three months to preserve quality and to avoid corrosion of the cans. *Dry foods* can last a long time, often more than a year, without refrigeration if they are protected against high temperatures and humidities. Dry foods that have been vacuum packed in water vapor–proof containers can maintain high quality and nutritional value for a long time. *Honey* can be stored at room temperature for about a year before any noticeable darkening or loss of flavor occurs. Cold storage below 10°C will extend the life of honey for several years. Storage of honey between 10 and 18°C is highly undesirable as it causes granulation.

The use of refrigeration is not limited to food items. It is commonly used in chemical and process industries to separate gases and solutions, to remove the heat of reaction, and to control pressure by maintaining low temperature. It is also used commonly in the beverage industry, in medicine, and even in the storage of furs and garments. Furs and wool products are commonly stored at 1 to 4°C to protect them against insect damage.

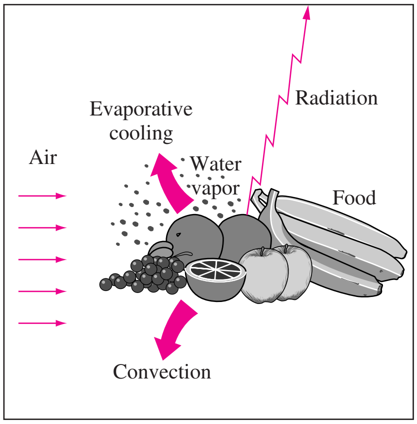


FIGURE 17–8
The cooling of food products by air involves heat transfer by convection, radiation, and evaporation.

During cooling or freezing, heat is removed from the food usually by the combined mechanisms of *convection, radiation*, and *evaporation*, and the *rate of heat transfer* between the food and the surrounding medium at any time can be expressed as (Fig. 17–8)

$$\dot{Q} = hA_s\Delta T = hA_s(T_{\text{surface}} - T_{\text{ambient}}) \quad \text{(W)} \tag{17–1}$$

where

h = average heat transfer coefficient for combined convection, radiation, and evaporation, W/m$^2\cdot$°C
A_s = exposed surface area of the food, m^2
T_{surface} = surface temperature of the food, °C
T_{ambient} = temperature of the refrigerated fluid (air, brine, etc.) away from the food surface, °C

The heat transfer *coefficient h* is not a property of the food or refrigerated fluid. Its value depends on the *shape* of the food, the *surface roughness*, the *type* of cooling fluid, the *velocity* of the fluid, and the *flow regime*. The heat transfer coefficient is usually determined experimentally and is expressed in terms of the Reynolds and Prandtl numbers. Some experimentally determined values of the heat transfer coefficient are given in Table 17–2. The values of h include *convection* as well as other effects such as *radiation* and *evaporative cooling*.

Methods of Freezing

The method of freezing is an important consideration in the freezing of foods. Common freezing methods include *air-blast freezing*, where high-velocity air at about −30°C is blown over the food products; *contact freezing*, where

TABLE 17–2

Surface heat transfer coefficients for food products cooled by air (adapted from ASHRAE *Handbook of Fundamentals*, Chap. 30, Table 10)

Food	Heat transfer mechanisms	Size or characteristic length, L	Air velocity, m/s	Heat transfer coefficient, h, W/m^2 · °C[a]
Jonathan apples	Forced convection, radiation, and evaporation	52–62 mm	0.0	11.1–11.4
			0.40	15.9–17.0
			0.90	26.1–27.3
			2.0	39.2–45.3
			5.1	50.5–54.5
Red delicious apples	Forced convection, radiation, and evaporation	63–76 mm	1.5	14.2–27.3
			4.6	34.6–56.8
			Water[b], 0.27	55.7–90.9
Beef carcasses	Forced convection, radiation, and evaporation	64.5 kg	1.8	21.8
		85 kg	0.3	10.0
Meat	Forced convection, radiation, and evaporation	23-mm-thick slabs	0.56	10.6
			1.4	20.0
			3.7	35.0
Perch fish	Forced convection, radiation, and evaporation	—	1.0–6.6	$h = 4.5k_{air}\,\text{Re}^{0.28}/L$[c]
Potatoes	Forced convection, radiation, and evaporation	—	0.66	14.0
			4.0	19.1
			1.36	20.2
			1.73	24.4
Chicken	Forced convection and radiation	1.2–2.0 kg	Agitated brine[d]	420–473
Turkey		5.4–9.5 kg		
Eggs	Forced convection and radiation	34 mm	2–8	$h = 0.46k_{air}\,\text{Re}_{0.56}/L$
		44 mm	2–8	$h = 0.71k_{air}\,\text{Re}^{0.55}/L$
Oranges, grapefruit, tangelos	Forced convection, radiation, and evaporation	53–80 mm	0.11–0.33	$h = 5.05k_{air}\,\text{Re}^{0.333}/L$

[a]To convert to Btu/h · ft° · °F, multiply the given h values by 0.1761.

[b]The cooling medium is water instead of air.

[c]The L in this last column is the characteristic length given under the "size" column and $\text{Re} = VL/\nu$ is the Reynolds number where V is the average air velocity and ν is the kinematic viscosity of air at the average temperature. The thermal conductivity and kinematic viscosity of air at 0°C are $k = 0.028$ W/m · °C and $\nu = 12.6 \times 10^{-6}$ m^2/s.

[d]The cooling medium is refrigerated brine instead of air.

packaged or unpackaged food is placed on or between cold metal plates and cooled by conduction; *immersion freezing*, where food is immersed in low-temperature brine; *cryogenic freezing*, where food is placed in a medium cooled by a cryogenic fluid such as liquid nitrogen or liquid or solid carbon dioxide; and the combination of the methods above.

In **air-blast freezers**, refrigerated air serves as the heat transfer medium and the heat transfer is primarily by convection. Perhaps the easiest method of

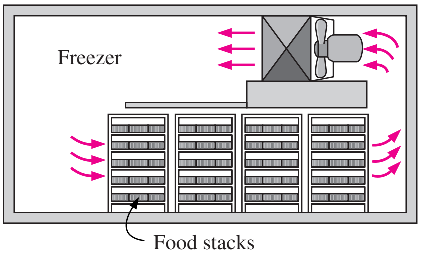


FIGURE 17–9
Schematic of a stationary blast cell freezer.

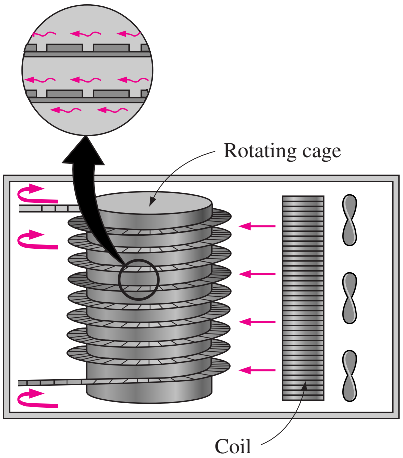


FIGURE 17–10
Schematic of a horizontal airflow spiral freezer.

freezing that comes to mind is to place the food items into a well-insulated *cold storage room* maintained at subfreezing temperatures. Heat transfer in this case is by natural convection, which is a rather slow process. The resulting low rates of freezing cause the growth of large ice crystals in the food and allow plenty of time for the flavors of different foods to mix. This hurts the quality of the product, and thus this simple method of freezing is usually avoided.

The next step is to use some large fans in the cold storage rooms to increase the convection heat transfer coefficient and thus the rate of freezing.These batch-type freezers, called *stationary blast cells* (Fig. 17–9), are still being used for many food products but are being replaced by conveyor-type air-blast freezers as appropriate since they allow the automation of the prod-cut flow and reduce labor costs. A simple version of mechanized freezers, called a *straight-belt freezer*, is very suitable for cooling fruits, vegetables, and uniform-sized products such as french fries. For smaller uniform-sized products such as peas and diced carrots, *fluidized-bed freezers* suspend the food items by a stream of cold air, usually at −40°C, as they travel on a conveyor belt. The high level of air motion and the large surface area result in high rates of heat transfer and rapid freezing of the food products. The floor space requirements for belt freezers can be minimized by using *multi-pass straight belt freezers or spiral belt freezers*, shown in Fig. 17–10, which now dominate the frozen food industry. In another type of air-blast freezer, called the *impingement-style freezer*, cold air impinges upon the food product vertically from both sides of the conveyor belt at a high velocity, causing high heat transfer rates and very fast freezing.

In **contact freezers**, food products are sandwiched between two cold metal plates and are cooled by conduction. The plates are cooled by circulating cold refrigerant through the channels in the plates. Contact freezers are fast and efficient, but their use is limited to flat foods no thicker than about 8 cm with good thermal conductivity, such as meat patties, fish fillets, and chopped leafy vegetables. In **immersion freezing**, food products are immersed in brine or another fluid with a low-freezing point.

At atmospheric pressure, *liquid nitrogen* boils at −195°C and absorbs 198 kJ/kg of heat during vaporization. Carbon dioxide is a solid at atmospheric pressure (called *dry ice*) and sublimes at −79°C while absorbing 572 kJ/kg of heat. The saturated nitrogen and carbon dioxide vapors can further be used to precool the incoming food products before the vapors are purged into the atmosphere. The low boiling points and safety of these cryogenic substances make them very suitable for **cryogenic freezing** of food products. A common type of nitrogen freezer involves a long tunnel with a moving belt in it. Food products are frozen by nitrogen as they pass through the channel. Nitrogen provides extremely fast freezing because of the large temperature difference. Cryogenic cooling is used in limited applications because of its high cost. Sometimes cryogenic cooling is used in combination with air-blast freezing for improved quality and reduced cost. The food product is first crust-frozen in a bath of nitrogen to seal moisture and flavor in, and then transferred into the air-blast freezing section, where the freezing process is completed at a lower cost. This practice also reduces to negligible levels the dehydration losses, which can be as high as 4 percent for poorly designed and maintained systems.

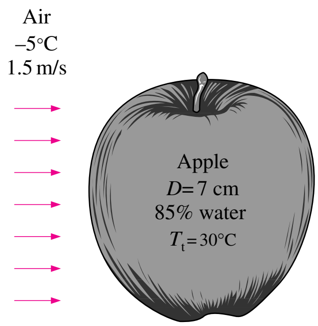


FIGURE 17–11
Schematic for Example 17–1.

EXAMPLE 17–1 Cooling of Apples while Avoiding Freezing

Red Delicious apples of 70 mm diameter and 85 percent water content initially at a uniform temperature of 30°C are to be cooled by refrigerated air at −5°C flowing at a velocity of 1.5 m/s (Fig. 17–11). The average heat transfer coefficient between the apples and the air is given in Table 17–2 to be 21 W/m² · °C. Determine how long it will take for the center temperature of the apples to drop to 6°C. Also, determine if any part of the apples will freeze during this process.

SOLUTION The center temperature of apples drops to 6°C during cooling. The cooling time and if any part of the apples will freeze are to be determined.

Assumptions **1** The apples are spherical in shape with a radius of r_o = 3.5 cm. **2** The thermal properties and the heat transfer coefficient are constant.

Properties The thermal conductivity and thermal diffusivity of apples are k = 0.418 W/m · °C and $\alpha = 0.13 \times 10^{-6}$ m²/s (Table A–7).

Analysis Noting that the initial and the ambient temperatures are T_i = 30°C and T_∞ = −5°C, the time required to cool the midsection of the apples to T_o = 6°C is determined from transient temperature charts for a sphere as follows:

$$\left.\begin{aligned} \frac{1}{\text{Bi}} = \frac{k}{hr_o} = \frac{0.418\ \text{W/m}\cdot{}^\circ\text{C}}{(21\ \text{W/m}^2\cdot{}^\circ\text{C})(0.035\ \text{m})} = 0.57 \\ \frac{T_o - T_\infty}{T_i - T_\infty} = \frac{6-(-5)}{30-(-5)} = 0.314 \end{aligned}\right\} \tau = \frac{\alpha t}{r_o^2} = 0.46$$

Therefore,

$$t = \frac{\tau r_o^2}{\alpha} = \frac{(0.46)(0.035\ \text{m})^2}{0.13 \times 10^{-6}\ \text{m}^2/\text{s}} = 4335\ \text{s} \cong \mathbf{1.20\ h}$$

The lowest temperature during cooling will occur on the surface (r/r_o = 1) of the apples that is in direct contact with refrigerated air and is determined from

$$\left.\begin{aligned} \frac{1}{\text{Bi}} = \frac{k}{hr_o} = 0.57 \\ \frac{r}{r_o} = 1 \end{aligned}\right\} \frac{T(r) - T_\infty}{T_o - T_\infty} = 0.50$$

It gives

$$T_{\text{surface}} = T(r) = T_\infty + 0.50(T_o - T_\infty) = -5 + 0.5[6 - (-5)] = 0.5^\circ\text{C}$$

which is above −1.1°C, the highest freezing temperature of apples. Therefore, **no part of the apples will freeze** during this cooling process.

17–3 ▪ THERMAL PROPERTIES OF FOOD

Refrigeration of foods offers considerable challenges to engineers since the structure and composition of foods and their thermal and physical properties vary considerably. Furthermore, the properties of foods also change with *time* and *temperature*. Fruits and vegetables offer an additional challenge since they *generate heat* during storage as they consume oxygen and give off carbon dioxide, water vapor, and other gases.

The thermal properties of foods are dominated by their *water content*. In fact, the specific heat and the latent heat of foods are calculated with reasonable accuracy on the basis of their water content alone. The *specific heats* of foods can be expressed by **Siebel's formula** as

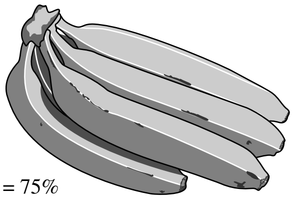
$$c_{p,\text{fresh}} = 3.35a + 0.48 \quad (\text{kJ/kg}\cdot{}^\circ\text{C}) \tag{17–2}$$

$$c_{p,\text{frozen}} = 1.26a + 0.84 \quad (\text{kJ/kg}\cdot{}^\circ\text{C}) \tag{17–3}$$

where $c_{p,\text{ fresh}}$ and $c_{p,\text{ frozen}}$ are the specific heats of the food before and after freezing, respectively; a is the fraction of water content of the food ($a = 0.65$ if the water content is 65 percent); and the constant 0.84 kJ/kg · °C represents the specific heat of the solid (nonwater) portion of the food. For example, the specific heats of fresh and frozen chicken whose water content is 74 percent are.

$$c_{p,\text{fresh}} = 3.35a + 0.84 = 3.35 \times 0.74 + 0.84 = 3.32 \text{ kJ/kg}\cdot{}^\circ\text{C}$$

$$c_{p,\text{frozen}} = 1.26a + 0.84 = 1.26 \times 0.74 + 0.84 = 1.77 \text{ kJ/kg}\cdot{}^\circ\text{C}$$



Bananas
Water content = 75%
Freezing point = –0.8°C

$c_{p,\text{ fresh}} = 3.35 \times 0.75 + 0.84 = 3.35 \text{ kJ/kg}\cdot{}^\circ\text{C}$

$c_{p,\text{ frozen}} = 1.26 \times 0.75 + 0.84 = 1.79 \text{ kJ/kg}\cdot{}^\circ\text{C}$

$h_{\text{latent}} = 334 \times 0.75 = 251 \text{ kJ/kg}$

FIGURE 17–12
The specific and latent heats of foods depend on their water content alone.

Siebel's formulas are based on the specific heats of *water* and *ice* at 0°C of 4.19 and 2.10 kJ/kg · °C, respectively, and thus they result in the specific heat values of water and ice at 0°C for $a = 100$ (i.e., pure water). Therefore, Siebel's formulas give the specific heat values at 0°C. However, they can be used over a wide temperature range with reasonable accuracy.

The *latent heat* of a food product during freezing or thawing (the heat of fusion) also depends on its water content and is determined from (Fig. 17–12)

$$h_{\text{latent}} = 334a \quad (\text{kJ/kg}) \tag{17–4}$$

where a is again the fraction of water content and 334 kJ/kg is the *latent heat of water* during freezing at 0°C at atmospheric pressure. For example, the latent heat of chicken whose water content is 74 percent is

$$h_{\text{latent,chicken}} = 334a = 334 \times 0.74 = 247 \text{ kJ/kg}$$

Perishable foods are mostly water in content that turns to ice during freezing. Therefore, we may expect the food items to freeze at 0°C, which is the freezing point of pure water at atmospheric pressure. But the water in foods is far from being pure, and thus the freezing temperature of foods will be somewhat below 0°C, depending on the composition of a particular food. In general, food products freeze over a *range of temperatures* instead of a single temperature since the composition of the liquid in the food changes (becomes more concentrated in sugar) and its freezing point drops when some of the liquid water freezes (Table 17–3). Therefore, we often speak of the *average* freezing the temperature, or, for foods like lettuce that are damaged by freezing, the temperature at which *freezing begins*. The freezing temperature of most foods is between −0.3 and −2.8°C. In the absence of the exact data the freezing temperature can be assumed to be −2.0°C for meats and −1.0°C for vegetables and fruits.

TABLE 17–3
The drop in the freezing point of typical ice cream whose composition is 12.5 percent milkfat, 10.5 percent serum solids, 15 percent sugar, 0.3 percent stabilizer, and 61.7 percent water (from ASHRAE *Handbook: Refrigeration*, Chap. 14, Table 9)

Percent water frozen	Freezing point of unfrozen part, °C
0	−2.47
10	−2.75
20	−3.11
30	−3.50
40	−4.22
50	−5.21
60	−6.78
70	−9.45
80	−14.92
90	−30.36
100	−55.0

The freezing temperature and specific and latent heats of common food products are given in Tables A-7 and A-7E. The *freezing temperature* in this table represents the temperature at which freezing starts for fruits and vegetables, and the average freezing starts for fruits and vegetables, and the average freezing temperature for other foods. The *water content* values are typical for mature products and may exhibit some variation. The specific and latent heat values given are valid only for the *listed water content*, but they can be reevaluated easily for different water contents using the formulas above.

The accurate determination of heat transfer from the food during freezing to a certain temperature requires a knowledge of the unfrozen amount of water at that temperature. Therefore, it is convenient to present the enthalpies of foods at various temperature in tabular or graphical form, as shown in Table 17–4 for sweet cherries and in Fig. 17–13 for beef. Once the enthalpies are available, the heat transfer Q from the food can be determined from

$$Q = m(h_{\text{initial}} - h_{\text{final}}) = m(h_1 - h_2) \qquad \text{(kJ)} \tag{17–5}$$

where m is the mass of the food and h_{initial} and h_{final} are the initial and final enthalpies of the food, respectively.

Other properties of foods such as density, thermal conductivity, and thermal diffusivity are listed in Tables A–7 and A–7E. Again, the exact values of these properties for a particular food depend on the composition, structure, and temperature of the food and may deviate from the listed values. However, sufficiently accurate heat transfer calculations can be made using the representative values in the tables.

The structures of some food products vary considerably in different directions, and thus the thermal conductivity and diffusivity of some food products can be somewhat different (usually about 10 percent) in directions parallel and perpendicular to the fiber structure. The lower values are listed in such cases to be conservative. Note that the thermal conductivity values for most foods are in the range of 0.2 to 1.0 W/m · °C, and the average thermal conductivity of foods is practically the same as the average thermal conductivity of water, which is 0.6 W/m · °C. In the absence of data, thermal diffusivity can be calculated from its definition, $\alpha = k/\rho c_p$.

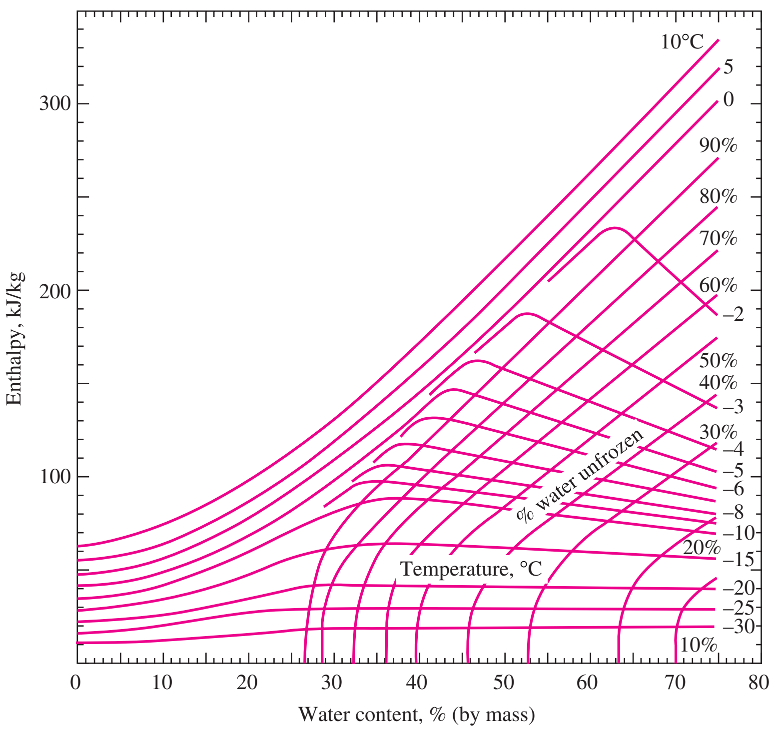


FIGURE 17–13
The enthalpy of beef.
(From Riedel, 1957.)

EXAMPLE 17–2 Freezing of Beef

A 50-kg box of beef at 8°C having a water content of 72 percent Is to be frozen to a temperature of −30°C in 4 h. Using data from Fig. 17–13, determine (*a*) the total amount of heat that must be removed from the beef, (*b*) the amount of unfrozen water in beef at −30°C, and (*c*) the average rate of heat removal from the beef.

SOLUTION A box of beef is to be frozen. The amount of heat removed, the remaining amount of unfrozen water, and the average rate of heat removal are to be determined.

Assumptions The beef is at uniform temperatures at the beginning and at the end of the process.

Properties At a water content of 72 percent, the enthalpies of beef at 8 and −30°C are h_1 = 312 kJ/kg and h_2 = 20 kJ/kg (Fig. 17–13).

Analysis (*a*) The total heat transfer from the beef is determined from

$$Q = m(h_1 - h_2) = (50\,\text{kg})[(312 - 20)\,\text{kJ/kg}] = \mathbf{14{,}600\ kJ}$$

(*b*) The unfrozen water content at −30°C and 72 percent water content is determined from Figure 17–13 to be about 10 percent. Therefore, the total amount of unfrozen water in the beef at −30°C is

$$m_{\text{unfrozen}} = (m_{\text{total}})(\%\,\text{unfrozen}) = (50\,\text{kg})(0.1) = \mathbf{5\,kg}$$

(*c*) Noting that 14,600 kJ of heat are removed from the beef in 4 h, the average rate of heat removal (or refrigeration) is

$$\dot{Q} = \frac{Q}{\Delta t} = \frac{14{,}600\,\text{kJ}}{(4 \times 3600\,\text{s})} = \mathbf{1.01\ kW}$$

Therefore, this facility must have a refrigeration capacity of at least 1.01 kW per box of beef.

This problem could also be solved by assuming the beef to be frozen completely at −2°C by releasing its latent heat of 240 kJ/kg and using specific heat values of 3.25 kJ/kg · °C above freezing and 1.75 kJ/kg · °C below freezing. The total heat removal from the box of beef in this case would be 16,075 kJ. Note that the difference between the two results is 16,075 − 14,600 = 1475 kJ, which is nearly equal to the latent heat released by 6 kg of water as it freezes.

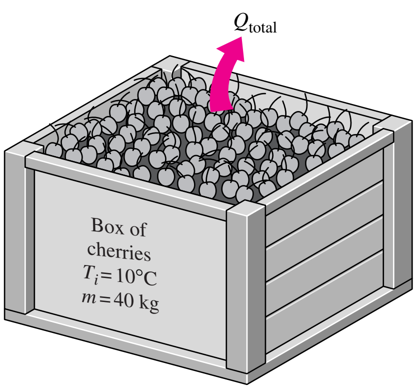


FIGURE 17–14
Schematic for Example 17–3.

EXAMPLE 17–3 Freezing of Sweet Cherries

A 40-kg box of sweet cherries at 10°C having a water content of 77 percent is to be frozen to a temperature of −30°C (Fig. 17–14). Using enthalpy data from Table 17–4, determine the total amount of heat that must be removed from the cherries.

SOLUTION A box of sweet cherries is to be frozen. The amount of heat that must be removed is to be determined.

Assumptions The cherries are at uniform temperatures at the beginning and at the end of the process.

Properties At a water content of 77 percent, the enthalpies of cherries at 0 and −30°C are h_1 = 324 kJ/kg and h_2 = 26 kJ/kg and the specific heat of fresh cherries is 3.43 kJ/kg · °C (Table 17–4).

Analysis The amount of heat removed as the cherries are cooled from 0°C to −30°C is

$$Q_{\text{freezing}} = m(h_1 - h_2) = (40\,\text{kg})[(324 - 26)\,\text{kJ/kg}] = 11{,}920\,\text{kJ}$$

The amount of heat removed as the cherries are cooled from 10°C to 0°C is

$$Q_{\text{cooling}} = mc_p\Delta T_{\text{cooling}} = (40\,\text{kg})(3.43\,\text{kJ/kg}\cdot{}^\circ\text{C})(10^\circ\text{C}) = 1372\,\text{kJ}$$

Then the total heat removed as the cherries are cooled from 10°C to −30°C becomes

$$Q_{\text{total}} = Q_{\text{cooling}} + Q_{\text{freezing}} = 1372 + 11{,}920 = \mathbf{13{,}292\,kJ}$$

Also, the cherries at −30°C will contain 3.6 kg of water since 9 percent of the water in the cherries will still be unfrozen at −30°C.

17–4 ▪ REFRIGERATION OF FRUITS AND VEGETABLES

Fruits and vegetables are frequently *cooled* to preserve preharvest freshness and flavor, and to extend storage and shelf life. Cooling at the field before the product is shipped to the market or storage warehouse is referred to as **precooling**. The cooling requirements of fruits and vegetables vary greatly, as do the cooling methods. Highly perishable products such as broccoli, ripe tomatoes, carrots, leafy vegetables, apricots, strawberries, peaches, and plums must be cooled as soon as possible after harvesting. Cooling is not necessary or as important for long-lasting fruits and vegetables such as potatoes, pumpkins, green tomatoes, and apples.

The refrigeration capacity of *precooling facilities* is usually much larger than that of cold storage facilities because of the requirement to cool the products to a specified temperature within a specified time. In applications where cooling is needed during daytime only, the size of the refrigeration equipment can be cut in half by utilizing cold storage facilities at night for activities such as ice making and during the day for precooling.

Fruits and vegetables are mostly water, and thus their properties are close in value to those of water. Initially, all of the heat removed from the product comes from the exterior of the products, causing a large temperature gradient within the product during fast cooling. But the *mass-average temperature*, which is the equivalent average temperature of the product at a given time, is used in calculations for simplicity.

The heat removed from the products accounts for the majority of the refrigeration load and is determined from

$$\dot{Q}_{\text{product}} = mc_p(T_{\text{initial}} - T_{\text{final}})/\Delta t \quad \text{(W)} \tag{17–6}$$

where $\dot{Q}_{\text{product}}$ is the *average rate of heat removal* from the fruits and vegetables, m is the total mass, c_p is the average specific heat, T_{initial} and T_{finial} are the mass-average temperatures of the products before and after cooling, respectively, and Δt is the cooling time (Fig. 17–15). The heat of respiration is negligible when the cooling time is less than a few hours.

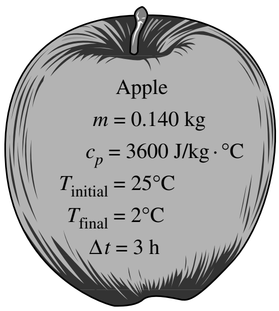
Fresh fruits and vegetables are *live products*, and they continue to *respire* at varying rates for days and even weeks after harvesting. During respiration, a sugar like glucose combines with O_2 to produce CO_2 and H_2O. **Heat of**

TABLE 17–4

The variation of enthalpy and the unfrozen water content of sweet cherries (77 percent water content by mass, no stones) with temperature (from ASHRAE, *Handbook of Fundamentals*, Chap. 30, Table 5)*

Temperature, °C	Percent water unfrozen	Enthalpy, kJ/kg
0	100	324
−1	100	320
−2	100	317
−3	86	276
−4	67	225
−5	55	190
−6	47	166
−7	40	149
−8	36	133
−9	32	123
−10	29	114
−12	26	100
−14	21	87
−16	19	76
−18	17	66
−20	15	58
−30	9	26

*The specific heat of fresh (unfrozen) cherries can be taken to be 3.43 kJ/kg · °C.



$$\dot{Q} = mc_p(T_{\text{initial}} - T_{\text{final}})/\Delta t$$
$$= (0.14\text{ kg})(3600\text{ J/kg}\cdot{}^\circ\text{C})(23^\circ\text{C})/(3\times 3600\text{ s})$$
$$= 1.07\text{ W} \quad \text{(per apple)}$$

FIGURE 17–15

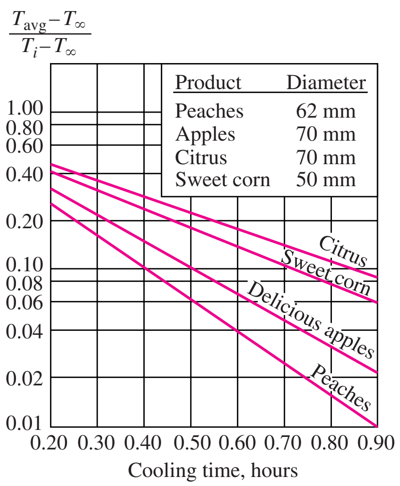
Refrigeration load of an apple-cooling facility that cools appeals from 25°C to 2°C in 3 h.

TABLE 17–5

Heat of respiration of some fresh fruits and vegetables at various temperatures (from ASHRAE *Handbook of Fundamentals*, Chap 30, Table 2)

	Heat of respiration, mW/kg	
Product	5°C	20°C
Apples	13–36	44–167
Strawberries	48–98	303–581
Broccoli	102–475	825–1011
Cabbage	22–87	121–437
Carrots	20–58	64–117
Cherries	28–42	83–95
Lettuce	39–87	169–298
Watermelon	*	51–74
Mushrooms	211	782–939
Onions	10–20	50
Peaches	19–27	176–304
Plums	12–27	53–77
Potatoes	11–35	13–92
Tomatoes	*	71–120

*Indicates a chilling temperature.



T_{avg} = average temperature
T_i = initial temperature
T_∞ = water temperature

FIGURE 17–16

The cooling time of some fruits under ideal conditions during hydrocooling.

(From ASHRAE, Handbook: Refrigeration, *Chap. 10, Fig. 2.)*

respiration is released during this exothermic reaction, which adds to the refrigeration load during cooling of fruits and vegetables. The rate of respiration varies strongly with temperature. For example, the average heats of respiration of strawberries at 0, 10, and 20°C are 44, 213, and 442 mW/kg, respectively. The heat of respiration also varies greatly from one product to another. For example, at 20°C, it is 34 mW/kg for mature potatoes, 77 mW/kg for apples, 167 mW/kg for cabbage, and 913 mW/kg for broccoli. The heat of respiration of most vegetables decreases with time. The opposite is true for fruits that ripen in storage such as apples and peaches. For plums, for example, the heat of respiration increases from 12 mW/kg shortly after harvest to 21 mW/kg after 6 days and to 27 mW/kg after 18 days when stored at 5°C. Being infected with decay organisms also increases the respiration time.

The heat of respiration of some fruits and vegetables are given in Table 17–5. We should use the *initial rates* of respiration when calculating the cooling load of fruits and vegetables for the first day or two, and the *long-term equilibrium rates* when calculating the heat load for long-term cold storage. The *refrigeration load due to respiration* is determined from

$$\dot{Q}_{\text{respiration}} = \sum m_i \dot{q}_{\text{respiration},i} \quad \text{(W)} \tag{17–7}$$

which is the sum of the mass times the heat of respiration for all the food products stored in the refrigerated space. Fresh fruits and vegetables with the highest rates of respiration are the most perishable, and refrigeration is the most effective way to slow down respiration and decay.

The primary precooling methods for fruits and vegetables are *hydro-cooling*, where the products are cooled by immersing them into chilled water; *forced-air cooling*, where the products are cooled by forcing refrigerated air through them; *package icing*, where the products are cooled by placing crushed ice into the containers; and *vacuum cooling*, where the products are cooled by vaporizing some of the water content of the products under low pressure conditions.

Hydrocooling is a popular and effective method of precooling fruits and vegetables and is done by immersing or flooding products in chilled water or spraying chilled water over the products. Water is a good heat transfer medium compared to air, and the convection resistance at the product surface is usually negligible. This means the primary resistance to heat transfer is the internal resistance of the product, and internal heat is removed as soon as it arrives at the surface. The temperature difference between the product surface and the cooling water is normally less than 0.5°C. Under idealized conditions, the convection heat transfer coefficient and the cooling rate per unit surface area can be 680 W/m^2 · °C and 300 W/m^2, respectively.

The variation of the mass-average product temperature with time is given in Fig. 17–16 for some fruits. Note that reducing the temperature difference between the fruit and the water to 10 percent of the initial value takes about 0.4 h for peaches but 0.7 h for citrus fruits. This is not much of a concern, however, since citrus fruits are often not cooled at all.

The water in a hydrocooling system is cooled by passing it through cooling coils in which a refrigerant flows at about −2°C. The water is normally recirculated to save water and energy. But recirculation also saves the microorganisms that come in with fruits and vegetables. Chemicals such as chlorine are commonly added (usually at a rate of 50 to 100 mg/kg water) to reduce bacteria build-up in water.

Forced-air cooling systems have the advantage that they are *simple* and easy to maintain and do not have leakage problems. But they are not as effective as hydrocooling systems. The heat transfer coefficients encountered in forced-air cooling are considerably lower than those encountered in hydrocooling, and thus the cooling of fruits and vegetables by forced air usually takes much longer. The refrigerated air usually approaches the cooling section at a velocity of 1.5 to 2 m/s, and the convection heat transfer coefficients range from about 30 to 60 W/m$^2 \cdot$ °C. The rate of airflow ranges from about 1 to 3 L/s per kg of product. The cooling time can be reduced by spacing the product containers and allowing for airflow throughout instead of stacking them closely and disturbing the airflow. Various air cooling methods, such as batch cooling in refrigerated rooms and impingement air cooling as products continuously pass through a cooling tunnel on conveyor belts, are in common use today. Cut flowers are commonly cooled by forced air.

Vacuum cooling is a batch process, and it is based on *reducing the pressure* of the sealed cooling chamber to the saturation pressure at the desired low temperature and evaporating some water from the products to be cooled. The heat of vaporization during evaporation is absorbed from the products, which lowers the product temperature. The saturation pressure of water at 0°C is 0.61 kPa, and the products can be cooled to 0°C by lowering the pressure to this level. The cooling rate can be increased by lowering the pressure below 0.61 kPa. But this is not desirable because of the danger of freezing and the added cost.

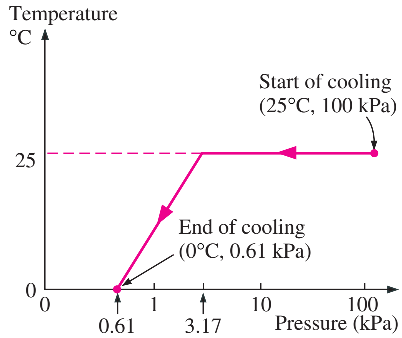


FIGURE 17–17
The variation in the temperature of the fruits and vegetables with pressure during vacuum cooling from 25°C to 0°C.

In vacuum cooling, there are two distinct stages. In the first stage, the products at ambient temperature, say at 25°C, are loaded into the flash chamber and the operation begins. The temperature in the chamber remains constant until the *saturation pressure* is reached, which is 3.17 kPa at 25°C. In the second stage that follows, saturation conditions are maintained inside at progressively *lower pressures* and the corresponding *lower temperatures* until the desired temperature, usually slightly above 0°C, is reached (Fig. 17–17).

The amount of heat removed from the product is proportional to the mass of water evaporated, m_v, and the heat of vaporization of water at the average temperature, h_{fg}, and is determined from

$$Q_{\text{vacuum}} = m_v h_{fg} \quad \text{(kJ)} \tag{17–8}$$

If the product is cooled from 30°C to 0°C, the average heat of vaporization can be taken to 2466 kJ/kg, which corresponds to the *average temperature* of 15°C. Noting that the specific heat of products is about 4 kJ/kg · °C the evaporation of 0.01 kg of water will lower the temperature of 1 kg of product by 24.66/4 = 6°C. That is, the vacuum-cooled products will lose 1 percent moisture for each 6°C drop in their temperature. This means the products will experience a *weight loss* of 4 percent for a temperature drop of about 24°C. To reduce the product moisture loss and enhance the effectiveness of vacuum cooling, the products are often *wetted* prior to cooling.

Vacuum cooling is usually more expensive than forced air or hydrocooling, and its use is limited to applications that result in much faster cooling. products with large surface area per unit mass and a high tendency to release moisture such as *lettuce* and *spinach* are well suited for vacuum cooling, products with low surface area to mass ratio are not suitable, especially those that have relatively impervious peel such as tomatoes and cucumbers. Some products such as mushrooms and green peas can be vacuum cooled successfully by wetting them first.

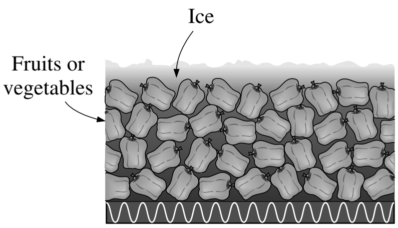


FIGURE 17–18
Ice is sometimes used to cool fruits and vegetables in the field and during short transit.

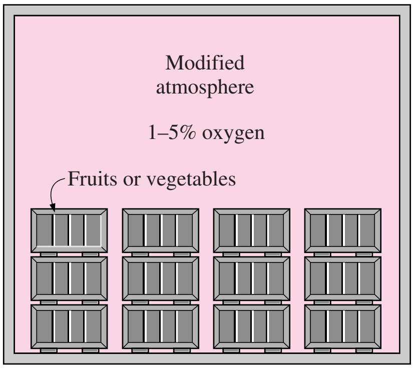


FIGURE 17–19
Reducing the oxygen level in storage rooms reduces respiration and extends storage life.

Package icing is used in small-scale applications to remove field heat and keep the product cool during transit, but its use is limited to products that are not harmed by contact with ice. Also, ice provides *moisture* as well as *refrigeration* (Fig. 17–18). Some shipping containers are cooled By pumping *slush ice* into them through a hose.

Fruits intended for long-term storage must be free of *mechanical injury* such as bruises and skin breaks since deterioration progresses rapidly in such areas. Also, the fruits must be harvested when *mature*. Undermature fruits will not ripen properly while overmature ones will deteriorate rapidly during storage. It is important that fruits be cooled as soon as possible after picking because at field temperatures some fruits deteriorate as much in one day as they do in one week in cold storage.

Fruits and vegetables are normally covered with *microorganisms* that cause decay and premature spoilage under favorable conditions. Refrigeration and the resulting low temperatures are the best protection against the damage caused by the growth of microorganisms. *High temperatures* increase the rate of ripening, decay, moisture loss, and loss of quality of food products during storage, transportation, and display. Precooling, cold storage, and refrigerated transportation have reduced these losses considerably and made it possible to move fruits and vegetables to distant markets at near-fresh conditions.

Fruits and vegetables require *oxygen* to respire, and studies have shown that the storage life of fruits and vegetables can be extended considerably by modifying the atmosphere in the cold storage rooms. This is usually done by reducing the oxygen level in the air to 1 to 5 percent and increasing the CO_2 level to retard the respiration rate and decay (Fig. 17–19). Therefore, many railcars and trucks that transport perishable products to distant cities are flipped with *modified atmosphere systems*. Lettuce is commonly shipped in a low oxygen atmosphere, but not all vegetables benefit from modified atmosphere. Certain vegetables benefit from a modified atmosphere for limited time only. Excess CO_2 accumulation can be prevented in the cargo space by utilizing hydrated lime to absorb CO_2. Liquid nitrogen is often allowed to vaporize in the cargo room and force the regular air and thus oxygen out.

The modified atmosphere measure did not find much acceptance because of the complexities and the risks involved. For example, when the oxygen level is reduced too much, the products cannot respire and develop an alcoholic off-flavor. Also, very high levels of CO_2 harm the products. Modified atmosphere may *supplement* refrigeration, but it can never replace it. In fact, modified atmosphere may actually increase deterioration instead of decreasing it at temperatures above recommended values. An alternative way of extending the storage life is to *reduce* the oxygen level by reducing the atmospheric pressure below 0.2 atm in the storage room, accompanied by the, removal of ethylene gas from the storage room to retard ripening.

Storage of fruits and vegetables in tightly sealed or tied *plastic bags* in order to keep the product moist is not recommended since the respiratory gases such as CO_2 and ethylene may reach harmful levels. Besides, the air packet inside acts as insulation that slows down the cooling of the product inside.

Most produce can be stored satisfactorily at 0°C and 90 to 95 percent relative humidity. An adequate refrigerator coil area should be provided to minimize the difference between the refrigerant and the air temperatures. A temperature difference of more than a few degrees will cause *excessive moisture removal* at the coils, and thus will make it difficult to maintain the storage room at the desired high humidity.

Different fruits and vegetables have different storage requirements, and they respond differently to prolonged cold storage. Therefore, the characteristics of a particular product must be known before an effective cooling and storage mechanism can be devised for it.

The recommended storage temperature for most varieties of *apples* is −1°C, which is 1°C above the highest freezing point of −2°C. But some apple varieties need to be stored at 2°C since they develop physiological disorders at −1°C. Some varieties susceptible to *chilling injury* are stored at about 4°C. *Pears* lose moisture faster than apples, and thus they should be maintained in humid environments. The recommended storage conditions for pears are −1°C and 90 to 90 percent relative humidity. Pears ripen best following storage at temperatures 16 to 21°C. *Plums* are usually stored at −1 to 0°C and 90 to 95 percent relative humidity. Most varieties of plums are not suitable for long-term storage, but some varieties can be stored for a few months with satisfactory results (Fig. 17–20).

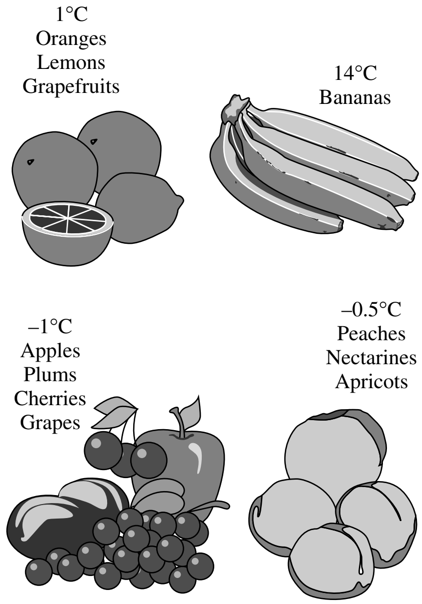


FIGURE 17–20
Recommended storage temperature for various fruits.

Grapes are harvested after they are completely ripened but before being overripe since overripening may cause weakening of the stem attachment and increase the susceptibility to organisms causing decay. Grapes are normally precooled shortly after harvesting to minimize damage by the hot and dry field conditions. Care should be exercised during air cooling since the grapes have a large surface-to-volume ratio that makes them susceptible to moisting loss and drying. This is also the case for the stems of the grapes. Dry stems become brittle and break easily, causing a considerable loss of quality. Grafts are usually precooled by air supplied at 1.5°C or below a rate of at least 0.17 L/s per kg of grape and a minimum velocity of 0.5 m/s through the channels of the container. Sometimes the air is also humidified to minimize drying. It is also recommended that grapes be stored at −1°C and 90 to 95 percent relative humidity. After precooling, the air velocity is lowered to below 0.1 m/s in the container channels. Also, some varieties of grapes are fumigated with sulfur dioxide prior to storage to minimize decay and prevent new infections.

Peaches, especially the early season varieties, are not suitable for long-term storage. However, some late season varieties can be stored for up to six weeks without any noticeable deterioration in texture and flavor. If left unattended, peaches begin to soften and decay in a few hours. Therefore, it is important to cool peaches to 4°C as soon as possible after harvesting, usually by hydrocooling or forced air. Peaches are stored at −0.5°C and 90 to 95 percent relative humidity with low air velocities. *Nectarines* and apricots can be stored under similar storage conditions. *Sweet cherries* intended for storage must be picked with stems attached and precooled rapidly to −1°C by hydrocooling or forced-air cooling. Cherries retain their quality during storage for two weeks. Controlled atmosphere with 20 to 25 percent CO_2 or 0.5 to 2 percent O_2 helps preserve firmness and full vivid color during storage.

Citrus fruits such as *oranges, grapefruit*, and *lemons* do not undergo much changes in their composition after they are picked, and thus the product quality depends mostly on the degree of ripeness when the fruit is harvested. After harvesting, the fruits are transported to packinghouses where they are sorted, washed, and disinfected. The fruits are then polished and waxed after they are dried by warm air. Most varieties of oranges can be stored for 2 to 3 months at

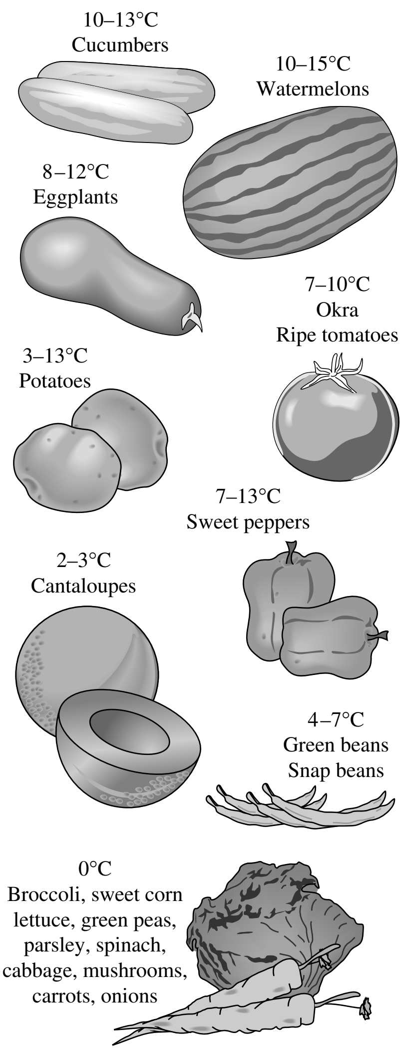


FIGURE 17–21
Recommended storage temperature for various vegetables.

0 to 1°C and 85 to 90 percent relative humidity. Maintaining high humidity in storage rooms is important since oranges tend to lose moisture rapidly. Storage temperatures up to 10°C can be used for shorter storage periods. Grapefruits and lemons can be stored at 10 to 15°C for more than a month.

Bananas are harvested when they are mature but unripe, as noticed by the green color of the peel. After they are washed and cut into retail-size clusters, they are boxed and transported from tropical climates to distant locations by refrigerated trucks or ships maintained at 14°C. The bananas are then moved to wholesale processing facilities by railcars or trucks again at 14°C. Product temperatures below 13°C can cause chilling injury, characterized by darkened areas of killed cells at the peel. Temperatures above about 16°C, on the other hand, may cause the bananas to ripen prematurely and must be avoided.

Unlike other produce storage facilities, bananas are ripened in carefully controlled wholesale processing facilities before they are shipped to retail stores, The ripening process takes four to eight days, depending on the temperatures used, which range between 14 and 18°C. The higher the storage temperature, the shorter the ripening time. The ripening process is initiated by the introduction of ethylene gas into the airtight storage air space at a mole fraction of 0.001 for one day. The refrigerant in the cooling system is maintained at a relatively high temperature (about 4.5°C) to avoid chilling injury.

The optimum temperatures and relative humidities for maximum storage at high quality of fruits and vegetables are well established and are available in handbooks (Fig. 17–21). The recommended storage temperatures and relative humidities are 0°C and 95 to 100 percent for artichokes, broccoli, brussels sprouts, leafy greens, lettuce, parsley, and radishes; 0°C and 98 to 100 percent for cabbage, carrots, celery, and parsnips; 0°C and 95 to 98 percent for sweet corn, green peas, and spinach; 0°C and 95 percent for cauliflower, mushrooms, and turnips; 0 to 2°C and 95 to 100 percent for asparagus; 0°C and 65 to 70 percent for dry garlic and onions; 2 to 3°C and 90 to 95 percent for cantaloupes; 3 to 13°C and 90 to 95 percent for potatoes, 4 to 7°C and 95 percent for green or snap beans; 7 to 10°C and 90 to 95 percent for okra and ripe tomatoes; 7 to 13°C and 90 to 95 percent for sweet peppers; 8 to 12°C and 90 to 95 percent for eggplants; 10 to 13°C and 95 percent for cucumbers; and 10 to 15°C and 90 to 95 percent for watermelons.

Sprouting of onions, potatoes, and carrots becomes a problem in storage facilities that are not adequately refrigerated. The problem can be controlled by using sprout inhibitors. Gamma radiation also suppresses sprouting.

Heat treatment or *radiation* can be used to control decay and kill the insects and microorganisms on or near the fruit surfaces. For example, immersing the peaches in 55°C water for 1.5 minutes (or in 49°C water for 3 minutes) reduces brown rot considerably. Also, ultraviolet lamps are successfully used to kill bacteria and fungi on the exposed surfaces of the cold storage rooms. Gamma radiation is effectively used to control decay in some products, but consumer resistance to irradiated foods remains a concern.

EXAMPLE 17–4 **Cooling of Bananas by Refrigerated Air**

A typical one-half-carlot-capacity banana room contains 18 pallets of bananas. Each pallet consists of 24 boxes, and thus the room stores 432 boxes of bananas. A box holds an average of 19 kg of bananas and is made of 2.3 kg of fiberboard. The specific heats of banana and the fiberboard are 3.55 kJ/kg · °C and 1.7 kJ/kg · °C, respectively. The peak heat of respiration of bananas is 0.3 W/kg. The bananas are cooled at a rate of 0.2°C/h. If the temperature rise of refrigerated air is not to exceed 1.5°C as it flows through the room, determine the minimum flow rate of air needed. Take the density and specific heat of air to be 1.2 kg/m^3 and 1.0 kJ/kg · °C.

SOLUTION A banana cooling room is being analyzed. The minimum flow rate of air needed to cool bananas at a rate of 0.2°C/h is to be determined.

Assumptions **1** Heat transfer through the walls, floor, and ceiling of the banana room is negligible. **2** Thermal properties of air, bananas, and boxes are constant.

Properties The average of properties air, bananas, and boxes are as specified in the problem statement.

Analysis A sketch of the banana room is given in Fig. 17–22. Noting that the banana room holds 432 boxes, the total masses of the bananas and the boxes are determined to be

$$\begin{aligned} m_{\text{banana}} &= (\text{Mass per box})(\text{Number of boxes}) = (19\,\text{kg/box})(432\,\text{boxes}) \\ &= 8208\text{ kg} \\ m_{\text{box}} &= (\text{Mass per box})(\text{Number of boxes}) = (2.3\,\text{kg/box})(432\,\text{box}) \\ &= 993.6\text{ kg} \end{aligned}$$

The total refrigeration load in this case is due to the heat of respiration and the cooling of the bananas and the boxes and is determined from

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{respiration}} + \dot{Q}_{\text{banana}} + \dot{Q}_{\text{box}}$$

where

$$\begin{aligned} \dot{Q}_{\text{respiration}} &= m_{\text{banana}}\,\dot{q}_{\text{respiration}} = (8208\text{ kg})(0.3\text{ W/kg}) = 2462\text{ W} \\ \dot{Q}_{\text{banana}} &= (mc_p\Delta T/\Delta t)_{\text{banana}} \\ &= (8208\,\text{kg})(3.55\,\text{kJ/kg}\cdot{}^\circ\text{C})(0.2^\circ\text{C/h}) = 5828\text{ kJ/h} \\ &= 1619\,\text{W} \quad (\text{since } 1\,\text{W} = 3.6\text{ kJ/h}) \\ \dot{Q}_{\text{box}} &= (mc_p\Delta T/\Delta t)_{\text{box}} \\ &= (993.6\,\text{kg})(1.7\,\text{kJ/kg}\cdot{}^\circ\text{C})(0.2^\circ\text{C/h}) = 338\text{ kJ/h} \\ &= 94\,\text{W} \quad (\text{since } 1\,\text{W} = 3.6\text{ kJ/h}) \end{aligned}$$

and the quantity $\Delta T/\Delta t$ is the rate of change of temperature of the products and is given to be 0.2°C/h. Then the total rate of cooling becomes

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{respiration}} + \dot{Q}_{\text{banana}} + \dot{Q}_{\text{box}} = 2462 + 1619 + 94 = 4175\text{ W}$$

The temperature rise of air is limited to 1.5°C as it flows through the load. Noting that the air picks up heat at a rate of 4175 W, the minimum mass flow rate of air is determined to be

$$\dot{m}_{\text{air}} = \frac{\dot{Q}_{\text{air}}}{(c_p\Delta T)_{\text{air}}} = \frac{4175\,\text{W}}{(1000\text{ J/kg}\cdot{}^\circ\text{C})(1.5^\circ\text{C})} = 2.78\text{ kg/s}$$

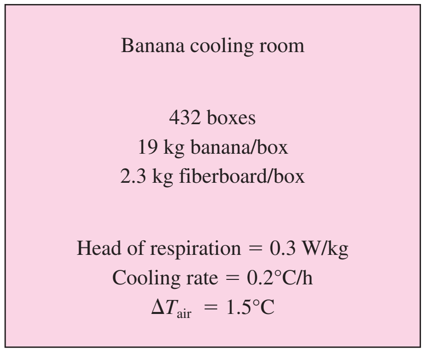


FIGURE 17–22
Schematic for Example 17–4.

Then the volume flow rate of air becomes

$$\dot{V}_{air} = \frac{\dot{m}_{air}}{\rho_{air}} = \frac{2.78\ \text{kg/s}}{1.2\ \text{kg/m}^3} = \mathbf{2.32\ m^3/s}$$

Therefore, the fan selected for the banana room must be large enough to circulate air at rate of 2.32 m^3/s.

17–5 ▪ REFRIGERATION OF MEATS, POULTRY, AND FISH

Meat carcasses in slaughterhouses should be cooled *as fast as possible* to a uniform temperature of about 1.7°C to reduce the growth rate of microorganisms that may be present on carcass surfaces, and thus minimize spoilage. The right level of *temperature, humidity*, and *air motion* should be selected to prevent excessive shrinkage, toughening, and discoloration.

The deep body temperature of an animal is about 39°C, but this temperature tends to rise a couple of degrees in the midsections after slaughter as a result of the *heat generated* during the biological reactions that occur in the cells. The temperature of the exposed surfaces, on the other hand, tends to drop as a result of heat losses. The thickest part of the carcass is the *round*, and the center of the round is the last place to cool during chilling. Therefore, the cooling of the carcass can best be monitored by inserting a thermometer deep into the central part of the round.

About 70 percent of the beef carcass is water, and the carcass is cooled mostly by *evaporative cooling* as a result of moisture migration toward the surface where evaporation occurs. But this shrinking translates into a loss of salable mass that can amount to 2 percent of the total mass during an overnight chilling. To prevent *excessive* loss of mass, carcasses are usually washed or sprayed with water prior to cooling. With adequate care, spray chilling can eliminate carcass cooling shrinkage almost entirely.

TABLE 17–6

Thermal properties of beef

Quantity	Typical value
Average density	1070 kg/m^3
Specific heat:	
Above freezing	3.14 kJ/kg · °C
Below freezing	1.70 kJ/kg · °C
Freezing point	−2.7°C
Latent heat of fusion	249 kJ/kg
Thermal conductivity	0.41 W/m · °C (at 6°C)

The average total mass of dressed beef, which is normally split into two sides, is about 300 kg, and the average specific heat of the carcass is about 3.14 kJ/kg · °C (Table 17–6). The *chilling room* must have a capacity equal to the daily kill of the slaughterhouse, which may be several hundred. A beef carcass is washed before it enters the chilling room and absorbs a large a amount of water (about 3.6 kg) at its surface during the washing process. This does not represent a net mass gain, however, since it is lost by dripping or evaporation in the chilling room during cooling. Ideally, the carcass does not lose or gain any net weight as it is cooled in the chilling room. However, it does lose about 0.5 percent of the total mass in the *holding room* as it continues to cool. The actual product loss is determined by first weighing the dry carcass before washing and then weighing it again after it is cooled.

The refrigerated air temperature in the chilling room of beef carcasses must be sufficiently high to avoid *freezing* and *discoloration* on the outer surfaces of the carcass. This means a long residence time for the massive beef carcasses in the chilling room to cool to the desired temperature. Beef carcasses are only partially cooled at the end of an overnight stay in the chilling room. The temperature of a

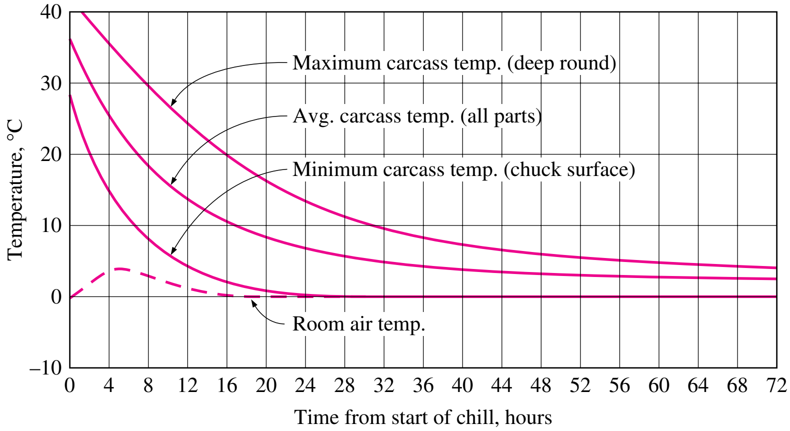


FIGURE 17–23
Typical cooling curve of a beef carcass in the chilling and holding rooms at an average temperature of 0°C.
(From ASHRAE, Handbook: Refrigeration, *Chap. 11, Fig. 2.)*

beef carcass drops to 1.7 to 7°C at the surface and to about 15°C in mid parts of the round in 10 h. It takes another day or two in the *holding room* maintained at 1 to 2°C to complete *chilling* and *temperature equalization*. But hog carcasses are fully chilled during that period because of their smaller size. The *air circulation* in the holding room is kept at minimum levels to avoid excessive moisture loss and discoloration. The refrigeration load of the holding room is much smaller than that of the chilling room, and thus it requires a smaller refrigeration system.

Beef carcasses intended for distant markets are shipped the day after slaughter in refrigerated trucks, where the rest of the cooling is done. This practice makes it possible to deliver fresh meat long distances in a timely manner.

The variation in temperature of the beef carcass during cooling is given in Fig. 17–23. Initially, the cooling process is dominated by *sensible* heat transfer. Note that the average temperature of the carcass is reduced by about 28°C (from 36 to 8°C) in 20 h. The cooling rate of the carcass could be increased by *lowering* the refrigerated air temperature and *increasing* the air velocity, but such measures also increase the risk of *surface freezing*.

Most meats are judged on their **tenderness**, and the preservation of tenderness is an important consideration in the refrigeration and freezing of meats. Meat consists primarily of bundles of tiny *muscle fibers* bundled together inside long strings of *connective tissues* that hold it together. The tenderness of a certain cut of beef depends on the location of the cut, the age, and the activity level of the animal. Cuts from the relatively inactive mid-backbone section of the animal such as short loins, sirloin, and prime ribs are more tender than the cuts from the active parts such as the legs and the neck (Fig. 17–24). The more active the animal, the more the connective tissue, and the tougher the meat. The meat of an older animal is more flavorful, however, and is preferred for stewing since the toughness of the meat does not pose a problem for moist-heat cooking such as boiling. The protein *collagen*, which is the main component of the connective tissue, softens and dissolves in hot and moist environments and gradually transforms into *gelatin*, and tenderizes the meat.

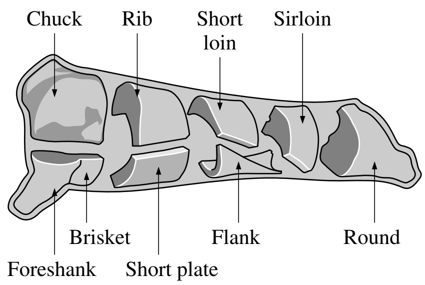


FIGURE 17–24
Various cuts of beef.
(From National Livestock and Meat Board.)

The old saying "one should either cook an animal immediately after slaughter or wait at least two days" has a lot of truth in it. The biomechanical, reactions in the muscle continue after the slaughter until the energy supplied to the muscle to do work diminishes. The muscle then stiffens and goes into *rigor mortis*. This process begins several hours after the animal is slaughtered and

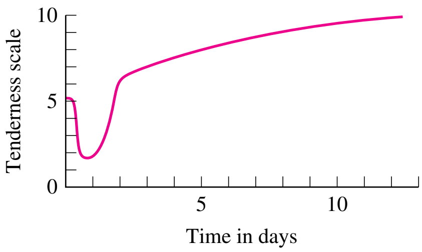


FIGURE 17–25
Variation of tenderness of meat stored at 2°C with time after slaughter.

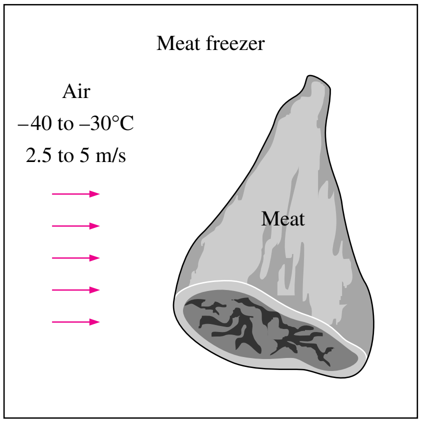


FIGURE 17–26
The freezing time of meat can be reduced considerably by using low temperature air at high velocity.

TABLE 17–7

Storage life of frozen meat products at different storage temperatures (from ASHRAE *Handbook: Refrigeration*, Chap. 10, Table 7)

	Storage life, months		
	Temperature		
Product	−12°C	−18°C	−23°C
Beef	4–12	6–18	12–24
Lamb	3–8	6–16	12–18
Veal	3–4	4–14	8
Pork	2–6	4–12	8–15
Chopped beef	3–4	4–6	8
Cooked foods	2–3	2–4	

continues for 12 to 36 h until an enzymatic action sets in and tenderizes the connective tissue, as shown in Fig. 17–25. it takes about seven days to complete tenderization naturally in storage facilities maintained at 2°C. Electrical stimulation also causes the meat to be tender. To avoid toughness, fresh meat should not be frozen before rigor mortis has passed.

You have probably noticed that steaks are tender and rather tasty when they are hot but toughen as they cool. This is because the gelatin that formed during cooking thickens as it cools, and meat loses its tenderness. So it is no surprise that first-class restaurants serve their steak on hot thick plates that keep the steaks warm for a long time. Also, cooking *softens* the connective tissue but *toughens* the tender muscle fibers. Therefore, barbecuing on *low heat* for a long time results in a tough steak.

Variety meats intended for long-term storage must be frozen rapidly to induce spoilage and preserve quality. Perhaps the first thought that comes to mind to freeze meat is to place the meat packages into the *freezer* and wait. But the freezing time is *too long* in this case, especially for large boxes. For example, the core temperature of a 13-cm-deep box containing 32 kg of variety meat can be as high as 16°C 24 h after it is placed into a −30°C freezer. The freezing time of large boxes can be shortened considerably by adding some *dry ice* into it.

A more effective method of freezing, called *quick chilling*, involves the use of lower air temperatures, −40 to −30°C, with higher velocities of 2.5 m/s to 5 m/s over the product (Fig. 17–26). The internal temperature should be lowered to −4°C for products to be transferred to a storage freezer and to −18°C for products to be shipped immediately. The *rate of freezing* depends on the *package material* and its insulating properties, the *thickness* of the largest box, the *type* of meat, and the *capacity* of the refrigeration system. Note that the air temperature will rise excessively during initial stages of freezing and increase the freezing time if the capacity of the system is inadequate. A smaller refrigeration system will be adequate if dry ice is to be used in packages. Shrinkage during freezing varies from about 0.5 to 1 percent.

Although the average freezing point of lean meat can be taken to be −2°C with a latent heat of 249 kJ/kg, it should be remembered that freezing occurs over a *temperature range*, with most freezing occurring between −1 and −4°C. Therefore, cooling the meat through this temperature range and removing the latent heat takes the most time during freezing.

Meat can be kept at an internal temperature of −2 to −1°C for local use and storage for *under a week*. Meat must be frozen and stored at much lower temperatures for *long-term storage*. The lower the storage temperature, the longer the storage life of meat products, as shown in Table 17–7.

The *internal temperature* of carcasses entering the cooling sections varies from 38 to 41°C for hogs and from 37 to 39°C for lambs and calves. It takes about 15 h to cool the hogs and calves to the recommended temperature of 3 to 4°C. The cooling-room temperature is maintained at −1 to 0°C and the temperature difference between the refrigerant and the cooling air is kept at about 6°C. Air is circulated at a rate of about 7 to 12 air changes per hour. *Lamb carcasses* are cooled to an internal temperature of 1 to 2°C, which takes about 12 to 14 h, and are held at that temperature with 85 to 90 percent relative humidity until shipped or processed. The recommended rate of *air circulation* is 50 to 60 air changes per hour during the first 4 to 6 h, which is reduced to 10 to 12 changes per hour afterward.

Freezing does not seem to affect the *flavor* of meat much, but it affects the *quality* in several ways. The *rate* and *temperature* of freezing may influence color, tenderness, and drip. Rapid freezing increases tenderness and reduces the tissue damage and the amount of drip after thawing. Storage at low freezing temperatures causes significant changes in *animal fat*. Frozen pork experiences more undesirable changes during storage because of its fat structure, and thus its acceptable storage period is shorter than that of beef, veal, or lamb.

Meat storage facilities usually have a *refrigerated shipping dock* where the orders are assembled and shipped out. Such docks save valuable storage space from being used for shipping purposes and provide a more acceptable working environment for the employees. Packing plants that ship whole or half carcasses in bulk quantities may not need a shipping dock; a load-out door is often adequate for such cases.

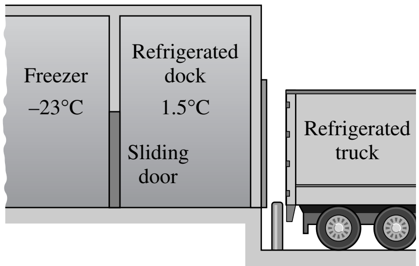


FIGURE 17–27
A refrigerated truck dock for loading frozen items to a refrigerated truck.

A refrigerated *shipping dock*, as shown in Fig. 17–27, reduces the *refrigeration load* of freezers or coolers and prevents *temperature fluctuations* in the storage area. It is often adequate to maintain the shipping docks at 4 to 7°C for the coolers and about 1.5°C for the freezers. The dew point of the dock air should be below the product temperature to avoid condensation on the surface of the products and loss of quality. The rate of *airflow* through the loading doors and other openings is proportional to the *square root* of the temperature difference, and thus reducing the temperature difference at the opening by half by keeping the shipping dock at the average temperature reduces the rate of airflow into the dock and thus into the freezer by $1 - \sqrt{0.5} \cong 0.3$, or 30 percent. Also, the air that flows into the freezer is already cooled to about 1.5°C by the refrigeration unit of the dock, which represents about 50 percent of the cooling load of the incoming air. Thus, the net effect of the refrigerated shipping dock is a reduction of the *infiltration load* of the freezer by about 65 percent since $1 - 0.7 \times 0.5 = 0.65$. The net gain is equal to the difference between the reduction of the infiltration load of the freezer and the refrigeration load of the shipping dock. Note that the dock refrigerators operate at much higher temperatures (1.5°C instead of about −23°C), and thus they consume much less power for the same amount of cooling.

Poultry Products

Poultry products can be preserved by *ice-chilling* to 1 to 2°C or deep *chilling* to about −2°C for short-term storage, or by *freezing* them to −18°C or below for long-term storage. Poultry processing plants are completely *automated*, and the small size of the birds makes continuous conveyor line operation feasible.

The birds are first electrically stunned before cutting to prevent struggling, and to make the killing process more humane (!). Following a 90- to 120-s bleeding time, the birds are *scalded* by immersing them into a tank of warm water, usually at 51 to 55°C, for up to 120 s to loosen the feathers. Then the feathers are removed by feather-picking machines, and the eviscerated carcass is *washed* thoroughly before chilling. The internal temperature, of the birds ranges from 24 to 35°C after washing, depending on the temperatures of the ambient air and the washing water as well as the extent of washing.

To control the microbial growth, the USDA regulations require that poultry be chilled to 4°C or below in less than 4 h for carcasses of less than 1.8 kg, in less than 6 h for carcasses of 1.8 to 3.6 kg. and in less than 8 h for carcasses more than 3.6 kg. Meeting these requirements today is not difficult since the

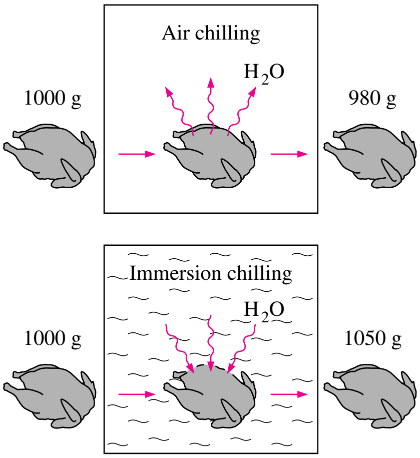


FIGURE 17–28
Air chilling causes dehydration and thus weight loss for poultry, whereas immersion chilling causes a weight gain as a result of water absorption.

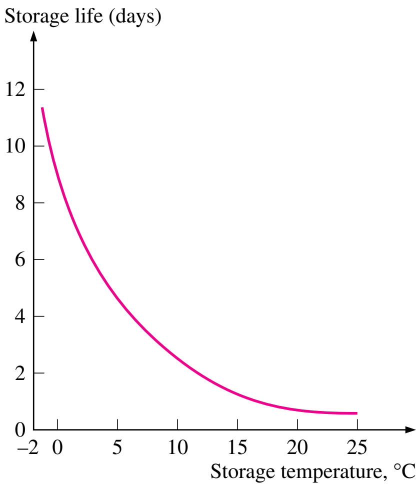


FIGURE 17–29
The storage life of fresh poultry decreases exponentially with increasing storage temperature.

slow *air chilling* is largely replaced by the rapid *immersion chilling* in tanks of slush ice. Immersion chilling has the added benefit that it hot only prevents dehydration, but it causes a *net absorption of water* and thus increases the mass of salable product. Cool air chilling of unpacked poultry can cause a moisture loss of 1 to 2 percent, while water immersion chilling can cause a moisture absorption of 4 to 15 percent (Fig. 17–28). Water spray chilling can cause a moisture absorption of up to 4 percent. Most water absorbed is held between the flesh and the skin and the connective tissues in the skin. In immersion chilling, some soluble solids are lost from the carcass to the water, but the loss has no significant effect on flavor.

Many slush ice tank chillers today are replaced by *continuous* flow-type immersion slush ice chillers. Continuous slush ice-chillers can reduce the internal temperature of poultry from 32 to 4°C in about 30 minutes at a rate up to 10,000 birds per hour. Ice requirements depend on the inlet and exit temperatures of the carcass and the water, but 0.25 kg of ice per kg of carcass is usually adequate. However, *bacterial contamination* such as salmonella remains a concern with this method, and it may be necessary to chloride the water to control contamination.

Tenderness is an important consideration for poultry products just as it is for red meat, and preserving tenderness is an important consideration in the cooling and freezing of poultry. Birds cooked or frozen before passing through rigor mortis remain very tough. Natural tenderization begins soon after slaughter and is completed within 24 h when birds are held at 4°C. Tenderization is rapid during the first three hours and slows down thereafter. Immersion in hot water and cutting into the muscle adversely affect tenderization. Increasing the *scalding temperature* or the scalding time has been observed to increase toughness, and decreasing the scalding time has been observed to increase tenderness. The *beating action* of mechanical feather-picking machines causes considerable toughening. Therefore, it is recommended that any cutting be done after tenderization. *Cutting up* the bird into pieces before natural tenderization is completed reduces tenderness considerably. Therefore, it is recommended that any cutting be done after tenderization. *Rapid chilling* of poultry can also have a toughening effect. It is found that the tenderization process can be speeded up considerably by a patented *electrical stunning* process.

Poultry products are *highly perishable*, and thus they should be kept at the *lowest* possible temperature to maximize their shelf life. Studies have shown that the populations of certain bacteria double every 36 h at −2°C, 14 h at 0°C, 7 h at 5°C, and less than 1 h at 25°C (Fig. 17–29). Studies also shown that the total bacterial counts on birds held at 2°C for 14 days are equivalent to those held at 10°C for 5 days or 24°C for 1 day. It has also been found that birds held at −1°C had 8 days of additional shelf life over those held at 4°C.

The growth of microorganisms on the *surfaces* of the poultry causes the development of an *off-odor* and *bacterial slime*. The higher the initial amount of bacterial contamination, the faster the sliming occurs. Therefore, good sanitation practices during processing such as cleaning the equipment frequently and washing the carcasses are as important as the storage temperature in extending shelf life.

Poultry must be frozen *rapidly* to assure a light, pleasing appearance Poultry that is frozen slowly appears dark and develops large ice crystals that damage the tissue. The ice crystals formed during rapid freezing are small.

Delaying freezing of poultry causes the ice crystals to become larger. Rapid freezing can be accomplished by forced air at temperatures of −23 to −40°C and velocities of 1.5 to 5 m/s in *air-blast tunnel freezers*. Most poultry is frozen this way. Also, the packaged birds freeze much faster on open shelves than they do in boxes. If poultry packages must be frozen in boxes, then it is very desirable to leave the boxes open or to cut holes on the boxes in the direction of airflow during freezing. For best results, the blast tunnel should be fully loaded across its cross-section with even spacing between the products to assure uniform airflow around all sides of the packages. The freezing time of poultry as a function of refrigerated air temperature is given in Fig. 17–30. Thermal properties of poultry are given in Table 17–8.

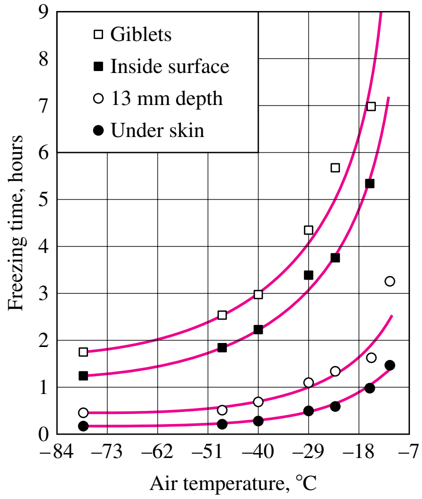
Other freezing methods for poultry include sandwiching between *cold plates, immersion* into a refrigerated liquid such as glycol or calcium chloride brine, and *cryogenic cooling* with liquid nitrogen. Poultry can be frozen in several hours by cold plates. Very high freezing rates can be obtained by *immersing* the packaged birds into a low-temperature brine. The freezing time of birds in −29°C brine can be as low as 20 min, depending on the size of the bird (Fig. 17–31). Also, immersion freezing produces a very appealing light appearance, and the high rates of heat transfer make continuous line operation feasible. It also has lower initial and maintenance costs than forced air, but *leaks* into the packages through some small holes or cracks remain a concern. The convection transfer coefficient is 17 $W/m^2 \cdot °C$ for air at −29°C and 2.5 m/s whereas it is 170 $W/m^2 \cdot °C$ for sodium chloride brine at −18°C and a velocity of 0.02 m/s. Sometimes liquid nitrogen is used to crust freeze the poultry products to −73°C. The freezing is then completed with air in a holding room at −23°C.

Properly packaged poultry products can be *stored* frozen for up to about a year at temperatures of −18°C or lower. The storage life drops considerably at higher (but still below-freezing) temperatures. Significant changes occur in flavor and juiciness when poultry is frozen for too long, and a stale rancid odor develops. Frozen poultry may become dehydrated and experience **freezer burn**, which may reduce the eye appeal of the product and cause toughening of the affected area. Dehydration and thus freezer burn can be controlled by *humidification, lowering* the storage temperature, and packaging the product in essentially *impermeable* film. The storage life can be extended by packing the poultry in an *oxygen-free* environment. The bacterial counts in precooked frozen products must be kept at safe levels since bacteria may not be destroyed completely during the reheating process at home.

Frozen poultry can be *thawed* in ambient air, water, refrigerator, or oven without any significant difference in taste. Big birds like turkey should be thawed safely by holding it in a refrigerator at 2 to 4°C for two to four days, depending on the size of the bird. They can also be thawed by immersing them into cool water in a large container for 4 to 6 h, or holding them in a paper bag. Care must be exercised to keep the bird's surface *cool* to minimize *microbiological growth* when thawing in air or water.

Fish

Fish is a *highly perishable* commodity, and the preservation of fish starts on the vessel as soon as it is caught. Fish deteriorates quickly because of bacterial and enzymatic activities, and *refrigeration* reduces these activities and



Note: Freezing time is the time required for temperature to fall from 0 to –4°C. The values are for 2.3 to 3.6 kg chickens with initial temperature of 0 to 2°C and with air velocity of 2.3 to 2.8 m/s.

FIGURE 17–30
The variation of freezing time of poultry with air temperature.
(From van der Berg and Lentz, 1958.)

TABLE 17–8
Thermal properties of poultry

Quantity	Typical value
Average density:	
Muscle	1070 kg/m^3
Skin	1030 kg/m^3
Specific heat:	
Above freezing	2.94 $kJ/kg \cdot °C$
Below freezing	1.55 $kJ/kg \cdot °C$
Freezing point	−2.8°C
Latent heat of fusion	247 kJ/kg
Thermal conductivity:	(in $W/m \cdot °C$)
Breast muscle	0.502 at 20°C
	1.384 at −20°C
	1.506 at −40°C
Dark muscle	1.557 at −40°C

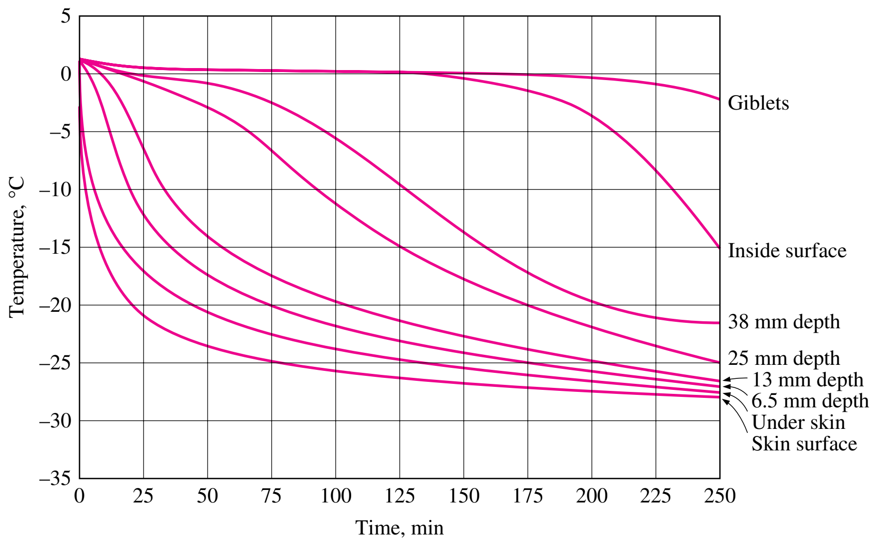


FIGURE 17–31
The variation of temperature of the breast of 6.8-kg turkeys initially at 1°C with depth during immersion cooling at −29°C.
(From van der Berg and Lentz, 1958.)

delays spoilage. Different species have different refrigeration requirements, and thus different practices exist for different species. *Large fish* are usually eviscerated, washed, and iced in the pens of the vessel's hold. *Smaller fish* such as ocean perch and flounder are iced directly without any processing. *Lobsters* and *crabs* axe usually stored alive on the vessel without refrigeration. The fish caught in the arctic waters in winter are frozen by the cold weather and marketed as frozen fish. Salmon and halibut are usually stored in tanks of refrigerated sea water at −1°C. Fish raised in *aquaculture farms* are usually caught on demand and sold fresh in containers covered with ice. The ice used in the fishing industry can be a source of bacterial contamination itself, and thus ice should be made from chlorinated or potable water.

Fish are normally stored in chill rooms at 2°C as they await processing. They are packed in containers of 2- to 16-kg capacity in wet ice after processing and are transported to intended locations. It is desirable to keep fish *uniformly chilled* within 0 to 2°C during transit. At retail stores, fish should be displayed in special fish counters. Displaying in meat cases reduces the shelf life of fish considerably since the temperature of the meat case may be 4°C or higher.

The *maximum storage life* of fresh fish is 10 to 15 days, depending on the particular species, if it is properly iced and stored in refrigerated rooms at 0 to 2°C. Temperatures below 0°C should be avoided in storage rooms since they slow ice melting, which can result in high fish temperatures. Also, the humidity of the storage facility should be over 90 percent and the air velocity should be low to minimize dehydration. The shelf life of fresh fish can be doubled or tripled by treating the fish with *ionizing radiation*. Radiation has no adverse effect on quality, but consumer resistance has prevented its wide spread use. The shelf life can also be extended by inhibiting the growth of bacteria by storing the fish in a *modified atmosphere* with high levels of carbon dioxide and low levels of oxygen.

Fish are commonly frozen for *long-term storage*. Some fatty fish species such as *mackerel* turn rancid during storage and are not suitable for long-term storage. But others such as *cod* respond well to freezing and have a much longer frozen storage life. The storage temperature of frozen fish should be as low as possible to maximize the storage life and to avoid oxidation of fish oils and the resulting off-flavor. Frozen fish should be stored at −26°C or below (Fig. 17–32). Storage at −29°C results in a shelf life of one year or more, but even occasional storage at −23°C or above results in a rapid loss of quality and shortened storage life. Low temperatures retard bacterial activity but do not stop deterioration entirely. As a result, fish that is stored too long exhibits a marked loss of quality. Poorly stored fish become opaque, dull, and spongy when thawed, and the flesh may lose integrity and break up. The overall quality of frozen fish depends on the *condition* of the fish before freezing, the *freezing method,* and the *temperature* and *humidity* during storage and transportation.

The *packaging material* used should be thick enough to protect the product, but thin enough to allow rapid freezing while providing adequate protection against moisture loss during frozen storage. It is important to snug fit the product in the package to reduce the air space and its insulating effect and the resulting high freezing costs. Also, the freezing time of packaged fish fillets in plate freezers is proportional to the square of the package thickness. Therefore, packages that are too thick should be avoided to keep freezing time and cost at reasonable levels. Tightly fit packages also reduce moisture migration from the product to the inner surfaces of the package.

Air-blast freezers are commonly used to freeze fish with air velocities between 2.5 and 7.5 m/s. High velocities result in faster freezing but also higher unit freezing cost. They may also cause *freezer burn* and dehydration of unpacked fish. Typical freezing times of various fish packages are given in Fig. 17–33.

Fish products packaged in 2.5- and 5-kg boxes are often cooled by *plate freezers* rapidly and efficiently. The air spaces in packages must be minimized for effective plate freezing. Fish fillets are sometimes frozen by combined

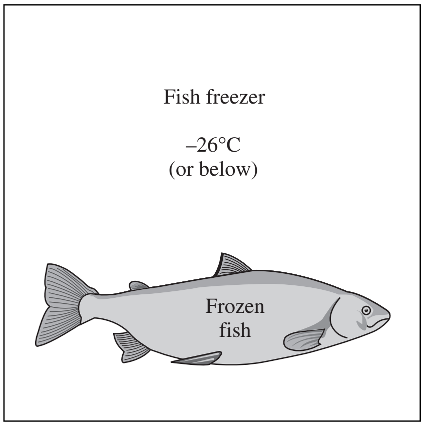


FIGURE 17–32
Frozen fish must be stored at −26°C or below to preserve high quality.

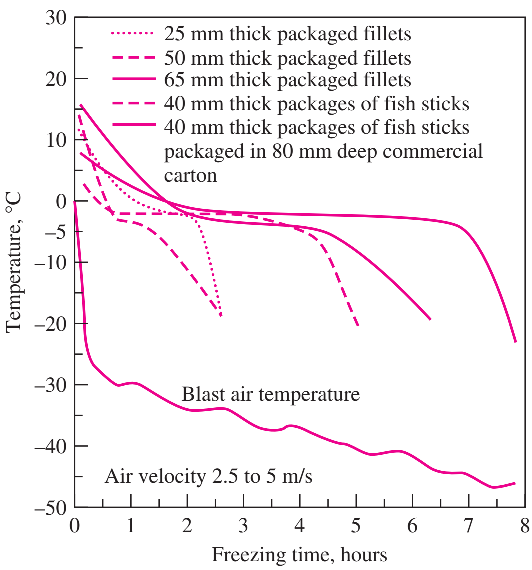


FIGURE 17–33
Freezing time of fish fillets and fish sticks in a tunnel-type blast freezer.
(From ASHRAE, Handbook: Refrigeration, *Chap. 13, Fig. 2.)*

conduction and convection by placing them on a slowly moving refrigerated stainless steel belt through an air-blast tunnel. Plate freezers are also used in large fishing vessels to freeze fish. *Immersion freezing* is not suitable for packaged products but is commonly used for freezing tuna at sea as well as shrimp and crab. Sodium chloride brine is commonly used for this purpose.

Frozen fish are *transported* in refrigerated trucks, railroad cars, or ships capable of maintaining −18°C over long distances under various weather conditions. The vehicles are precooled to at least −12°C before loading, and fish is stored at −18°C or below in retail stores. Frozen fish must be thawed in a refrigerator to avoid rapid deterioration.

EXAMPLE 17–5 Chilling of Beef Carcasses in a Meat Plant

The chilling room of a meat plant is 18 m × 20 m × 5.5 m in size and has a capacity of 450 beef carcasses. The power consumed by the fans and the lights of the chilling room are 26 and 3 kW, respectively, and the room gains heat through its envelope at a rate of 13 kW. The average mass of beef carcasses is 285 kg. The carcasses enter the chilling room at 36°C after they are washed to facilitate evaporative cooling and are cooled to 15°C in 10 h. The water is expected to evaporate at a rate of 0.080 kg/s. The air enters the evaporator section of the refrigeration system at 0.7°C and leaves at −2°C. The air side of the evaporator is heavily finned, and the overall heat transfer coefficient of the evaporator based on the air side is 20 W/m^2 · °C. Also, the average temperature difference between the air and the refrigerant in the evaporator is 5.5°C. Determine (*a*) the refrigeration load of the chilling room, (*b*) the volume flow rate of air, and (*c*) the heat transfer surface area of the evaporator on the air side, assuming all the vapor and the fog in the air freezes in the evaporator.

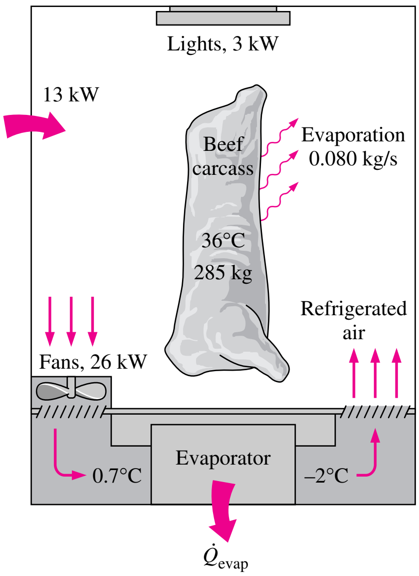


FIGURE 17–34
Schematic for Example 17–5.

SOLUTION The chilling room of a meat plant with a capacity of 450 beef carcasses is considered. The cooling load, the air-flow rate, and the heat transfer area of the evaporator are to be determined.

Assumptions **1** Water evaporates at a rate of 0.080 kg/s. **2** All the moisture in the air freezes in the evaporator.

Properties The heat of fusion and the heat of vaporization of water at 0°C are 333.7 kJ/kg and 2501 kJ/kg. The density and specific heat or air at 0°C are 1.292 kg/m^3 and 1.006 kJ/kg. · °C. Also, the specific heat of beef carcass is determined from the relation in Table A–7*b* to be

$$c_p = 1.68 + 2.51 \times (\text{water content}) = 1.68 + 2.51 \times 0.58 = 3.14 \text{ kJ/kg} \cdot {}^\circ\text{C}$$

Analysis (*a*) A sketch of the chilling room is given in Fig. 17–34. The amount of beef mass that needs to be cooled per unit time is

$$\begin{aligned}\dot{m}_{\text{beef}} &= (\text{Total beef mass cooled})/(\text{Cooling time})\\ &= (450 \text{ carcasses})(285 \text{ kg/carcass})/(10 \times 3600 \text{ s}) = 3.56 \text{ kg/s}\end{aligned}$$

The product refrigeration, load can be viewed as the energy that needs to be removed from the beef carcass as it is cooled from 36 to 15°C at a rate of 3.56 kg/s and is determined to be

$$\dot{Q}_{\text{beef}} = (\dot{m}c_p\Delta T)_{\text{beef}} = (3.56 \text{ kg/s})(3.14 \text{ kJ/kg} \cdot {}^\circ\text{C})(36 - 15){}^\circ\text{C} = 235 \text{ kW}$$

Then the total refrigeration load of the chilling room becomes

$$\dot{Q}_{\text{total, chill room}} = \dot{Q}_{\text{beef}} + \dot{Q}_{\text{fan}} + \dot{Q}_{\text{lights}} + \dot{Q}_{\text{heat gain}} = 235 + 26 + 3 + 13 = \mathbf{277\ kW}$$

The amount of carcass cooling due to evaporative cooling of water is

$$\dot{Q}_{\text{beef, evaporate}} = (\dot{m}h_{fg})_{\text{water}} = (0.080\text{ kg/s})(2501\text{ kJ/kg}) = 200\text{ kW}$$

which is 200/235 = 85 percent of the total product cooling load. The remaining 15 percent of the heat is transferred by convection and radiation.

(*b*) Heat is transferred to air at the rate determined above, and the temperature of the air rises from −2°C to 0.7°C as a result. Therefore, the mass flow rate of air is

$$\dot{m}_{\text{air}} = \frac{\dot{Q}_{\text{air}}}{(c_p \Delta T_{\text{air}})} = \frac{277\text{ kW}}{(1.006\text{ kJ/kg}\cdot°\text{C})[0.7 - (-2)°\text{C}]} = 102.0\text{ kg/s}$$

Then the volume flow rate of air becomes

$$\dot{V}_{\text{air}} = \frac{\dot{m}_{\text{air}}}{r_{\text{air}}} = \frac{102.0\text{ kg/s}}{1.292\text{ kg/m}^3} = \mathbf{78.9\ m^3/s}$$

(*c*) Normally the heat transfer load of the evaporator is the same as the refrigeration load. But in this case the water that enters the evaporator as a liquid is frozen as the temperature drops to 22°C, and the evaporator must also remove the latent heat of freezing, which is determined from

$$\dot{Q}_{\text{freezing}} = (\dot{m}h_{\text{latent}})_{\text{water}} = (0.080\text{ kg/s})(333.7\text{ kJ/kg}) = 27\text{ kW}$$

Therefore, the total rate of heat removal at the evaporator is

$$\dot{Q}_{\text{evaporator}} = \dot{Q}_{\text{total, chill room}} + \dot{Q}_{\text{freezing}} = 277 + 27 = \mathbf{304\ kW}$$

Then the heat transfer surface area of the evaporator on the air side is determined from $\dot{Q}_{\text{evaporator}} = (UA)_{\text{air side}}\,\Delta T$,

$$A = \frac{\dot{Q}_{\text{evaporator}}}{U\Delta T} = \frac{304{,}000\text{ W}}{(20\text{ W/m}^2\cdot°\text{C})(5.5°\text{C})} = \mathbf{2764\ m^2}$$

Obviously, a finned surface must be used to provide such a large surface area on the air side.

17–6 ▪ REFRIGERATION OF EGGS, MILK, AND BAKERY PRODUCTS

Eggs are important sources of nutrients, minerals, and vitamins, and they have a unique place in the diets of practically all cultures. Most eggs are consumed as *shell eggs*, while the rest are processed for use in other products such as mayonnaise and dehydrated egg products. The production and consumption of eggs remain fairly steady throughout the year, and thus the freezing of eggs

TABLE 17–9

Some properties of fresh chicken eggs

Quantity	Typical value
Average mass	60 g
Average density	1080 kg/m^3
Specific heat	3.23 kJ/kg · °C
Freezing point	−2.2°C
Water content	66 percent
Latent heat	220 kJ/Kg

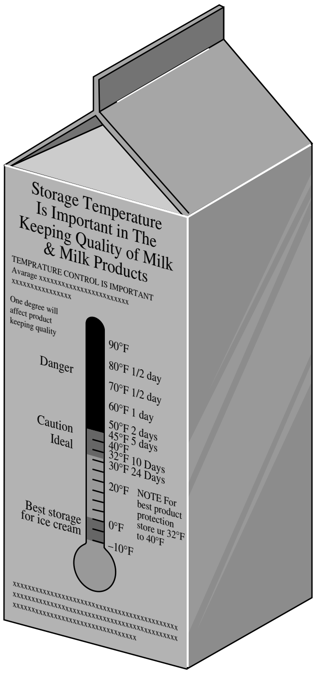


FIGURE 17–35

A label on a milk carton by Model Dairy that emphasizes the importance of storage temperature.

for long-term storage is not practical. However, eggs are highly perishable and must be *refrigerated* to preserve quality and to assure a reasonable shelf life.

Various properties of eggs are listed in Table 17–9. The average density of fresh eggs is 1080 kg/m^3, and thus fresh eggs settle at the bottom when they are put into a cup of water. The density decreases with time, however, as the egg loses moisture and the vacant space is filled with air. The egg shell contains about 17,000 pores through which air, water vapor, and microorganisms can pass. The *mass* of a chicken egg varies from about 35 to 80 g, with an average of 60 g. The white, the yolk, and the shell of an egg constitute 58, 31, and 11 percent of the egg mass, respectively.

In modern farms, eggs *laid* by the hens roll through the sloped floor onto a *conveyor* that transports the eggs to a *packing machine* that aligns the eggs into rows of 12 or 18. The dirt on eggs is a source of bacteria that may cause m decomposition and spoilage. Therefore, the eggs are routed to the *washing section* where they are washed with warm detergent water at a temperature of 43 to 52°C by a series of sprays and brushes and are *rinsed* with warm water and sanitized with chlorine or another chemical. The temperature, of eggs rises by about 3°C during washing. The eggs are then *dried* by air, *oiled*, and *checked* for internal and external defects under a high intensity light The defective eggs are removed, and the remaining ones are *sized* automatically and are *packaged* into 12- or 18-egg cartons or flats.

Egg cartons are made of paper pulp or foam plastic, which are good insulating materials. Cartons that have *openings* on the top facilitate both viewing and cooling. Eggs in such stacks of cartons can be cooled by blasting cold air toward the openings. Cooling pallets of packed eggs by leaving them in cold storage may take two days or more since cold air will have difficulty reaching the mid section. Eggs are cooled most effectively on a *spiral belt cooler* after washing and before packaging, but incorporation of this cooling approach may require some costly modifications in most facilities. Cooling the eggs from about 32°C to about 7 to 13°C takes usually less than 1 h in this case. The eggs could also be cooled after they are packed provided that the boxing material does not prevent the air from flowing through the eggs, but the cooling time in this case would be considerably longer.

The most practical and effective way of preserving the quality of eggs and extending the storage life is *refrigeration*, which should start at the farm and continue through retail outlets. Shell eggs can be stored at 7 to 13°C and 75 to 80 percent relative humidity for *a few weeks*. Eggs lose about 1 percent of their mass per week as moisture. *Condensation* on the egg surfaces should be avoided since wet surfaces are conducive to bacterial and mold growth. Therefore, high moisture levels in storage rooms are undesirable. The chemical reactions that occur in eggs over time cause the yolk membrane to thin and the white to become watery. Absorption of *odors* from the environment also affects the flavor of eggs.

Milk

Milk is one of the most essential foods for humans, but also one of the most suitable environments for the *growth* of microorganisms (Fig. 17–35). Therefore, the production and processing of milk are heavily regulated. A dairy farmer must meet stringent federal and state *regulations* to produce Grade A milk, such as having healthy cows and adequate and sanitary facilities and equipment, and maintaining a bacteria count of less than 100,000 per mL. Also, the milk should not have objectionable flavors and odors.

The cows in a dairy farm are *mechanically milked*, and the milk flows into an insulated stainless steel *bulk tank* through sanitary tubes. The milk is *stirred* by an agitator and is *cooled* as milking continues. The raw milk is constantly agitated to maintain uniform milkfat distribution. The refrigeration capacity of the tank must be sufficient to cool 50 percent of its capacity from 32.2 to 10°C during the first hour, and from 10 to 4.4°C during the second hour. Milk is usually delivered to a dairy plant in a *stainless steel tank* on a truck. The tank is adequately *insulated* so that refrigeration is not required during transportation. The temperature rise of the tank filled with milk should not exceed 1.1°C in 18 h when the average temperature difference between the milk and the ambient air is 16.7°C. Horizontal storage tanks must also meet the same requirement.

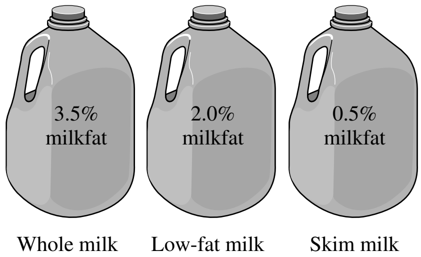


FIGURE 17–36
Typical milkfat contents of whole, lowfat, and skim milk.

A dairy plant receives, processes, and packages the milk. The minimum amounts of *milkfat* and *nonfat solids* in the milk are regulated. For example, the minimum legal milkfat requirements are 3.25 percent for whole milk, 0.5 percent for lowfat or skim milk (the milkfat contents of lowfat and skim milk in the market are about 2.0 and 0.5 percent, respectively), 18 percent. for sour cream, and 36 percent for heavy cream (Fig. 17–36). The minimum legal requirement for nonfat solids in milk is 8.25 percent. The stored milk is first **standardized** to bring the milkfat content to desired levels using a *milk separator*. The separation of milkfat is easier and more efficient at higher temperatures. Therefore, milk is usually heated from the storage temperature of 4.4°C to about 20 to 33°C in warm milk separators. Only a portion of the milk needs to be separated. The remaining milk can be standardized by adding the required amount of skim milk or milkfat.

To kill the bacteria, milk is **pasteurized** in a batch or continuous flow type system by heating the milk to a *minimum temperature* of 62.8°C normally by hot water or steam and holding it at that temperature for at least 30 min. Milk can also be pasteurized *quickly* by heating it to 71.7°C or above and holding it at that temperature at least 15 s (Fig. 17–37). Fast pasteurization is very suitable for continuous-type systems.

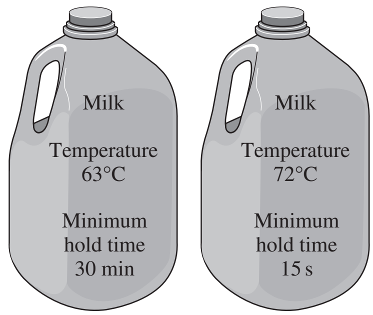


FIGURE 17–37
The pasteurizing time of milk can be minimized by raising the pasteurization temperature.

The pasteurized milk is first *cooled* to the environment temperature by the plant's *cold water*, and then it is cooled to 4.4°C or less by *refrigerated water* usually in plate-type heat exchangers. The entire cooling process should be completed in less than 1 h for sanitary reasons. The continuous-type pasteurizers are equipped, with a *regenerator*, which is a counterflow heat exchanger in which the incoming cold raw milk is heated by the hot pasteurized milk as it is cooled. The flow rates of both the pasteurized and the raw milk are the same, and thus the temperature drop of pasteurized milk will be practically equal to the temperature rise of the raw milk. The effectiveness of the regenerators are in the range of 80 to 90 percent.

The taste of milk depends on the feed of the cattle, and the milk is usually **vacuum processed** after pasteurization to reduce the *undesirable flavors* and *odors* in it. In this process, the temperature of pasteurized milk is raised to 82 to 93°C by injecting hot steam into it and then spraying the mixture into a vacuum chamber where it is cooled by evaporation to the pasteurizing temperatures. The vapor as well as the noncondensible gases responsible for the odors and off-flavor are removed by the vacuum pump. The unit is designed such that the amount of moisture removed is equal to the amount of steam added by the steam injector.

The milk is also **homogenized** before it is packaged to *break up* the large fat globules into smaller ones, usually under 2 μm in size, to give it a "homogeneous" appearance. Homogenization distributes milkfat throughout the body of milk and prevents the milkfat from collecting at the top because of its lower density. This is done by pumping the warm milk at 56 to 82°C to n high pressure (usually 8 to 17 MPa) and shearing off the large globules by forcing the milk through homogenizing valves.

The homogenized milk is *refrigerated* again to about 4°C and is *packaged* in the familiar paperboard, plastic, or glass containers for distribution in refrigerated trucks. The paperboard carton is made of a 0.41-mm-thick paper layer with 0.025- and 0.019-mm polyethylene film laminated on the inside and outside, respectively. Plastic containers have a mass of about 60 g and are made from polyethylene resin by blow-molding. Other milk products such as yogurt, cheese, cream, and ice cream are produced by processing the milk further.

Baked Products

Refrigeration plays an important part in all stages of modern bakery production from the preservation of raw materials such as flour and yeast to the cooling of finished dough. *Flour* is usually stored in bins in air-conditioned spaces at ambient temperatures. It is important to filter the *flour dust* in the air since it may settle on the heat transfer surfaces of the air-conditioning system and reduce heat transfer. *Yeast* is dormant at temperatures below 7°C, and thus it is stored in refrigerated spaces below 7°C but above its freezing point of −3.3°C since freezing kills most cells. Yeast is most active in the temperature range of 27 to 38°C, especially in the presence of nutrients such as *sugar* and *water,* but temperatures above 60°C must be avoided since yeast cells cannot survive at those temperatures. Ingredients such as *corn syrup* and *liquid sugar* are stored in heated tanks at about 52°C to prevent thickening and crystallization.

The first step in the preparation of baked products is the *mixing* of flour yeast, water, and other ingredients, depending on the kind of product, into dough. The temperature of the dough tends to rise during mixing as a result of the *heat of hydration,* which is the heat released when dry flour absorbs water, and the *heat of friction,* which is the mechanical energy supplied to the mixer by the motor. Therefore, *cooling* is needed during kneading of the dough. The easiest way to maintain the dough at the desired temperature of 26 to 27°C is to cool the water to 2 to 4°C before mixing it with the other ingredients. Another method is to cool the mixing chamber externally with water jackets.

After mixing, the dough is allowed to *ferment* in a room maintained at about 27°C and 75 percent relative humidity for a period of 3.5 to 5 h. The dough temperature rises by about 5°C during fermentation. Some water as well as other *fermentation gases* such as alcohols and esters evaporate from the dough surface, and the rate of evaporation depends on the relative humidity of the environment and the air velocity.

The dough is formed into *loaves* and is kept in an enclosure at 35 to 49°C for about 1 h. The fully developed loaves are then *baked,* usually in gas-fired ovens at 200 to 230°C for 18 to 30 min, depending on the type of bread. The hot air in the oven is circulated to ensure uniform baking. The exposed surfaces of the loaves are *sprayed with steam* to caramelize the sugars on the surface at early stages of baking to obtain a gold-colored crust. The temperature of the baked loaves is about 95°C inside and 230°C on the crust. The baked loaves are allowed to *cool* in racks to about 32 to 35°C, which takes about 1.5 to 3 h before they are bagged and shipped. The cooling time can be shortened by using forced airflow. The cooling rate is high initially because of the large temperature difference between the bread and the ambient air and the evaporative cooling due to the vaporization of the moisture in the bread (Fig. 17–38).

Bread starts losing its *freshness* shortly after baking as a result of the *starch crystallizing* and *losing moisture,* producing a crumbly texture. A tight wrap can slow the process by sealing the moisture in. Bread freezes at about −8 °C. To preserve quality and to keep the cellular structure intact, the bread must be cooled as fast as possible; Wrapped bread loaves can be cooled from an internal temperature of 21°C to −10°C with cold air at −29°C and 3.5 m/s in about 3 h. Unwrapped bread will freeze faster, but the moisture loss in this case will be excessive. *Frozen bread* can be defrosted at room temperature with satisfactory results. The thermal properties of baked products are given in Table 17–10.

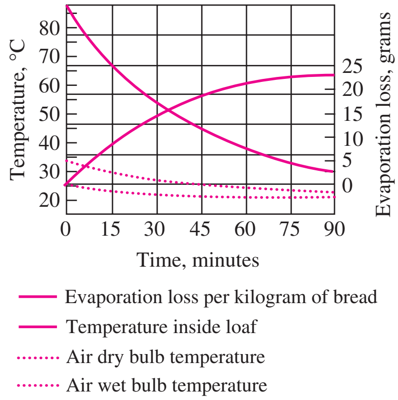


FIGURE 17–38

The variation of temperature and moisture loss of a hot bread with time in a counterflow bread-cooling tunnel.

(From ASHRAE, Handbook: Refrigeration, *Chap.20 Fig. 1.)*

TABLE 17–10

Thermal properties of baked products and their ingredients (from ASHRAE *Handbook: Refrigeration,* Chap. 20, Table 2)

Quantity	Typical value
Specific heat	
Dough	2.51 kJ/kg · °C
Flour	1.76 kJ/kg · °C
Milk	3.98 kJ/kg · °C
Ingredient mixture	1.68 kJ/kg · °C
Baked bread:	
Above freezing	2.93 kJ/kg · °C
Below freezing	1.42 kJ/kg · °C
Freezing point	−9 to −7°C
Latent heat of baked bread	109.3 kJ/kg
Head of hydration of dough	1.51 kJ/kg

EXAMPLE 17–6 Retrofitting a Dairy Plant with a Regenerator

In a dairy plant, milk at 40°F is pasteurized continuously at 162°F at a rate of 2 gallons/s (Fig. 17–39). The milk is heated to pasteurizing temperature by hot water heated in a natural gas-fired boiler having an efficiency of 78 percent. The pasteurized milk is then cooled by cold water at 60°F before it is finally refrigerated back to 40°F. The plant is considering buying a regenerator with a certified effectiveness of 86 percent to save energy and water. The cost of the regenerator is $150,000 installed, and the plant is not interested In any retrofitting project that has a payback period of more than three years. If the cost of natural gas is $0.60/therm (1 therm = 100,000 Btu), determine if the dairy plant can justify purchasing this regenerator.

SOLUTION A regenerator is considered to save heat during the cooling of milk in a dairy plant. It is to be determined if such a generator will pay for itself from the fuel it saves in less than three years.

Assumptions The density and specific heat of milk are constant.

Properties The average density and specific heat of milk can be taken to be $\rho_{\text{milk}} \cong \rho_{\text{water}} = 62.4\ \text{lbm/ft}^3 = 8.35\ \text{lbm/gal}$ and $c_{p,\ \text{milk}} = 0.928\ \text{Btu/lbm} \cdot {}^\circ\text{F}$ (Table A–7E*b*).

Analysis The mass flow rate of the milk is

$$\dot{m}_{\text{milk}} = \rho \dot{V}_{\text{milk}} = (8.35\,\text{lbm/gal})(2\,\text{gal/s}) = 16.7\,\text{lbm/s} = 60{,}120\ \text{lbm/h}$$

To heat the milk from 40 to 162°F, as is being done currently, heat must be transferred to the milk at a rate of

$$\dot{Q}_{\text{current}} = [\dot{m}c_p(T_{\text{pasteurization}} - T_{\text{refrigeration}})]_{\text{milk}}$$
$$= (60{,}120\,\text{lbm/h})(0.928\,\text{Btu/lbm} \cdot {}^\circ\text{F})(162 - 40)^\circ\text{F} = 6{,}807{,}000\ \text{Btu/h}$$

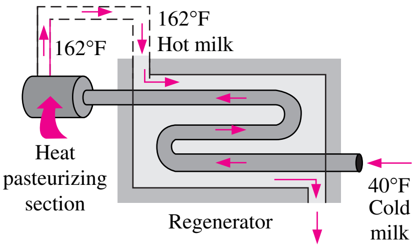


FIGURE 17–39
Schematic for Example 17–6.

The proposed regenerator has an effectiveness of $\varepsilon = 0.86$, and thus it will save 86 percent of this energy. Therefore,

$$\dot{Q}_{saved} = \varepsilon \dot{Q}_{current} = (0.86)\ (6{,}807{,}000\ \text{Btu/h}) = 5{,}854{,}000\ \text{Btu/h}$$

The boiler has an efficiency of $\eta_{boiler} = 0.78$, and thus the energy savings above correspond to fuel savings of

$$\begin{aligned}\text{Fuel savings} &= \dot{Q}_{saved}/\eta_{boiler}\\ &= (5{,}854{,}000\ \text{Btu/h})/0.78\left(\frac{1\ \text{therm}}{100{,}000\ \text{Btu}}\right) = 75.05\ \text{therm/h}\end{aligned}$$

Nothing that 1 year $= 365 \times 24 = 8760$ h, the annual savings from the fuel cost will be

$$\begin{aligned}\text{Cost savings} &= (\text{Fuel savings})(\text{Unit cost of fuel})\\ &= (75.05\ \text{therm/h})(8760\ \text{h/yr})(\$0.60/\text{therm}) = \$394{,}500/\text{yr}\end{aligned}$$

This gives the simple payback period of

$$\text{Payback period} = \frac{\text{Cost of equipment}}{\text{Annual cost savings}} = \frac{\$150{,}000}{\$394{,}500/\text{yr}} = 0.38\ \text{yr} = \mathbf{4.6\ months}$$

Therefore, **the proposed regenerator will pay for itself in about 4.6 months** from the natural gas cost it saves. The purchase and installation of the regenerator are definitely indicated in this case.

17–7 ▪ REFRIGERATION LOAD OF COLD STORAGE ROOMS

Refrigerated spaces are maintained *below* the temperature of their surroundings, and thus there is always a driving force for heat flow toward the refrigerated space from the surroundings. As a result of this heat flow, the *temperature* of the refrigerated space will *rise* to the surrounding temperature unless the heat gained is promptly *removed* from the refrigerated space. A refrigeration system should obviously be large enough the remove the entire heat gain in order to maintain the refrigerated space at the desired low temperature. Therefore, the *size* of a refrigeration system for a specified refrigerated space is determined on the basis of the *rate of heat gain* of the refrigerated space.

The *total* rate of heat gain of a refrigerated space through all mechanisms under peak (or times of highest demand) conditions is called the **refrigeration load**, and it consists of (1) *transmission load,* which is heat conducted into the refrigerated space through its walls, floor, and ceiling; (2) *infiltration load*, which is due to surrounding warm air entering the refrigerated space through the cracks and open doors; (3) *product load,* which is the heat removed from the food products as they are cooled to refrigeration temperature; (4) *internal load,* which is heat generated by the lights, electric motors, and people in the refrigerated space; and (5) *refrigeration equipment load,* which is the heat generated by the refrigeration equipment as it performs certain tasks such as reheating and defrosting (Fig. 17–40).

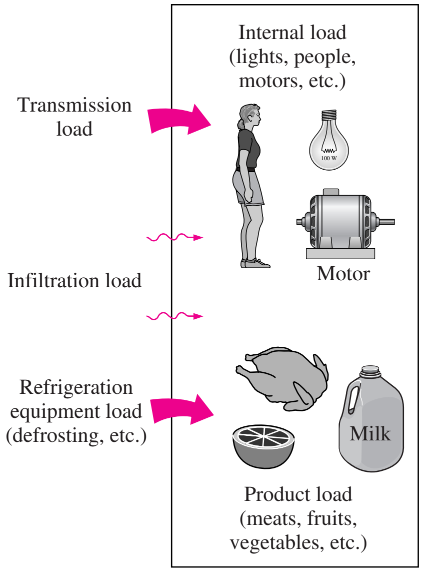


FIGURE 17–40
Various mechanisms of heat gain that make up the total refrigeration load of a refrigerated space.

The size of the refrigeration equipment must be based on *peak refrigeration load,* which usually occurs when the outside temperature is high and the maximum amount of products is brought into the cool storage room at field temperatures.

1 Transmission Load

The *transmission load* depends on the materials and construction of the walls, floor, and ceiling of the refrigerated space, the surface area, the air motion or wind conditions inside or outside, and the temperature difference between the refrigerated space and the ambient air. The *rate of heat transfer* through a particular wall, floor, or ceiling section can be determined from

$$\dot{Q}_{\text{transmission}} = UA_o\Delta T \quad \text{(W)} \tag{17–9}$$

where

A_o = outside surface area of the section
ΔT = temperature difference between the outside air and the air inside the refrigerated space
U = overall heat transfer coefficient

Noting that the *thickness-to-thermal-conductivity* ratio of a layer represents its unit thermal resistance, the **overall heat transfer coefficient** is determined from (Fig. 17–41)

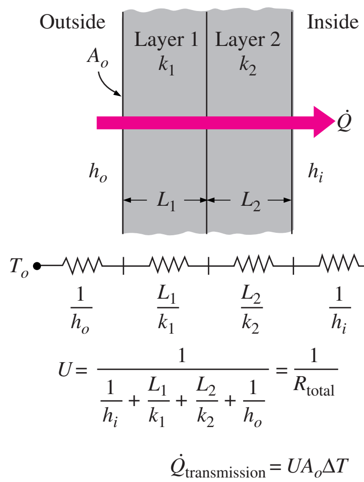


FIGURE 17–41
The determination of thermal resistance and the overall heat transfer coefficient for a two-layer wall section for the calculation of transmission losses.

$$U = \frac{1}{\dfrac{1}{h_i} + \sum \dfrac{L}{k} + \dfrac{1}{h_o}} \quad (\text{W/m}^2 \cdot {}^\circ\text{C}) \tag{17–10}$$

where

h_i = heat transfer coefficient at the inner surface of the refrigerated space
h_o = heat transfer coefficient at the outer surface of the refrigerated space
$\sum L/k$ = sum of the thickness-to-thermal-conductivity ratios of the layers that make up the section under consideration

For still air, it is common practice to take 10 W/m^2 · °C for h_i and h_o. A value of 20 or 30 W/m^2 · °C can be used for h_0 for low or moderate wind conditions outside, respectively.

The walls, floor, and ceiling of typical refrigerated rooms are well insulated, and the *unit thermal resistance L/k* of the *insulation layer* is usually much larger than the L/k of other layers such as the sheet metals and the convective resistance $1/h_i$, and $1/h_o$. Therefore, the thermal resistances of sheet metal layers can always be ignored. Also, the *convection resistances* $1/h_i$ and $1/h_o$ are often negligible, and thus having very accurate values of h_i and h_o is usually not necessary.

When constructing refrigerated rooms, it is desirable to use *effective* insulation materials to *minimize* the refrigerated space for a fixed floor area. Minimum insulation thicknesses for expanded polyurethane (k = 0.023 W/m · °C) recommended by the refrigeration industry are given in Table 17–11. Note that the *larger* the temperature difference between the refrigerated space and

TABLE 17–11

Minimum recommended expanded polyurethane insulation thicknesses for refrigerated rooms (from ASHRAE, *Handbook: Refrigeration*, Chap. 26, Table 2)

Storage Temperature	Northern United States	Southern United States
10 to 16°C	25 mm	50 mm
4 to 10°C	50 mm	75 mm
−4 to 4°C	50 mm	75 mm
−9 to −4°C	75 mm	100 mm
−18 to −9°C	75 mm	100 mm
−26 to −18°C	100 mm	100 mm
−40 to −26°C	125 mm	125 mm

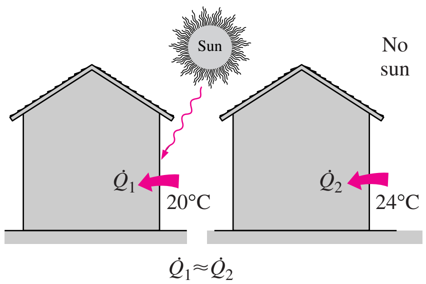


FIGURE 17–42
Solar heating effect on the west or east wall can be compensated for by adding 4°C to the ambient temperature.

the ambient air, the *thicker* the insulation required to reduce the transmission heat gain to reasonable levels. *Equivalent thicknesses* for other insulating materials can be obtained by multiplying the values in this table by k_{ins}/k_{poly} where k_{ins} and k_{poly} are the thermal conductivities of the insulation material and the polyurethane, respectively.

Direct exposure to the *sun* increases the refrigeration load of a refrigerated room as a result of the solar energy absorbed by the outer surface being conducted into the refrigerated space. The effect of *solar heating* can conveniently be accounted for by adding a few degrees to the ambient temperature. For example, the solar heating effect can be compensated for by adding 4°C to the ambient temperature for the east and west walls, 3°C for the south walls, and 9°C for flat rooms with medium-colored surfaces such as unpainted wood, brick, and dark cement (Fig. 17–42). For dark- (or light-) colored surfaces, we should add (or subtract) to 1°C (or from) these values.

2 Infiltration Load

The heat gain due to the surrounding warm air entering the refrigerated space through the cracks and the open doors continues the *infiltration load* of the refrigeration system (Fig 17–43). The infiltration load changes with time. We should consider the *maximum value* to properly size the refrigeration system, and the *average value* to properly estimate the average energy consumption. In installations that require the doors to remain open for long periods of time, such as distribution warehouses, the infiltration load may amount to more than half of the total refrigeration load.

In the absence of any *winds,* the infiltration is due to the *density difference* between the cold air in the refrigerated space and the surrounding warmer air. When the average velocity of the air entering the refrigerated space under the influence of winds or pressure differentials is known, the rate of infiltration heat gain can be determined from ASHRAE, *Handbook: Refrigeration*, Chap. 26, p. 5:

$$\dot{Q}_{\text{infiltration windy air}} = 6V_{air}A_{leak}c_{p,air}(T_{warm} - T_{cold})\rho_{cold}D_{time} \quad (17\text{–}11)$$

where

V_{air} = average air velocity, usually between 0.3 and 1.5 m/s
A_{leak} = smaller of the inflow or outflow opening areas, m^2
$c_{p,\,air}$ = specific heat of air, 1.0 kJ/kg · °C
T_{warm} = temperature of the warm infiltration air, °C
T_{cold} = temperature of the cold infiltration air, °C
ρ_{cold} = temperature of the cold refrigerated air, kg/m^3
D_{time} = density open-time factor

There is considerable uncertainty in the determination of the infiltration load, and field experience from similar installations can be a valuable aid in calculations. A practical way of determining the infiltration load is to estimate the rate of air infiltration in terms of **air changes per hour** (ACH), which is the number of times tire entire air content of a room is replaced by the infiltrating air per hour. Once the number of air changes per hour is estimated, the *mass flow rate* of air infiltrating into the room is determined from

$$\dot{m}_{air} = \frac{V_{room}}{v_{air}}\text{ACH} \quad (\text{kg/h}) \quad (17\text{–}12)$$

where V_{room} is the volume of the room and v_{room} is the specific volume of the dry air in the room. Once $\dot{m}_{air}$ is available, the sensible and latent infiltration loads of the cold storage room can be determined from

$$\dot{Q}_{\text{infiltration, sensible}} = \dot{m}_{air}(h_{ambient} - h_{room}) \quad \text{(kJ/h)} \tag{17–13}$$

$$\dot{Q}_{\text{infiltration, latent}} = (\omega_{ambient} - \omega_{room})\dot{m}_{air}h_{fg} \quad \text{(kJ/h)} \tag{17–14}$$

where ω is the humidity ratio of air (the mass of water vapor in 1 kg of dry air), h is the enthalpy of air, and h_{fg} is the heat of vaporization of water. The values of specific volume v, enthalpy h, and the humidity ratio ω can be determined from the *psychrometric chart* when the temperature and relative humidity (or wet-bulb temperature) of air are specified. The total infiltration load is then the sum of the sensible and latent components.

The value of ACH should be determined under the most adverse operating conditions (such as during loading or unloading and high winds) to ensure satisfactory performance under those conditions.

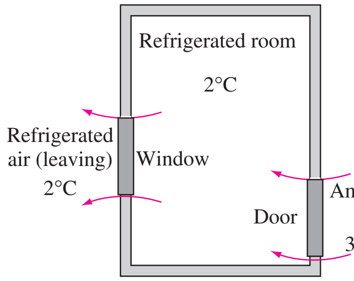


FIGURE 17–43
The warm air that enters a refrigerated space finds its way out after it is cooled, and the heat removed from the air constitutes the infiltration load.

3 Product Load

The *heat removed* from the food products as they are cooled to refrigeration temperature and the heat released as the fresh fruits and vegetables respire in storage constitute the **product load** of the refrigeration system (Fig. 17–44). As we mentioned earlier, the *refrigeration* of foods involves cooling only, but the *freezing* of foods involves cooling to the freezing point (removing the sensible heat), freezing (removing the latent heat), and further cooling to the desired subfreezing temperature (removing the sensible heat of frozen food). The three components of the product load can be determined from

$$Q_{\text{cooling, fresh}} = mc_{p,\text{fresh}}(T_1 - T_{freeze}) \quad \text{(kJ)} \tag{17–15}$$

$$Q_{freezing} = mh_{latent} \quad \text{(kJ)} \tag{17–16}$$

$$Q_{\text{cooling, frozen}} = mc_{p,\text{frozen}}(T_{freeze} - T_2) \quad \text{(kJ)} \tag{17–17}$$

where

m = mass of the food product
$c_{p,\text{ fresh}}$ = specific heat of the food before freezing
$c_{p,\text{ frozen}}$ = specific heat of the food after freezing
h_{latent} = latent heat of fusion of the food
T_{freeze} = freezing temperature of the food
T_1 = initial temperature of the food (before refrigeration)
T_2 = final temperature of the food (after freezing)

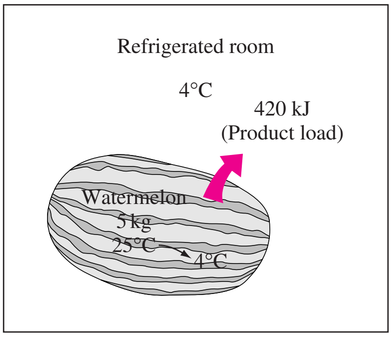


FIGURE 17–44
The heat removed form the food products as they are cooled constitutes the product load of a refrigeration system.

The *rate of refrigeration* needed to cool a product from T_1 to T_2 during a time interval Δt can be determined from

$$\dot{Q}_{product} = \frac{Q_{\text{product, total}}}{\Delta t} = \frac{Q_{\text{cooling, fresh}} + Q_{freezing} + Q_{\text{cooling, frozen}}}{\Delta t} \tag{17–18}$$

Note that it will take a relatively short time for a powerful refrigeration system to accomplish the desired cooling.

Food products are usually refrigerated in their *containers*, and the product load also includes cooling the containers. The amount of heat that needs to be removed from the container as it is cooled from T_1 to T_2 can be determined from

$$Q_{\text{container}} = mc_{p,\text{container}}(T_1 - T_2) \quad \text{(kJ)} \tag{17–19}$$

where m is the mass of the container and $c_{p,\text{ container}}$ is the specific heat of the container, which is 0.50 kJ/kg · °C for stainless steel, 1.7 kJ/kg · °C for nylon, 1.9 kJ/kg · °C for polypropylene, and 2.3 kJ/kg · °C for polyethylene containers. The contribution of $\dot{Q}_{\text{container}}$ to the refrigeration load is usually very small and can be neglected.

4 Internal Load

The heat generated by the *people, lights, electric motors, and other heat-dissipating equipment* in the refrigerated space constitutes the **internal load** of the refrigeration system (Fig. 17–45). The rate of heat dissipation by people depends on the size of the person, the temperature of the refrigerated space, the activity level, and the clothing, among other things. A person must generate more heat at lower temperatures to compensate for the increased rate of heat transfer at higher temperature differences. The *heat dissipated* by an *average person* in a refrigerated space maintained at temperature T in °C is expressed as (ASHRAE, *Handbook: Refrigeration*, Chap. 26, p. 3)

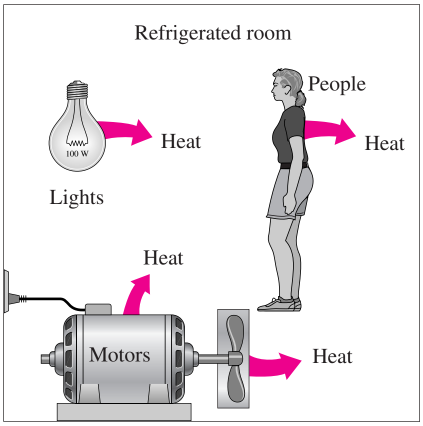


FIGURE 17–45
The heat generated by the people lights, electric motors, and other heat-dissipating equipment in a refrigerated space constitutes the internal load.

$$\dot{Q}_{\text{people}} = 270 - 6T(°\text{C}) \quad \text{(W/person)} \tag{17–20}$$

Therefore, an average person will dissipate 210 W of heat in a space maintained at 10°C and 360 W in a space at −15°C.

The rate of heat dissipation from *lights* is determined by simply adding the wattage of the light bulbs and the fluorescent tubes. For example, five 100-W incandescent light bulbs and eight 40-W fluorescent tubes contribute 820 W to the refrigeration load when they all are on.

The calculation of the heat dissipation from the *motors* is more complicated because of the uncertainties involved in the operation such as the *motor efficiency,* the *load factor* (the fraction of the rated load at which the motor normally operates), and the *utilization factor* (the fraction of the time during which the motor actually runs), and whether the motor running a device such as a fan is located inside the refrigerated space. Noting that the motors are usually oversized, the rated power of a motor listed on its tag tells us little about its contribution to the refrigeration load. When the body of a motor running a device is housed *outside* the refrigerated space, then the internal heat load of this motor is simply the power consumed by the device in the refrigerated space. But when the motor is housed *inside* the refrigerated space, then the heat dissipated by the motor also becomes part of the internal heat load since this heat now must be removed from the refrigeration system. Keeping the motors inside the refrigerated space may increase the internal load due to motors by 30 to 80 percent.

5 Refrigeration Equipment Load

The *refrigeration equipment load* refers to the heat generated by the refrigeration equipment itself as it performs certain tasks such as *circulating* the cold air with a fan, *electric reheating* to prevent condensation on the surfaces of the refrigerator, and *defrosting* to prevent frost build-up and to evaporate moisture. Equipment load can be as little as 5 percent of the total refrigeration load for simple refrigeration systems or it may exceed 15 percent for systems maintained at very low temperatures. When the total refrigeration load is determined as described above, it is common practice to apply a safety factor of 10 percent to serve as a cushion to cover any unexpected situations.

EXAMPLE 17–7 Freezing of Chicken

A supply of 50 kg of chicken at 6°C contained in a box is to be frozen to −18°C in a freezer (Fig. 17–46). Determine the amount of heat that needs to be removed. The container box is 1.5 kg, and the specific heat of the box material is 14 kJ/kg · °C.

SOLUTION A box of chicken is to be frozen in a freezer. The amount of heat removal is to be determined.

Assumptions **1** The thermal properties of fresh and frozen chicken are constant. **2** The entire water content of chicken freezes during the process.

Properties For chicken, the freezing temperature is −2.8°C, the latent heat of fusion is 247 kJ/kg, the specific heat is 3.32 kJ/kg · °C above freezing and 1.77 kJ/kg · °C below freezing (Table A–7*a*).

Analysis The total amount of heat that needs to be removed (the cooling load of the freezer) is the sum of the latent heat and the sensible heats of the chicken before and after freezing as well as the sensible heat of the box, and is deter mined as follows:

Cooling fresh chicken from 6°C to −2.8°C:

$$Q_{\text{cooling, fresh}} = (mc_p\Delta T)_{\text{fresh}} = (50\text{ kg})(3.32\text{ kJ/kg}\cdot{}^\circ\text{C})[6-(-2.8)]^\circ\text{C} = 1461\text{ kJ}$$

Freezing chicken at −2.8°C:

$$Q_{\text{freezing}} = mh_{\text{latent}} = (50\text{ kg})(247\text{ kJ/kg}) = 12{,}350\text{ kJ}$$

Cooling frozen chicken from −2.8°C to −18°C:

$$\begin{aligned} Q_{\text{cooling, frozen}} &= (mc_p\Delta T)_{\text{frozen}} \\ &= (50\text{ kg})(1.77\text{ kJ/kg}\cdot{}^\circ\text{C})[-2.8-(-18)]^\circ\text{C} = 1345\text{ kJ} \end{aligned}$$

Cooling the box from 6°C to −18°C:

$$Q_{\text{box}} = (mc_p\Delta T)_{\text{box}} = (1.5\text{ kg})(1.4\text{ kJ/kg}\cdot{}^\circ\text{C})[6-(-18)]^\circ\text{C} = 50\text{ kJ}$$

Therefore, the total amount of cooling that needs to be done is

$$\begin{aligned} Q_{\text{total}} &= Q_{\text{cooling, fresh}} = Q_{\text{freezing}} + Q_{\text{cooling, frozen}} + Q_{\text{box}} \\ &= 1461 + 12{,}350 + 1345 + 50 = \mathbf{15{,}206\text{ kJ}} \end{aligned}$$

DISCUSSION Note that most of the cooling load (81 percent of it) is due to the removal of the latent heat during the phase change process. Also note that the cooling load due to the box is negligible (less than 1 percent), and can be ignored in calculations.

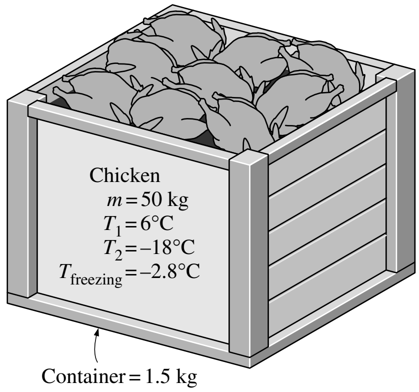


FIGURE 17–46
Schematic for Example 17–7.

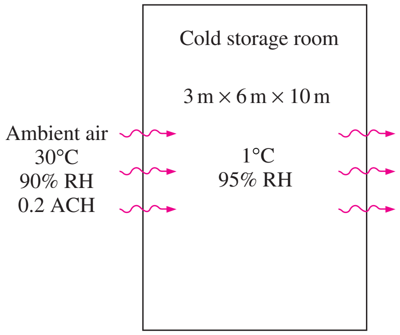


FIGURE 17–47
Schematic for Example 17–8.

EXAMPLE 17–8 Infiltration Load of Cold Storage Rooms

A cold storage room whose internal dimensions are 3 m × 6 m × 10 m is maintained at 1°C and 95 percent relative humidity (Fig. 17–47). Under worst conditions, the amount of air infiltration is estimated to be 0.2 air changes per hour at the ambient conditions of 30°C and 90 percent relative humidity. Using the psychrometric chart, determine the total infiltration load of this room under these conditions.

SOLUTION The infiltration rate of a cold storage room is given to be 0.2 ACH. The total infiltration load of the room is to be determined.

Assumptions The entire infiltrating air is cooled to 1°C before It exfiltrates.

Properties The heat of vaporization of water at the average temperature 15°C is 2466 kJ/kg (Table A–9). The properties of the cold air in the room and the ambient air are determined from the psychrometric chart to be

$$\left.\begin{aligned} T_{\text{ambient}} &= 30°\text{C} \\ \phi_{\text{ambient}} &= 90\% \end{aligned}\right\} \quad \left.\begin{aligned} \omega_{\text{ambient}} &= 0.024 \text{ kg/kg dry air} \\ h_{\text{ambient}} &= 93 \text{ kJ/kg dry air} \end{aligned}\right\}$$

$$\left.\begin{aligned} T_{\text{room}} &= 1°\text{C} \\ \phi_{\text{room}} &= 95\% \end{aligned}\right\} \quad \left.\begin{aligned} \omega_{\text{room}} &= 0.0038 \text{ kg/kg dry air} \\ h_{\text{room}} &= 11 \text{ kJ/kg dry air} \\ v_{\text{room}} &= 0.780 \text{ m}^3\text{/kg dry air} \end{aligned}\right\}$$

Analysis Noting that the infiltration of ambient air will cause the air in the cold storage room to be changed 0.2 times every hour, the air will enter the room at a mass flow rate of

$$\dot{m}_{\text{air}} = \frac{V_{\text{room}}}{v_{\text{room}}}\text{ACH} = \frac{3 \times 6 \times 10 \text{ m}^3}{0.780 \text{ m}^3\text{/kg dry air}}(0.2 \text{ h}^{-1}) = 46.2 \text{ kg/h} = 0.0128 \text{ kg/s}$$

Then the sensible and latent infiltration heat gain of the room become

$$\begin{aligned} \dot{Q}_{\text{infiltration, sensible}} &= \dot{m}_{\text{air}}(h_{\text{ambient}} - h_{\text{room}}) \\ &= (0.0128 \text{ kg/s})(93 - 11)\text{kJ/kg} = 1.05 \text{ kW} \end{aligned}$$

$$\begin{aligned} \dot{Q}_{\text{infiltration, latent}} &= (\omega_{\text{ambient}} - \omega_{\text{room}})\dot{m}_{\text{air}} h_{fg} \\ &= (0.024 - 0.0038)(0.0128 \text{ kg/s})(2466 \text{ kJ/kg}) = 0.64 \text{ kW} \end{aligned}$$

Therefore,

$$\dot{Q}_{\text{infiltration}} = \dot{Q}_{\text{infiltration, sensible}} + \dot{Q}_{\text{infiltration, latent}} = 1.05 + 0.64 = \mathbf{1.69 \text{ kW}}$$

That is, the refrigeration system of this cold storage room must be capable of removing heat at a rate of 1.69 kJ/s to meet the infiltration load. Of course, the total refrigeration capacity of the system will have to be larger to meet the transmission, product, and other loads as well.

17–8 ▪ TRANSPORTATION OF REFRIGERATED FOODS

Perishable food products are transported by *trucks and trailers, railroad cars, ships, airplanes,* or a *combination* of them from production areas to distant markets. Transporting some farm products to a nearby market by a small truck may not require any special handling, but transporting large quantities over long distances usually requires strict climate control by refrigeration and adequate ventilation (Fig.17–48).

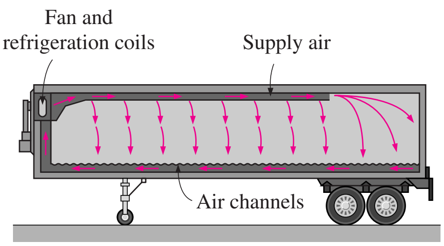


FIGURE 17–48
Airflow patterns in a refrigerated trailer.

Refrigerated *trucks* and *trailers* can be up to 17 m long, 2.6 m wide, and 4.3 m high, and they may have several compartments held at different temperatures. The body of the truck should be lightweight but stiff with good insulating characteristics. Using a *thick* insulation layer on walls reduces the rate *heat gain* into the refrigerated space, but it also reduces the available *cargo space* since the outer dimensions of the trucks and trailers are limited. Urethane foam is commonly used as an insulating material because of its low thermal conductivity ($k = 0.026$ W/m · °C). The *thickness* of polyurethane insulation used is in the range of 7.5 to 10 cm for *freezer trucks* maintained at −18°C or lower, and 2.5 to 6.5 cm for *refrigerated trucks* maintained above freezing temperatures (Fig. 17–49). The outer surface of the truck must be vapor proof to prevent water vapor from entering the insulation and condensing within the insulation.

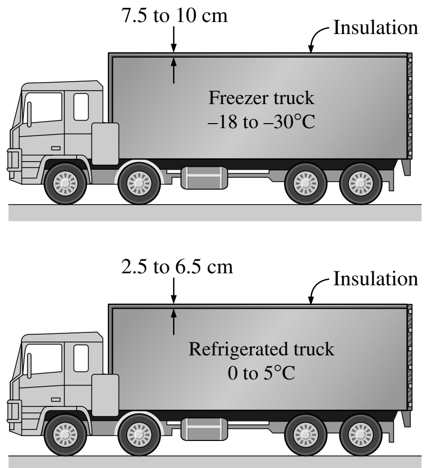


FIGURE 17–49
Proper thickness polyurethane insulation for the walls of refrigerated and freezer trucks.

Air entering inside the refrigerated space of the truck through cracks represents a significant heat gain since the *moisture* in the air will be cooled inside and condensed, releasing its latent heat. The *large temperature difference* between the ambient air and the interior of the refrigerated truck serves as a driving force for air infiltration. Air leakage is also caused by the *ram effect* of air during motion. It can be shown from Bernoulli's equation that a truck moving at a velocity of V will generate a ram air pressure of $\Delta P = \rho V^2/2$ at the front section (ρ is the density of air). This corresponds to a *pressure rise* of about 300 Pa on the surface of the truck at a velocity of 80 km/h. Road tests have shown that air leakage rates for large trailers can reach 12.5 L/s at 80 km/h. Further, the water vapor in the air that condenses inside the refrigerated space may cause *corrosion, damage to insulation, rotting,* and *odors*.

Products with a *large heat capacity* such as milk and orange juice can be transported safely without refrigeration by subcooling them before loading into the truck. For example, orange juice shipped from Florida to New York (a distance of 2300 km) warmed up only 5°C without any refrigeration. *Liquid nitrogen, dry ice,* or *ordinary ice* can also be used for refrigeration in trucks. The cargo space must be maintained at −18°C for most frozen products and −29°C for other deep-frozen products such as ice cream.

The rate of heat gain by properly insulated trailers that are 11 to 16 m long ranges from 40 to 130 W/°C under steady conditions. But on a sunny day the *solar radiation* can increase this number by more than 20 percent. The rate of heat gain can also increase significantly as a result of the product cooling load, air infiltration, and opening of the door during loading and unloading.

The interior of refrigerated trucks should be *precooled* to the desired temperature before loading. The fruits and vegetables should also be cooled to the proper storage temperature before they are loaded into the refrigerated railcars or trucks. This is because the refrigerated cars or trucks do not have the additional refrigeration capacity to cool the products fast enough. Also, the products must be protected from freezing in winter. Refrigerated cars or trucks provide *heating* in cold weather by electric heating or by operating the refrigeration system in reverse as a heat pump. Switching from cooling to heating is done automatically.

The heating and cooling processes in refrigerated cars and trucks are well automated, and all the operator needs to do is set the thermostat at the desired level. The system then provides the necessary refrigeration (or healing in cold weather) to maintain the interior at the set temperature. Thermostats must be calibrated regularly to ensure reliable operation since a deviation of a few degrees from the intended temperature setting may cause the products to be damaged by freezing or excessive decay.

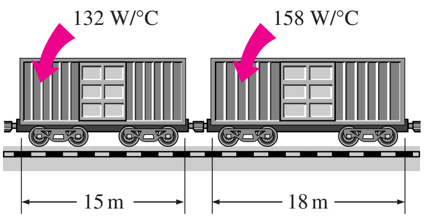


FIGURE 17–50
Typical rates of the heat gain by 15- and 18-m-long refrigerated railcars.

Food products are normally loaded into cars or trucks in *containers* that can be handled by people or forklifts. The containers must allow for heat exchange while protecting the products. The containers must allow for air circulation through channels for uniform and effective cooling and ventilation.

The *railroad industry* also provides refrigerated car service for the transportation of perishable foods. The walls, floors, and ceiling of the cars are constructed with a minimum of 7.5-cm-thick insulation. Typical rates of heat gain are 132 W/°C for 15-m-long cars and 158 W/°C for 18-m-long cars (Fig. 17–50). Other aspects of transportation are similar to the trucks.

Perishable foods are also transported economically from one port to another by *refrigerated ships*. Some ships are designed specifically to transport fruits and vegetables, while others provide refrigerated sections for the transport of foods in various sizes of specially built containers that facilitate faster loading and unloading. Containers used to carry frozen food are insulated with at least 7.5-cm-thick urethane foam insulation. In fishing vessels, ice picked up from the port is commonly used to preserve fish and seafood for days with little or no additional refrigeration. Some fishing vessels cool the seawater to about 2°C and then use it to refrigerate the fish.

Perishable food products are also being transported by *air* in the cargo sections of passenger planes or in specifically designed cargo planes. As you would expect, air transport is more expensive, but the extra cost is justified for commodities that can command a high market price. Also, for some highly perishable products, the only means of transportation is air transportation. *Papaya* and *flowers*, for example, are transported from Hawaii to the mainland almost always by air. Likewise, *flowers* are transported to distant markets mostly by air. *Strawberries* are being transported anywhere in the world again by air at an increasing rate. *Fresh meats, seafood*, and *early season fruits and vegetables* are also commonly shipped by air. Many inland restaurants are able to serve high-quality fresh fish and seafood because of air transport. Air transportation may become economical for many perishable food items at times of short supply and thus higher prices (Fig 17–51).

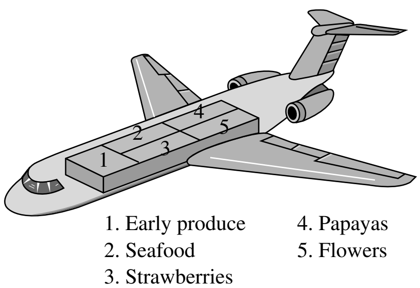


FIGURE 17–51
High-priced food products are commonly transported by air economically.

Air transport is completed in a matter of hours, and it is not practical to equip the airplanes with powerful but heavy refrigeration systems for such short periods. Airplane refrigeration is primarily based on *precooling* prior to loading, and the prevention of *temperature rise* during transit. This is achieved by precooling the products in a refrigerated storage facility; transporting them in refrigerated trucks; storing them in a refrigerated warehouse at the airport, if necessary; and transporting the products in well-insulated containers. Of course, quick loading and unloading are also important to minimize exposure to adverse conditions. Sometimes dry ice is used to provide temporary refrigeration to the container.

Air transport also offers some *challenges* to refrigeration engineers. For example, the outer surface temperature of an airplane cruising at a Mach number of 0.9 increases by about 28°C over the ambient. Also, the relative humidity of the cabin of an airplane cruising at high altitudes is very low, typically under 10 percent. However, the humidity level can still be maintained at about 90 percent without adding any water, thanks to the moisture released during respiration from fruits and vegetables.

EXAMPLE 17–9 Interstate Transport of Refrigerated Milk by Trucks

Milk is to be transported from Texas to California for a distance of 2100 km in a 7-m-long, 2-m-external-diameter cylindrical tank (Fig. 17–52). The walls of the tank are constructed of 5-cm-thick urethane insulation (k = 0.029 W/m · °C) sandwiched between two metal sheets. The milk is precooled to 3°C before loading and its temperature is not to exceed 7°C on arrival. The average ambient temperature can be as high as 30°C, and the effect of solar radiation and the radiation from hot pavement surfaces can be taken to be equivalent to a 4°C rise in ambient temperature. If the average velocity during transportation is 60 km/h, determine if the milk can be transported without any refrigeration.

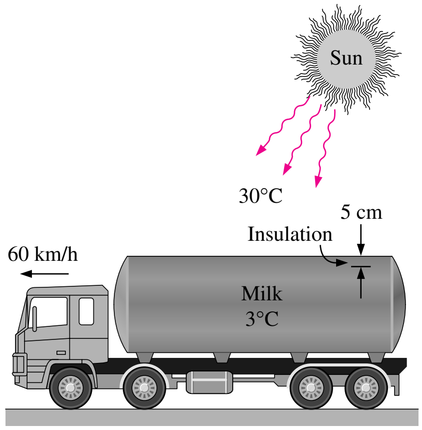


FIGURE 17–52
Schematic for Example 17–9.

SOLUTION Milk is to be transported in a cylindrical tank by a truck. It is to be determined if the milk can be transported without any refrigeration.

Assumptions Thermal properties of milk and insulation are constant.

Properties The thermal conductivity of urethane is given to be k = 0.029 W/m · °C. The density and specific heat of refrigerated milk at temperatures near 0°C are $\rho_{\text{milk}} = \rho_{\text{water}} = 1000$ kg/m^3 and $c_{p,\,\text{milk}} = 3.79$ kJ/kg · °C (Table A–7).

Analysis Problems of this kind that involve "checking" are best solved by performing the calculations under the worst conditions, with the understanding the if the performance is satisfactory under those conditions, it will surely be satisfactory under any conditions.

We take the average ambient temperature to be 30°C, which is the highest possible, and raise it to 34°C to account for the radiation from the sun and the pavement. We also assume the metal sheets to offer no resistance to heat transfer and assume the convection resistances on the inner and outer sides of the tank wall to be negligible. Under these conditions, the inner and outer surface temperatures of the insulation will be equal to the milk and ambient temperatures, respectively. Further, we take the milk temperature to be 3°C during heat transfer calculations (to maximize the temperature difference) and the heat transfer area to be the outer surface area of the tank (instead of the smaller inner surface area), which is determined to be

$$
\begin{aligned}
A &= 2A_{\text{base}} + A_{\text{side}} = 2(\pi D_o^2/4) + (\pi D_o)L_o \\
&= 2\pi(2\,\text{m})^2/4 + \pi(2\,\text{m})(7\,\text{m}) = 50.3\,\text{m}^2
\end{aligned}
$$

Then the rate of heat transfer through the insulation into the milk becomes

$$\dot{Q} = k_{ins} A \frac{\Delta T_{ins}}{L_{ins}} = (0.029 \text{ W/m} \cdot \text{°C})(50.3 \text{ m}^2)\frac{(34 - 3)\text{°C}}{0.05 \text{ m}} = 904.4 \text{ W}$$

This is the highest possible rate of heat transfer into the milk since it is determined under the most favorable conditions for heat transfer.

At an average velocity of 60 km/h, transporting the milk 2100 km will take

$$\Delta t = \frac{\text{Distance traveled}}{\text{Average velocity}} = \frac{2100 \text{ km}}{60 \text{ km/h}} = 35 \text{ h}$$

Then the total amount of heat transfer to the milk during this long trip becomes

$$Q = \dot{Q}\Delta t = (904.4 \text{ kJ/s})(35 \times 3600 \text{ s}) = 113{,}950{,}000 \text{ J} = 113{,}950 \text{ kJ}$$

The volume and mass of the milk in a full tank is determined to be

$$V_{milk} = (\pi D_i^2/4)L_i = [\pi(1.9 \text{ m})^2/4](6.9 \text{ m}) = 19.56 \text{ m}^3$$
$$m_{milk} = \rho V_{milk} = (1000 \text{ kg/m}^3)(19.56 \text{ m}^3) = 19{,}560 \text{ kg}$$

The transfer of 113,950 kJ of heat into the milk will raise its temperature to

$$Q = mc_p(T_2 - T_1) \rightarrow T_2 = T_1 + \frac{Q}{mc_p}$$
$$= 3\text{°C} + \frac{113{,}950 \text{ kJ}}{(19{,}560 \text{ kg})(3.79 \text{ kJ/kg} \cdot \text{°C})} = \mathbf{4.5°C}$$

That is, the temperature of the milk will rise from 3 to 4.5°C during this long trip under the most adverse conditions, which is well below the 7°C limit. Therefore, the milk can be transported even longer distances without any refrigeration.

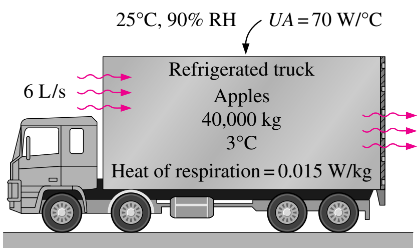


FIGURE 17–53
Schematic for Example 17–10.

EXAMPLE 17–10 Transport of Apples by Refrigerated Trucks

A large truck is to transport 40,000 kg of apples precooled to 3°C under average ambient conditions of 25°C and 90 percent relative humidity (Fig. 17–53). The structure of the walls of the truck is such that the rate of heat transmission is UA = 70 W per °C temperature difference between the ambient and the apples. From past experience, ambient air is estimated to enter the cargo space of the truck through the cracks at a rate of 6 L/s, and the average heat of respiration of the apples at 3°C is 0.015 W/kg for this particular load. Determine the refrigeration load of this truck and the amount of ice needed to meet the entire refrigeration need of the truck for a 20-h-long trip.

SOLUTION A large truck is to transport 40,000 kg of apples. The refrigeration load of the truck and the amount of ice needed to meet this during a 20 h long trip is to be determined.

Assumptions **1** Infiltrating air exits the truck saturated at 3°C. **2** The moisture in the air is condensed out at the exit temperature of 3°C.

Properties The humidity ratio of air is 0.0180 kg water vapor/kg dry air at 25°C and 90 percent relative humidity, and 0.0047 at 3°C and 100 percent relative humidity. The latent heat of vaporization of water at 3°C is 2494 kJ/kg (Table A–9). The density of air at the ambient temperature of 25°C and 1 atm is 1.184 kg/m^3, and its specific heat is c_p = 1.007 kJ/kg · °C (Table A–15). The latent heat of ice is 333.7 kJ/kg.

Analysis The total refrigeration load of the truck is due to the heat gain by transmission, infiltration, and respiration. Noting that *UA* is given to be 70 W/°C, the rate of heat gain by transmission is determined to be

$$\dot{Q}_{\text{transmission}} = UA\Delta T = (70\ \text{W/°C})(25 - 3)\text{°C} = 1540\,\text{W}$$

The rate of heat generation by the apples as a result of respiration is

$$\dot{Q}_{\text{respiration}} = mh_{\text{respiration}} = (40{,}000\,\text{kg})(0.015\,\text{W/kg}) = 600\,\text{W}$$

Ambient air enters the cargo space at a rate of 6 L/s, which corresponds to a mass flow rate of

$$\dot{m}_{\text{air}} = \rho\dot{V}_{\text{air}} = (1.184\ \text{kg/m}^3)(0.006\ \text{m}^3\text{/s}) = 0.00710\ \text{kg/s}$$

Noting that an equal amount of air at 3°C must leave the truck, the sensible heat gain due to infiltration is

$$\begin{aligned}\dot{Q}_{\text{infiltration, sensible}} &= (\dot{m}c_p\Delta T)_{\text{air}} = (0.00710\ \text{kg/s})(1.007\ \text{kJ/kg}\cdot\text{°C})(25 - 3)\text{°C} \\ &= 0.157\,\text{kJ/s} = 157\,\text{W}\end{aligned}$$

Ambient air enters with a humidity ratio of 0.0180 kg H_2O/kg air and leaves at of 0.0047 kg H_2O/kg air. The difference condenses in the truck and is drained out as a liquid, releasing h_{fg} = 2494 kJ/kg of latent heat. Then the latent heat gain of the truck becomes

$$\begin{aligned}\dot{Q}_{\text{infiltration, latent}} &= \dot{m}_{\text{water}}h_{fg} \\ &= (0.0180 - 0.0047)(0.00710\ \text{kg/s})(2494\ \text{kJ/kg}) = 236\ \text{W}\end{aligned}$$

Then the refrigeration load, or the total rate of heat gain by the truck, becomes

$$\begin{aligned}Q_{\text{total}} &= \dot{Q}_{\text{transmission}} + \dot{Q}_{\text{respiration}} + \dot{Q}_{\text{infiltration}} \\ &= 1540 + 600 + (157 + 236) = \mathbf{2533\ W}\end{aligned}$$

The total amount of heat gain during the 20-h-long trip is

$$Q_{\text{total}} = \dot{Q}_{\text{total}}\Delta t = (2533\ \text{J/s})(20 \times 3600\ \text{s}) = 182{,}376{,}000\ \text{J} = 182{,}376\ \text{kJ}$$

Then the amount of ice needed to meet this refrigeration load is determined from

$$m_{\text{ice}} = \frac{Q_{\text{total}}}{h_{\text{latent,ice}}} = \frac{182{,}376\ \text{kJ}}{333.7\ \text{kJ/kg}} = \mathbf{547\ kg}$$

Discussion Note that about half a ton of ice (1.5 percent of the mass of the load) is sufficient in this case to maintain the apples at 3°C.

SUMMARY

Refrigeration and freezing of perishable food products are major application areas of heat transfer and thermodynamics. *Microorganisms* such as bacteria, yeasts, molds, and viruses cause off-flavors and odors, slime production, changes in the texture and appearance, and eventual spoilage of foods. The rate of growth of microorganisms in a food item depends on the characteristics of the food itself as well as the environmental conditions, such as the temperature and relative humidity of the environment and the air motion. Refrigeration slows down the chemical and biological processes in foods and the accompanying deterioration. The storage life of fresh perishable foods such as meats, fish, vegetables and fruits can be extended by several days by storing them at temperatures just above freezing, and by several months by storing them at subfreezing temperatures.

Some fruits and vegetables experience undesirable physiological changes when exposed to low (but still above-freezing) temperatures, usually between 0 and 10°C. The resulting tissue damage is called the *chilling injury*. It differs from *freezing injury,* which is caused by prolonged exposure of the fruits and vegetables to subfreezing temperatures and thus the actual freezing at the affected areas. *Dehydration* or *moisture loss* causes a product to shrivel or wrinkle and lose quality. The loss of moisture from fresh fruits and vegetables is also called *transpiration*. Common freezing methods include *air-blast freezing,* where high-velocity air at about −30°C is blown over the food products; *contact freezing,* where packaged or unpackaged food is placed on or between cold metal plates and cooled by conduction; *immersion freezing,* where the food is immersed in low-temperature brine; and *cryogenic freezing,* where food is placed in a medium cooled by a cryogenic fluid such as liquid nitrogen or solid carbon dioxide.

The thermal properties of foods are dominated by their water content. The *specific heats* of foods can be expressed by **Siebel's formula** as

$$c_{p,\text{fresh}} = 3.35a + 0.84 \quad (\text{kJ/kg}\cdot{}^\circ\text{C})$$
$$c_{p,\text{frozen}} = 1.26a + 0.84 \quad (\text{kJ/kg}\cdot{}^\circ\text{C})$$

where $c_{p,\text{fresh}}$ and $c_{p,\text{frozen}}$ are the specific heats of the food before and after freezing, respectively, and a is the fraction of water content of the food. The *latent heat* of a food product during freezing or thawing (the heat of fusion) also depends on its water content and is determined from

$$h_{\text{latent}} = 334a \quad (\text{kJ/kg})$$

The heat removed from the food products accounts for the majority of the refrigeration load and is determined, from

$$\dot{Q}_{\text{product}} = mc_p(T_{\text{initial}} - T_{\text{final}})/\Delta t \quad (\text{W})$$

where $\dot{Q}_{\text{product}}$ is the *average rate of heat removal* from the fruits and vegetables; m is the total mass; c_p is the average specific heat; T_{initial} and T_{final} are the average temperatures of the products before and after cooling, respectively; and Δt is the cooling time. Fresh fruits and vegetables are live products, and they continue to respire after harvesting. *Heat of respiration* is released during this exothermic reaction. The refrigeration load due to respiration is determined from

$$\dot{Q}_{\text{respiration}} = \sum m_i \dot{q}_{\text{respiration},i} \quad (\text{W})$$

which is the sum of the mass times the heat of respiration for all the food products stored in the refrigerated space.

The primary precooling methods for fruits and vegetables are *hydro-cooling,* where the products are cooled by immersing them into chilled water; *forced-air cooling,* where the products are cooled by forcing refrigerated air through them; *package icing,* where the products are cooled by placing crushed ice into the containers; and *vacuum cooling,* where the products are cooled by vaporizing some of the water content of the products under low pressure conditions. Most produce can be stored satisfactorily at 0°C and 90 to 95 percent relative humidity.

Meat carcasses in slaughterhouses should be cooled as fast as possible to a uniform temperature of about 1.7°C to reduce the growth rate of microorganisms that may be present on carcass surfaces, and thus minimize spoilage. About 70 percent of the beef carcass is water, and the carcass is cooled mostly by *evaporative cooling* as a result of moisture migration toward the surface where evaporation occurs. Most meats are judged on their *tenderness,* and the preservation of tenderness is an important consideration in the refrigeration and freezing of meats. *Poultry products* can be preserved by *ice chilling* to 1 to 2°C or *deep chilling* to about −2°C for short-term storage, or by *freezing* them to −18°C or below for long-term storage. Poultry processing plants are completely automated, and several processes involve strict temperature control. *Fish* is a highly perishable commodity, and the preservation of fish starts on the vessel as soon as it is caught.

Eggs must be refrigerated to preserve quality and to assure a reasonable shelf life. Refrigeration should start at the farm and continue through retail outlets. Shell eggs can be stored at 7 to 13°C and 75 to 80 percent relative humidity for a few weeks. *Milk* is one of the most essential foods for humans, but also one of the most suitable environments for the growth of microorganisms. The stored milk is first *standardized* to bring the milkfat content to desired levels using a milk separator. To kill the bacteria, milk is *pasteurized* in a batch or continuous flow-type system by heating the milk to a minimum temperature of 62.8°C and holding it at that temperature for at least 30 min. The milk is usually *vacuum processed* after pasteurization to reduce the undesirable flavors and odors in it. The milk is also *homogenized* before it is packaged to break up the large fat globules into smaller ones to give it a "homogeneous" appearance. Refrigeration plays an important part in all stages of modern *baker production* from the preservation of raw materials such as flour and yeast to the cooling of baked products.

The *total* rate of heat gain of a refrigerated space through all mechanisms under peak conditions is called the *refrigeration load,* and it consists of (1) *transmission load,* which is heat conducted into the refrigerated space through its walls, floor, and ceiling; (2) *infiltration load,* which is due to surrounding warm air entering the refrigerated space through the cracks and open doors; (3) *product load,* which is the heat removed from the food products as they are cooled to refrigeration temperature; (4) *internal load,* which is heat generated by the lights, electric motors, and people in the refrigerated space; and (5) *refrigeration equipment load*, which is the heat generated by the refrigeration equipment as it performs certain tasks such as reheating and defrosting.

The *rate of heat transfer* through a particular wall, floor, or ceiling section can be determined from

$$\dot{Q}_{\text{transmission}} = UA_o\Delta T \quad \text{(W)}$$

where A_o = the outside surface area of the section, ΔT = the temperature difference between the outside air and the air inside the refrigerated space, and U = the overall heat transfer coefficient. The infiltration load can be determined by estimating the rate of air infiltration in terms of *air changes per hour* (ACH), which is the number of times the entire air content of a room is replaced by the infiltrating air per hour. Then the *mass flow rate* of infiltrating air is determined from

$$\dot{m}_{\text{air}} = \frac{V_{\text{room}}}{v_{\text{room}}}\text{ACH} \quad \text{(kg/h)}$$

where V_{room} is the volume of the room and v_{room} is the specific volume of the dry air in the room. Once $\dot{m}_{\text{air}}$ is available, the sensible and latent infiltration loads of the cold storage room can be determined from

$$\dot{Q}_{\text{infiltration, sensible}} = \dot{m}_{\text{air}}(h_{\text{ambient}} - h_{\text{room}}) \quad \text{(kJ/h)}$$
$$\dot{Q}_{\text{infiltration, latent}} = (\omega_{\text{ambinet}} - \omega_{\text{room}})\dot{m}_{\text{air}}\, h_{fg} \quad \text{(kJ/h)}$$

where ω is the humidity ratio of air (the mass of water vapor in 1 kg dry air), h is the enthalpy of air, and h_{fg} is the heat of vaporization of water. The total infiltration load is then the sum of the sensible and latent components.

Perishable food products are transported by *trucks and trailers, railroad cars, ships, airplanes*, or a *combination* of them from production areas to distant markets. Transporting large quantities over long distances usually requires strict climate control by refrigeration and adequate ventilation, and adequate insulation to keep the heat transfer rates at reasonable levels.

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PROBLEMS*

Control of Microorganisms in Foods

17–1C What are the common kinds of microorganisms? What undesirable changes do microorganisms cause in foods?

17–2C How does refrigeration prevent or delay the spoilage of foods? Why does freezing extend the storage life of foods for months?

17–3C What are the environmental factors that affect the growth rate of microorganisms in foods?

17–4C What is the effect of cooking on the microorganisms in foods? Why is it important that the internal temperature of a roast in an oven be raised above 70°C?

17–5C How can the contamination of foods with microorganisms be prevented or minimized? How can the growth of microorganisms in foods be retarded? How can the microorganisms in foods be destroyed?

17–6C How does (*a*) the air motion and (*b*) the relative humidity of the environment affect the growth of microorganisms in foods?

Refrigeration and Freezing of Foods

17–7C What is the difference between the freezing injury and the chilling injury of fruits and vegetables?

17–8C How does the rate of freezing affect the size of the ice crystals that form during freezing and the quality of the frozen food products?

17–9C What is transpiration? Does lettuce or an apple have a higher coefficient of transpiration? Why?

17–10C What are the mechanisms of heat transfer involved during the cooling of fruits and vegetables by refrigerated air?

17–11C What are the four primary methods of freezing foods?

17–12C What is air-blast freezing? How does it differ from contact freezing of foods?

17–13C What is cryogenic freezing? How does it differ from immersion freezing of foods?

17–14C Which type of freezing is more likely to cause dehydration in foods: air-blast freezing or cryogenic freezing?

17–15 White potatoes ($k = 0.50$ W/m · °C and $\alpha = 0.13 \times 10^{-6}$ m^2/s) that are initially at a uniform temperature of 25°C and have an average diameter of 6 cm are to be cooled by refrigerated air at 2°C flowing at a velocity of 4 m/s. The average heat transfer coefficient between the potatoes and the air is experimentally determined to be 19 W/m^2 · °C. Determine how long it will take for the center temperature of the potatoes to drop to 6°C. Also, determine if any part of the potatoes will experience chilling injury during this process.

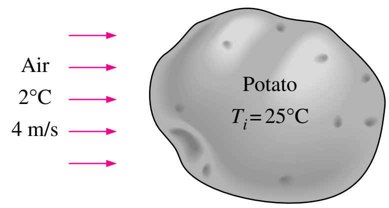

FIGURE P17–15

17–16E Oranges of 2.5-in diameter ($k = 0.26$ Btu/h · ft · °F and $\alpha = 1.4 \times 10^{-6}$ ft^2/s) initially at a uniform temperature of 78°F are to be cooled by refrigerated air at 25°F flowing at a velocity of 1 ft/s. The average heat transfer coefficient between the oranges and the air is experimentally determined to be 4.6 Btu/h · ft^2 · °F. Determine how long it will take for the center temperature of the oranges to drop to 40°F. Also, determine if any part of the oranges will freeze during this process.

17–17 A 65-kg beef carcass ($k = 0.47$ W/m · °C and $\alpha = 0.13 \times 10^{-6}$ m^2/s) initially at a uniform temperature of 37°C is to be cooled by refrigerated air at −6°C flowing at a velocity of 1.8 m/s. The average heat transfer coefficient between the carcass and the air is 22 W/m^2 · °C. Treating the carcass as a cylinder of diameter 24 cm and height 1.4 m and disregarding heat transfer from the base and top surfaces, determine how long it will take for the center temperature of the carcass to drop to 4°C. Also, determine if any part of the carcass will freeze during this process. *Answer:* 14.0 h

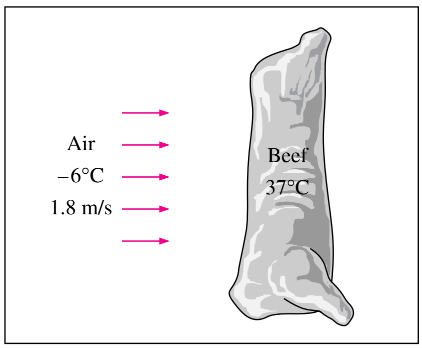

FIGURE P17–17

17–18 Layers of 23-cm-thick meat slabs ($k = 0.47$ W/m · °C and $\alpha = 0.13 \times 10^{-6}$ m^2/s) initially at a uniform temperature of 7°C are to be frozen by refrigerated air at −30°C flowing at a velocity of 1.4 m/s. The average heat transfer coefficient between the meat and the air is 20 W/m^2 · °C. Assuming the size of the meat slabs to be large relative to their thickness, determine low long it will take for the center temperature of the

*Students are encouraged to answer *all* the concept "C" questions.

slabs to drop to $-18°C$. Also, determine the surface temperature of the meat slab at that time.

17–19E Layers of 6-in-thick meat slabs ($k = 0.26$ Btu/h · ft · °F and $\alpha = 1.4 \times 10^{-6}$ ft²/s) initially at a uniform temperature of 50°F are cooled by refrigerated air at 23°F to a temperature of 36°F at their center in 12 h. Estimate the average heat transfer coefficient during this cooling process.
Answer: 1.5 Btu/h · ft² · °F

17–20 Chickens with an average mass of 1.7 kg (k = 0.45 W/m · °C and $\alpha = 0.13 \times 10^{-6}$ m²/s) initially at a uniform temperature of 15°C are to be chilled in agitated brine at $-10°C$. The average heat transfer coefficient between the chicken and the brine is determined experimentally to be 440 W/m² · °C. Taking the average density of the chicken to be 0.95 g/cm³ and treating the chicken as a spherical lump, determine the center and the surface temperatures of the chicken in 2 h and 30 min. Also, determine if any part of the chicken will freeze during this process.

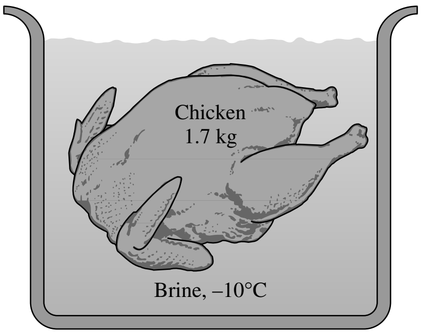

FIGURE P17–20

Thermal Properties of Foods

17–21C Explain how to determine the latent heat of fusion of food products whose water content is known.

17–22C Whose specific heat is greater: apricots with a water content of 70 percent or apples with a water content of 82 percent?

17–23C Do carrots freeze at a fixed temperature or over a range of temperatures? Explain.

17–24C Consider 1 kg of cherries with a water content of 75 percent and 1 kg of roast beef also with a water content of 75 percent, both at 5°C. Now both the cherries and the beef are completely frozen to $-40°C$. The heat removed from the cherries will be (*a*) less than, (*b*) about equal to, or (*c*) greater than the heat removed from the beef.

17–25C Consider 1 kg of carrots with a water content of 65 percent and 1 kg of chicken also with a water content of 65 percent. Now both the carrots and the chicken are cooled from 12°C to 3°C. The heat removed from the carrots will be (*a*) less than, (*b*) about equal to, or (*c*) greater than the heat removed from the chicken.

17–26 A 35-kg box of beef at 6°C having a water content of 60 percent is to be frozen to a temperature of $-20°C$ in 3 h. Using data from Figure 17–13, determine (*a*) the total amount of heat that must be removed from the beef, (*b*) the amount of unfrozen water in beef at $-20°C$, and (*c*) the average rate of heat removal from the beef.

17–27 A 50-kg box of sweet cherries at 8°C having a water content of 77 percent is to be frozen to a temperature of $-20°C$. Using enthalpy data from Table 17–4, determine (*a*) the total amount of heat that must be removed from the cherries and (*b*) the amount of unfrozen water in cherries at $-20°C$.

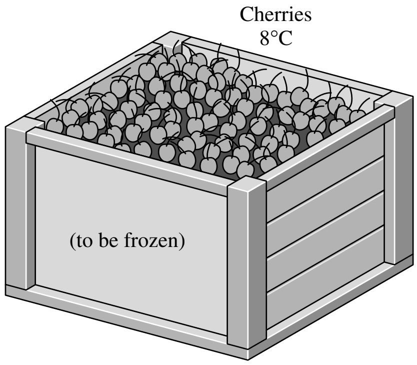

FIGURE P17–27

17–28 A 2-kg box made of polypropylene (c_p = 1.9 kJ/kg · °C) contains 40 kg of cod fish with a water content of 80.3 percent (by mass) at 18°C. The fish is to be frozen to an average temperature of $-18°C$ in 2 h in its box. The enthalpy of the fish is given to be 323 kJ/kg at 0°C and 47 kJ/kg at $-18°C$. It is also given that the unfrozen water content of the fish at $-18°C$ is 12 percent. Taking the average specific heat of the fish above freezing temperatures to be c_p = 3.69 kJ/kg · °C, determine (*a*) the total amount of heat that must be removed from the fish and its container, (*b*) the amount of unfrozen water in fish at $-18°C$, and (*c*) the average rate of heat removal.
Answers: (*a*) 13,830 kJ, (*b*) 4.8 kg, (*c*) 1.92 kW

17–29E A 5-lbm container made of stainless steel (c_p = 0.12 Btu/lbm · °F) contains 90 lbm of applesauce with a water content of 82.8 percent (by mass) at 77°F. The applesauce is to be frozen to an average temperature of 7°F in its container. The enthalpy of the applesauce is given to be 147.5 Btu/lbm at 32°F and 31.4 Btu/lbm at 7°F. It is also given that the unfrozen water

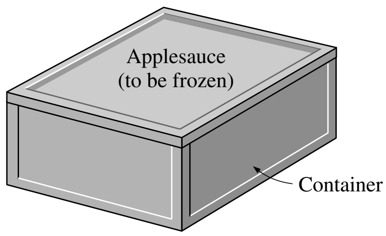

FIGURE P17–29E

content of the applesauce at 7°F is 14 percent. Taking the average specific heat of the applesauce above freezing temperatures to be $c_p = 0.89$ Btu/lbm · °F, determine (*a*) the total amount of heat that must be removed from the applesauce and its container and (*b*) the amount of unfrozen water in applesauce at 7°F.

17–30 Fresh strawberries with a water content of 89.3 percent (by mass) at 26°C are stored in 0.8-kg boxes made of polyethylene ($c_p = 2.3$ kJ/kg · °C). Each box contains 25 kg of strawberries, and the strawberries are to be frozen to an average temperature of −16°C at a rate of 80 boxes per hour. The enthalpy of the strawberries is given to be 367 kJ/kg at 0°C and 54 kJ/kg at −16°C. Taking the average specific heat of the strawberries above freezing temperatures to be $c_p = 3.94$ kJ/kg · °C, determine the rate of heat removal from the strawberries and their boxes. *Answer:* 232.5 kW

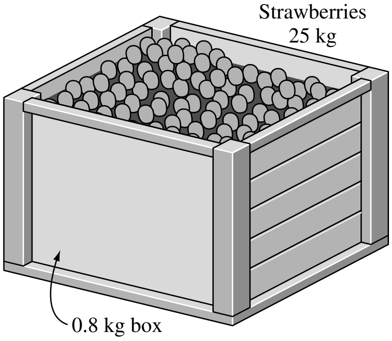

FIGURE P17–30

Refrigeration of Fruits, Vegetables, and Cut Flowers

17–31C What is precooling? Why is it commonly practiced for fruits and vegetables?

17–32C What are the primary cooling methods of fruits and vegetables?

17–33C What is the heat of respiration of fruits and vegetables?

17–34C How does hydrocooling differ from forced-air cooling of fruits and vegetables with respect to (*a*) cooling time and (*b*) moisture loss.

17–35C What is the operating principle of vacuum cooling of fruits and vegetables? How can moisture loss of fruits and vegetables be minimized during vacuum cooling?

17–36C What is modified atmosphere? How does modified atmosphere extend the storage life of some fruits and vegetables?

17–37C Why are apples, cucumbers, and tomatoes not suitable for vacuum cooling?

17–38C Why is it not recommended to store bananas below 13°C while it is highly recommended that apples be stored at −1°C?

17–39 A typical full-carlot-capacity banana room contains 36 pallets of bananas. Each pallet consists of 24 boxes, and thus the room stores 864 boxes of bananas. A box holds an average of 19 kg of bananas and is made of 2.3 kg of fiberboard. The specific heats of banana and the fiberboard are 3.55 kJ/kg · °C and 1.7 kJ/kg · °C, respectively. The peak heat of respiration of bananas is 0.3 W/kg. The bananas are cooled at a rate of 0.4°C/h. The rate of heat gain through the walls and other surfaces of the room is estimated to be 1800 kJ/h. If the temperature rise of refrigerated air is not to exceed 2.0°C as it flows through the room, determine the minimum flow rate of air needed. Take the density and specific heat of air to be 1.2 kg/m^3 and 1.0 kJ/kg · °C, respectively.

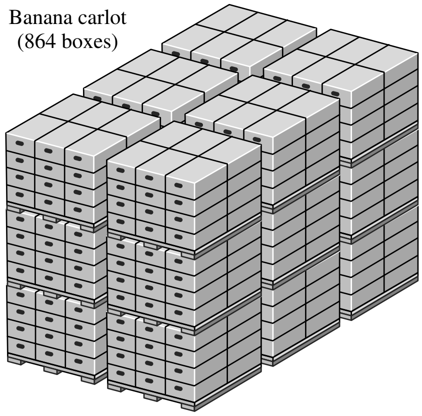

FIGURE P17–39

17–40 It is claimed that fruits and vegetables are cooled by 6°C for each percentage point of weight loss as moisture during vacuum cooling. Using calculations, demonstrate if this claim is reasonable.

17–41 Using Fig. 17–16, determine how long it will take to cool 6-cm-diameter peaches from 30°C to an average temperature of 5°C by chilled water at 2°C. Compare your result with that obtained from transient one-term solutions using a heat transfer coefficient of 550 W/m^2 · °C. Also, determine how many metric tons of peaches can be cooled per day during a 10-h work day by a hydrocooling unit with a refrigeration capacity of 120 tons (1 ton of refrigeration = 211 kJ/min).

17–42 Using Fig. 17–16, determine how long it will take to cool 7-cm-diamameter apples from 28°C to an average temperature of 4°C by chilled water at 1.5°C. Compare your result with that obtained from transient one-term solutions using a heat transfer coefficient of 540 W/m^2 · °C. Also, determine how many metric tons of apples can be cooled per day during a 10-h work day by a hydrocooling unit with a refrigeration capacity of 80 tons (1 ton of refrigeration = 211 kJ/min) *Answers*: 0.39 h, 155.4 ton/day

17–43E Apples ($\rho = 52.4$ lbm/ft^3, $c_p = 0.91$ Btu/lbm · °F, $k = 0.242$ Btu/h · ft · °F, and $\alpha = 1.47 \times 10^{-6}$ ft^2/s) with a diameter of 2.5 in and an initial temperature of 80°F are to be cooled to an average temperature of 38°F with air at 28°F that approaches the cooling section at a velocity of 5 ft/s. The average heat transfer coefficient between the apples and the air is estimated to be 7.8 Btu/h · ft^2 · °F, and it is recommended that air be supplied at a rate of 0.07 ft^3/s per kg of apples. The rectangular cooling section has a capacity of 10,000 lbm of apples with a porosity of 0.38 (i.e., the voids between the apples comprise 38 percent of the total volume). Disregarding the heat of respiration, determine (*a*) the volume of the cooling section where the apples are placed and its dimensions, (*b*) the amount of total heat transfer from a full load of apples to the cooling air, and (*c*) how long it will take for the center temperature of the apples to drop to 40°F.

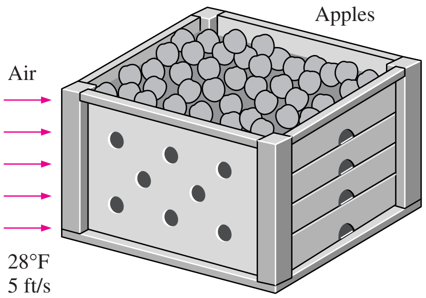

FIGURE P17–43E

17–44 Fresh strawberries with a water content of 88 percent (by mass) at 30°C are stored in 0.8-kg boxes made of nylon (c_p = 1.7 kJ/kg · °C). Each box contains 23 kg of strawberries, and the strawberries are to be cooled to an average temperature of 4°C at a rate of 60 boxes per hour. Taking the average specific heat of the strawberries to be c_p = 3.89 kJ/kg · °C and the average rate of heat of respiration to be 210 mW/kg, determine the rate of heat removal from the strawberries and their boxes, in kJ/h. What would be the percent error involved if the strawberry boxes were ignored in calculations?

17–45 Lettuce is to be vacuum cooled from the environment temperature of 24°C to a temperature of 2°C in 45 min in a 4-m outer diameter insulated spherical vacuum chamber whose walls consist of 3-cm-thick urethane insulation (k = 0.020 W/m · °C) sandwiched between metal plates. The vacuum chamber contains 5000 kg of lettuce when loaded. Disregarding any heat transfer through the walls of the vacuum chamber, determine (*a*) the final pressure in the vacuum chamber and (*b*) the amount of moisture removed from the lettuce. It is claimed that the error involved in (*b*) due to neglecting heat transfer through the wall of the chamber is less than 2 percent. Is this a reasonable claim? *Answers:* (*a*) 0.714 kPa, (*b*) 179 kg

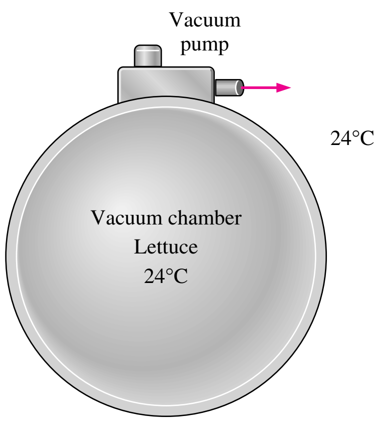

FIGURE P17–45

17–46 Spinach is to be vacuum cooled from the environment temperature of 27°C to a temperature of 3°C in 50 min in a 5-m outer diameter insulated spherical vacuum chamber whose walls consist of 2.5-cm-thick urethane insulation (k = 0.020 W/m · °C) sandwiched between metal sheets. The vacuum chamber contains 6500 kg of spinach when loaded. Disregarding any heat transfer through the walls of the vacuum chamber, determine (*a*) the final pressure in the vacuum chamber and (*b*) the amount of moisture removed from the spinach in kg. It is claimed that the error involved in (*b*) due to neglecting heat transfer through the wall of the chamber is less than 2 percent. Is this a reasonable claim?

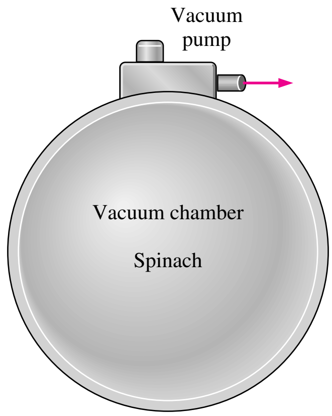

FIGURE P17–46

Refrigeration of Meats, Poultry, and Fish

17–47C Why does a beef carcass lose up to 2 percent of its weight as it is cooled in the chilling room? How can this weight loss be minimized?

17–48C The cooling of a beef carcass from 37°C to 5°C with refrigerated air at 0°C in a chilling room takes about 48 h. To reduce the cooling time, it is proposed to cool the carcass with refrigerated air at −10°C. How would you evaluate this proposal?

17–49C Consider the freezing of packaged meat in boxes with refrigerated air. How do (*a*) the temperature of air, (*b*) the velocity of air, (*c*) the capacity of the refrigeration system, and (*d*) the size of the meat boxes affect the freezing time?

17–50C How does the rate of freezing affect the tenderness, color, and the drip of meat during thawing?

17–51C It is claimed that beef can be stored for up to two years at −23°C but no more than one year at −12°C. Is this claim reasonable? Explain.

17–52C What is a refrigerated shipping dock? How does it reduce the refrigeration load of the cold storage rooms?

17–53C How does immersion chilling of poultry compare to forced-air chilling with respect to (*a*) cooling time, (*b*) moisture loss of poultry, and (*c*) microbial growth.

17–54C What is the proper storage temperature of frozen poultry? What are the primary methods of freezing for poultry?

17–55C What are the factors that affect the quality of frozen fish?

17–56 The chilling room of a meat plant is 15 m × 18 m × 5.5 m in size and has a capacity of 350 beef carcasses. The power consumed by the fans and the lights in the chilling room are 22 and 2 kW, respectively, and the room gains heat through its envelope at a rate of 14 kW. The average mass of beef carcasses is 220 kg. The carcasses enter the chilling room at 35°C, after they are washed to facilitate evaporative cooling, and are cooled to 16°C in 12 h. The air enters the chilling room at −2.2°C and leaves at 0.5°C. Determine (*a*) the refrigeration load of the chilling room and (*b*) the volume flow rate of air. The average specific heats of beef carcasses and air are 3.14 and 1.0 kJ/kg · °C, respectively, and the density of air can be taken to be 1.28 kg/m^3.

17–57 Turkeys with a water content of 64 percent that are initially at 1°C and have a mass of about 7 kg are to be frozen by submerging them into brine at −29°C. Using Figure 17–31, determine how long it will take to reduce the temperature of the turkey breast at a depth of 3.8 cm to −18°C. If the temperature at a depth of 3.8 cm in the breast represents the average temperature of the turkey, determine the amount of heat transfer per turkey assuming (*a*) the entire-water content of the turkey is frozen and (*b*) only 90 percent of the water content of the turkey is frozen at −18°C. Take the specific heats of turkey to be 2.98 and 1.65 kJ/kg · °C above and below the freezing point of −2.8°C, respectively, and the. latent heat of fusion of turkey to be 214 kJ/kg. *Answers*: (*a*) 1753 kJ, (*b*) 1617 kJ

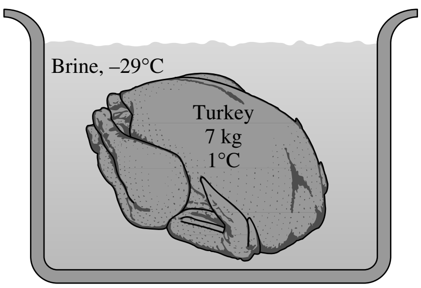

FIGURE P17–57

17–58E Chickens with a water content of 74 percent, an initial temperature of 32°F, and a mass of about 7.5 lbm are to be frozen by refrigerated air at −40°F. Using Fig. 17–30, determine how long it will take to reduce the inner surface temperature of chickens to 25°F. What would your answer be if the air temperature were −80°F?

17–59 Chickens with an average mass of 2.2 kg and average specific heat of 3.54 kJ/kg · °C are to be cooled by chilled water that enters a continuous flow-type immersion chiller at 0.5°C. Chickens are dropped into the chiller at a uniform temperature of 15°C at a rate of 500 chickens per hour and are cooled to an average temperature of 3°C before they are taken out. The chiller gains heat from the surroundings at a rate of 210 kJ/min. Determine (*a*) the rate of heat removal from the chicken, in kW, and (*b*) the mass flow rate of water, in kg/s, if the temperature rise of water is not to exceed 2°C.

17–60 In a meat processing plant, 10-cm-thick beef slabs (ρ = 1090 kg/m^3, c_p = 3.54 kJ/kg · °C, k = 0.47 W/m · °C, and α = 0.13 × 10^{-6} m^2/s) initially at 15°C are to be cooled in the racks of a large freezer that is maintained at −12°C. The meat slabs are placed close to each other so that heat transfer from the 10-cm-thick edges is negligible. The entire slab is to be cooled below 5°C, but the temperature of the steak is not to drop below −1°C anywhere during refrigeration to avoid "frost bite." The convection heat transfer coefficient and thus the rate of heat transfer from the steak can be controlled by varying the speed of a circulating fan inside. Using the transient temperature charts, determine the heat transfer coefficient h that will enable us to meet both temperature constraints while keeping the refrigeration time to a minimum. *Answer:* 9.9 W/m^2 · °C

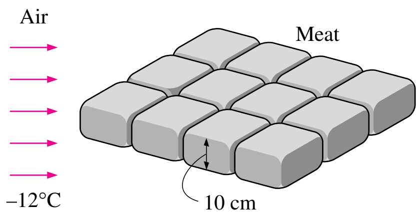

FIGURE 17–60

Refrigeration of Eggs, Milk, and Bakery Products

17–61C Why does a fresh egg settle at the bottom of a cup full of water while an old egg rises to the top?

17–62C What is standardization of milk? How is milk standardized?

17–63C Why and how is milk pasteurized? How can the pasteurization time be minimized? How does a regenerator reduce the energy cost of pasteurization?

17–64C What is the homogenization of milk? How is the milk homogenized?

17–65C Why is yeast usually stored between 1 and 7°C? Why is the range of optimum dough temperature from 27 to 38°C?

17–66C What is heat of hydration? How can the temperature rise of dough due to the heat of hydration be prevented during kneading?

17–67 In a dairy plant, milk at 4°C is pasteurized continuously at 72°C at a rate of 12 L/s for 24 hours a day and 365 days a year. The milk is heated to the pasteurizing temperature by hot water heated in a natural gas-fired boiler that has an efficiency of 82 percent. The pasteurized milk is then cooled by cold water at 18°C before it is finally refrigerated back to 4°C. To save energy and money, the plant installs a regenerator that has an effectiveness of 82 percent. If the cost of natural gas is \$1.05/therm (1 therm = 105,500 kJ), determine how much fuel and money the regenerator will save this company per year.

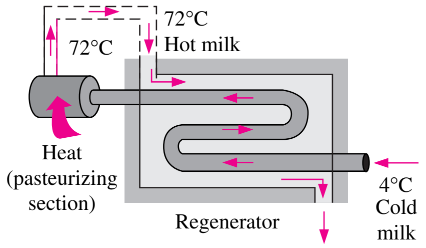

FIGURE P17–67

17–68 A 1.5-kg box made of polypropylene (c_p = 1.9 kJ/kg · °C) contains 30 loaves of white bread, each 0.45 kg, with a water content of 37.3 percent (by mass) at 20°C. The breads are to be frozen to an average temperature of −12°C in 3 h in their box by refrigerated air. The enthalpy of bread is given to be 137 kJ/kg at 0°C and 56 kJ/kg at −12°C. Taking the average specific heat of the bread above 0°C to be c_p = 2.60 kJ/kg · °C, determine (*a*) the total amount of heat that must be removed from a box of breads and (*b*) the average rate of heat removal from the breads and their box to the air per box.

17–69 Eggs (ρ = 1.08 g/cm^3, k = 0.56 W/m · °C, c_p = 3.34 kJ/kg · °C, and $\alpha = 0.14 \times 10^{-6}$ m^2/s) with an average mass of 70 g and initially at a uniform temperature of 32°C are to be cooled by refrigerated air at 2°C flowing at a velocity of 3 m/s with an average heat transfer coefficient between the eggs and the air of 45 W/m^2 · °C. Determine how long it will take for the center temperature of the eggs to drop to 12°C. Also, determine the temperature difference between the center and the surface of the eggs and.the amount of heat transfer per egg.
Answers: 26.7 min, 5.6°C, 5.50 kJ

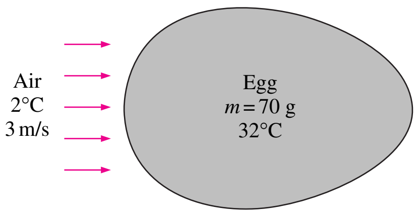

FIGURE P17–69

17–70E A refrigeration system is being designed to cool eggs (ρ = 67.4 lbm/ft^3, k = 0.32 Btu/h · ft · °F, c_p = 0.80 Btu/lbm · °F, and $\alpha = 1.5 \times 10^{-6}$ ft^2/s) with an average mass of 0.14 lbm from an initial temperature of 90°F to a final average temperature of 50°F by air at 34°F at a rate of 10,000 eggs per hour. Determine (*a*) the rate of heat removal from the eggs, in Btu/h, (*b*) the required volume flow rate of air, in ft^3/h, if the temperature rise of air is not to exceed 10°F, and (*c*) the size of the compressor of the refrigeration system, in kW, for a COP of 3.5 for the refrigeration system.

17–71 The heat of hydration of dough, 15 kJ/kg, will raise the dough's temperature to undesirable levels unless some cooling mechanism is utilized. A practical way of absorbing the heat of hydration is to use refrigerated water when kneading the dough. If a recipe calls for mixing 2 kg of flour with 1 kg of water, and the temperature of the city water is 15°C, determine the temperature to which the city water must be cooled before mixing it with flour in order for the water to absorb the entire heat of absorption when the water temperature rises to 15°C. Take the specific heats of the flour and the water to be 1.76 and 4.18 kJ/kg · °C, respectively. *Answer:* 4.2°C

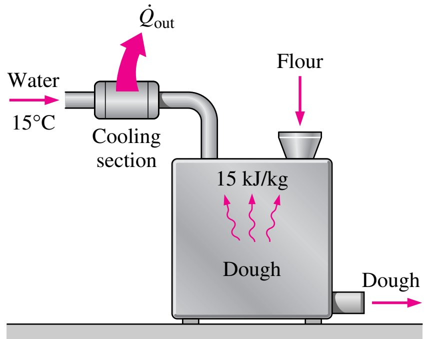

FIGURE P17–71

Refrigeration Load of Cold Storage Rooms

17–72C What does the refrigeration load of a cold storage room represent? What does the refrigeration load consist of?

17–73C Define the transmission load of a cold storage room, and explain how it is determined. Discuss how the transmission load can be minimized.

17–74C What is infiltration heat gain for cold storage rooms? How can it be minimized?

17–75C Define the product load of a frozen food storage room, and explain how it is determined.

17–76C Define the internal load of a refrigeration room. Name the factors that constitute the internal load.

17–77C Consider the motors that power the fans of a refrigerated room. How does locating the motors inside the refrigeration room or outside of it affect the refrigeration load of the room?

17–78 A supply of 40 kg of shrimp at 8°C contained in a box is to be frozen to −18°C in a freezer. Determine the amount of heat that needs to be removed. The latent heat of the shrimp is 277 kJ/kg, and its specific heat is 3.62 kJ/kg · °C above freezing and 1.89 kJ/kg · °C below freezing. The container box is 1.2 kg and is made up of polyethylene, whose specific heat is 2.3 kJ/kg · °C. Also, the freezing temperature of shrimp is −2.2°C.

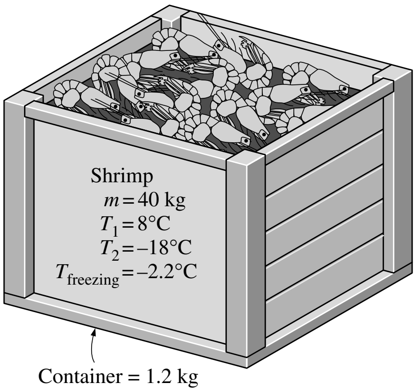

FIGURE P17–78

17–79E A cold storage room whose internal dimensions are 12 ft × 15 ft × 30 ft is maintained at 35°F and 95 percent relative humidity. Under worst conditions, the amount of air infiltration is estimated to be 0.4 air change per hour at the ambient conditions of 90°F and 90 percent relative humidity. Using the psychrometric chart, determine the total infiltration load of this room under these conditions. *Answer:* 92,940 Btu/h

17–80 A holding freezer whose outer dimensions are 80 m × 25 m × 7 m is maintained at −25°C at a location where the annual mean ambient temperature is 15°C. The construction of the walls is such that it has an *R*-value of 3 m² · °C/W (equivalent to *R*-17 in English units of h · ft² · °F/Btu), which is well below the recommended value of *R*-6.5. The refrigeration system has a COP of 1.3, and the cost of electricity is $0.10/kWh. Taking the heat transfer coefficients on the inner and outer surfaces of the walls to be 10 and 20 W/m² · °C, respectively, determine the amount of electrical energy and money this facility will save per year by increasing the insulation value of the walls to the recommended level of *R*-6.5. Assume continuous operation for the entire year. What is the percent error involved in the total thermal resistance of the wall in neglecting the convection resistances on both sides?

17–81 A chilling room whose outer dimensions are 60 m × 30 m × 6 m is maintained at −2°C at a location where the annual mean ambient temperature is 18°C. The construction of the roof of the room is such that it has an *R*-value of 2 m² · °C/W (equivalent to *R*-11.4 in English units of h · ft² · °F/Btu), which is well below the recommended value of *R*-7. The refrigeration system has a COP of 2.4, and the cost of electricity is $0.09/kWh. Taking the heat transfer coefficients on the inner and outer surfaces of the walls to be 10 and 25 W/m² · °C, respectively, determine the amount of electrical energy and money this facility will save per year by increasing the insulation value of the walls to the recommended level of *R*-7. *Answers*: 42,997 kWh/yr, $3870/yr

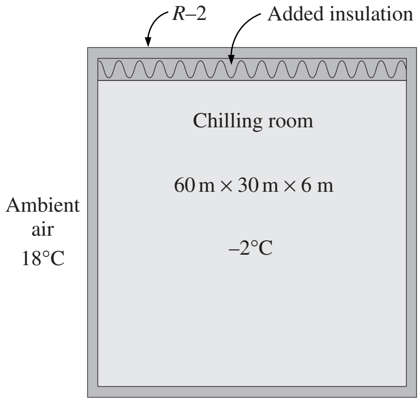

FIGURE P17–81

17–82 A cold storage room whose inner dimensions are 50 m × 30 m × 7 m is maintained at 6°C. At any given time, 15 people are working in the room, and lighting for the facility is provided by 150 light bulbs, each consuming 100 W. There are also several electric motors in the facility that consume a total of 25 kW of electricity. It is estimated that the ambient air that enters the room through the cracks and openings is equivalent to 0.2 air change per hour. Taking the ambient air temperature to be 20°C and disregarding any condensation of moisture, determine (*a*) the internal load of this cold storage room and (*b*) the infiltration load, both in kW.

In order to save energy, it is proposed that the incandescent lights be replaced by 40 high-efficiency fluorescent tubes, each consuming 110 W. If the lights are on for an average of 15 h a day, every day, determine the amount of electrical energy and money this facility will save per year as a result of switching to fluorescent lighting. Assume the refrigeration system has a COP of 2.8, and the cost of electricity is $0.09/kWh.

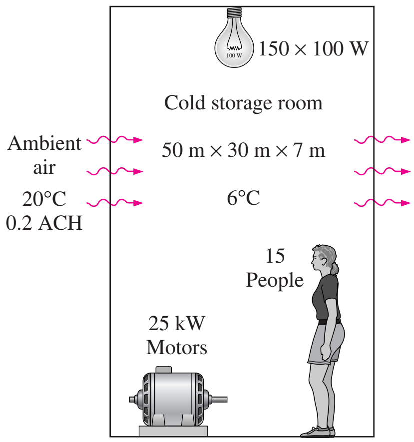

FIGURE P17–82

Transportation of Refrigerated Foods

17–83C Why are the refrigerated trucks insulated? What are the advantages and disadvantages of having a very thick layer of insulation in the walls of a refrigerated truck?

17–84C Under what conditions is it worthwhile to transport food items by airplanes?

17–85C Why are the trucks precooled before they are loaded? Also, do refrigerated trucks need to be equipped with heating systems? Why? Explain.

17–86C A truck driver claims to have transported orange juice from Florida to New York in warm weather without any refrigeration, and that the temperature of the orange juice rose by only 4°C during this long trip. Is this claim reasonable?

17–87E Orange juice (ρ = 62.4 lbm/ft^3 and c_p = 0.90 Btu/lbm · °F) is to be transported from Florida to New York for a distance of 1250 miles in a 27-ft-long, 6.3-ft-external-diameter cylindrical tank. The walls of the tank are constructed of l-in-thick urethane insulation (k = 0.017 Btu/h · ft · °F) sandwiched between two metal sheets. The juice is precooled to 35°F before loading, and its temperature is not to exceed 46°F on arrival. The average ambient temperature can be as high as 92°F, and the effect of solar radiation and the radiation from hot pavement surfaces can be taken to be equivalent to a 12°F rise in ambient temperature. If the average velocity during transportation is 35 mph, determine if the orange juice can be transported without any refrigeration.

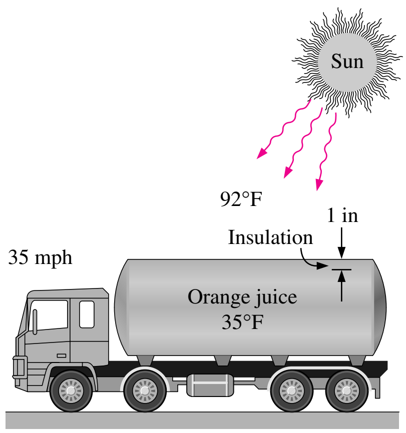

FIGURE P17–87E

17–88 A large truck is to transport 30,000 kg of oranges precooled to 4°C under average ambient conditions of 27°C and 90 percent relative humidity, which corresponds to a humidity ratio of 0.0205 kg water vapor/kg dry air. The structure of the walls of the truck is such that the rate of heat transmission is UA = 80 W per °C temperature difference between the ambient and the oranges. From past experience, ambient air is estimated to enter the cargo space of the truck through the cracks at a rate of 4 L/s. The moisture in the air is condensed out at an average temperature of 15°C, at which the latent heat of vaporization of water is 2466 kJ/kg. Also, the average heat of respiration of the oranges at 4°C is 0.017 W/kg for this particular load. Taking the density of air to be 1.15 kg/m^3, determine the refrigeration load of this truck and the amount of ice needed to meet the entire refrigeration need of the truck for a 15-h-long trip.

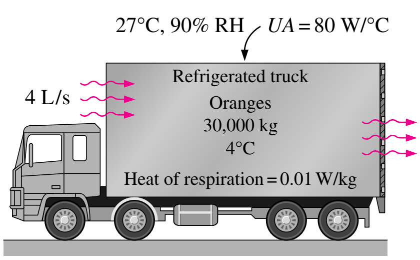

FIGURE P17–88

17–89 Consider a large freezer truck whose outer dimensions are 14 m × 2.5 m × 4 m that is maintained at −18°C at a location where the ambient temperature is 25°C. The walls of the truck are constructed of 2.5-cm-thick urethane insulation (k = 0.026 W/m · °C) sandwiched between thin metal plates. The recommended minimum thickness of insulation in this case is 8 cm. Taking the heat transfer coefficients on the inner and outer surfaces of the walls to be 8 and 4 W/m^2 · °C, respectively, determine the reduction in the transmission part of the refrigeration load if the insulation thickness is upgraded to the recommended value. Also, taking the gross density of the load to be 600 kg/m^3, determine the reduction in the cargo load of the truck, in kg, as a result of increasing the thickness of insulation while holding the outer dimensions constant.

17–90 The cargo space of a refrigerated truck whose inner dimensions are 12 m × 2.3 m × 3.5 m is to be precooled from 25°C to an average temperature of 5°C. The construction of the truck is such that a transmission heat gain occurs at a rate of 80 W/°C. If the ambient temperature is 25°C, determine how long it will take for a system with a refrigeration capacity of 8 kW to precool this truck. Take the density of air to be 1.20 kg/m^3. *Answer: 5.4 min*

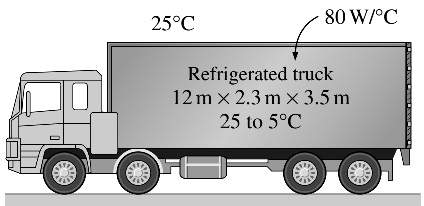

FIGURE P17–90

Review Problems

17–91 Wet broccoli is to be vacuum cooled from the environment temperature of 25°C to a temperature of 4°C in 1 h in a 4-m outer diameter insulated spherical vacuum chamber whose walls consist of 3-cm-thick fiberglass insulation (k = 0.026 W/m · °C) sandwiched between metal plates. The vacuum chamber contains 6000 kg of broccoli when loaded, but 2 percent of this mass is due to water that sticks to the surface of the broccoli during wetting. Disregarding any heat transfer through the walls of the vacuum chamber, determine the final mass of the broccoli after cooling. It is claimed that the error involved in the predicted final mass of broccoli due to neglecting heat transfer through the wall of the chamber is less than 5 percent. Is this a reasonable claim?

Answer: 5801 kg

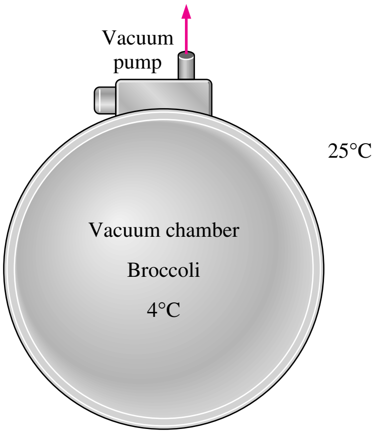

FIGURE P17–91

17–92 Red Delicious apples of 65-mm diameter and 85 percent water content ($k = 0.42$ W/m · °C and $\alpha = 0.14 \times 10^{-6}$ m²/s) initially at a uniform temper ature of 22°C are to be cooled by (*a*) refrigerated air at 1°C flowing at a velocity of 1.5 m/s with an average heat transfer coefficient of 45 W/m² · °C between the apples and the air and (*b*) chilled water at 1°C flowing at a velocity of 0.3 m/s with an average heat transfer coefficient of 80 W/m² · °C between the apples and the water. Determine how long it will take for the center temperature of the apples to drop to 8°C and the temperature difference between the center and the surface of the apples for each case.

17–93E A 3.5-lbm box made of polypropylene (c_p = 0.45 Btu/lbm · °F) contains 70 lbm of haddock fish with a water content of 83.6 percent (by mass) at 60°F. The fish is to be frozen to an average temperature of −4°F in 4 h in its box. The enthalpy of the fish is given to be 145 Btu/lbm at 32°F and 18 Btu/lbm at −4°F. It is also given that the unfrozen water content of the fish at −4°F is 9 percent. Taking the average specific heat of the fish above freezing temperatures to be c_p = 0.89 Btu/lbm · °F, determine (*a*) the total amount of heat that must be removed from the fish, (*b*) the amount of unfrozen water in fish at −4°F, and (*c*) the average rate of heat removal from the fish.

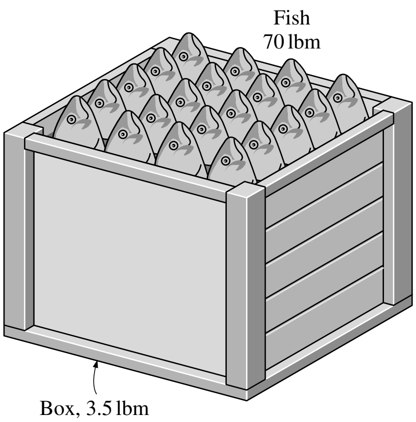

FIGURE P17–93E

17–94 Fresh carrots with a water content of 87.5 percent (by mass) at 22°C are stored in 1.4-kg boxes made of polyethylene (c_p = 2.3 kJ/kg · °C). Each box contains 30 kg of carrots, and the carrots are to be frozen to an average temperature of −18°C at a rate of 50 boxes per hour. The enthalpy of the carrots is given to be 361 kJ/kg at 0°C and 51 kJ/kg at −18°C. It is also given that the unfrozen water content of the carrots at −18°C is 7 percent. Taking the average specific heat of the carrots above freezing temperatures to be c_p = 3.90 kJ/kg · °C, determine (*a*) the rate of heat removal from the carrots and their boxes, and (*b*) the rate at which the water in carrots freezes during this process. *Answers:* (*a*) 166.7 kW, (*b*) 0.336 kg/s

17–95 The chilling room of a meat plant is 15 m × 18 m × 5.5 m in size and has a capacity of 350 beef carcasses. The power consumed by the fans and the lights of the chilling room are 22 and 2 kW, respectively, and the room gains heat through its envelope at a rate of 11 kW. The average mass of beef carcasses is 280 kg. The carcasses enter the chilling room at 35°C, after they are washed to facilitate evaporative cooling, and are cooled to 16°C in 10 h. The water is expected to evaporate at a rate of 0.080 kg/s. The air enters the evaporator section of the refrigeration system at 0.5°C and leaves at −2.2°C. The air side of the evaporator is heavily finned, and the overall heat transfer coefficient of the evaporator based on the air side is 22 W/m² · °C. Also, the average temperature difference between the air and the refrigerant in the evaporator is 5.5°C. Determine (*a*) the refrigeration load of the chilling room, (*b*) the volume flow rate of air, and (*c*) the heat transfer surface area of the evaporator on the air side, assuming all the vapor and the fog in the air freeze

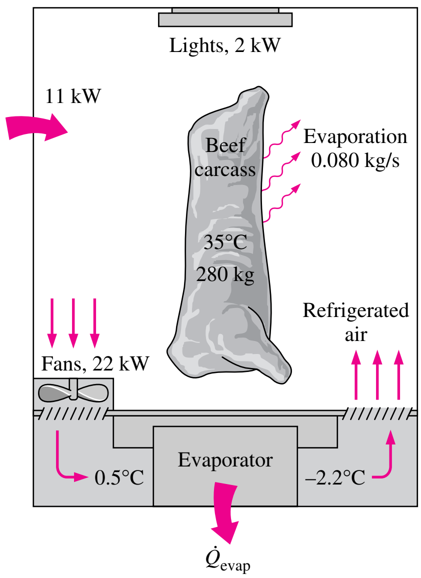

FIGURE P17–95

in the evaporator. The average specific heats of beef carcasses and air are 3.14 and 1.0 kJ/kg · °C, respectively. Also, the heat of fusion of water is 334 kJ/kg and the heat of vaporization of water and the density of air can be taken to be 2490 kJ/kg and 1.28 kg/m^3, respectively.

17–96 Turkeys with an average mass of 7.5 kg and average specific heat of 3.28 kJ/kg · °C are to be cooled by chilled water that enters a continuous flow-type immersion chiller at 0.6°C. Turkeys are dropped into the chiller at a uniform temperature of 14°C at a rate of 200 turkeys per hour and are cooled to an average temperature of 4°C before they are taken out. The chiller gains heat from the surroundings at a rate of 120 kJ/h. Determine (*a*) the rate of heat removal from the turkeys, in kW, and (*b*) the mass flow rate of water, in kg/s, if the temperature rise of water is not to exceed 2.5°C.

17–97E In a chicken processing plant, whole chickens (ρ = 65.5 lbm/ft^3, c_p = 0.85 Btu/lbm · °F, k = 0.27 Btu/h · ft · °F, and $\alpha = 1.4 \times 10^{-6}$ ft^2/s) averaging five pounds each and initially at 60°F are to be cooled in the racks of a large refrigerator that is maintained at 5°F. The entire chicken is to be cooled below 40°F, but the temperature of the chicken is not to drop below 33°F anywhere during refrigeration. The convection heat transfer coefficient and thus the rate of heat transfer from the chicken can be controlled by varying the speed of a circulating fan inside. Treating the chicken as a homogeneous spherical object, determine the heat transfer coefficient that will enable us to meet both temperature constraints while keeping the refrigeration time to a minimum.

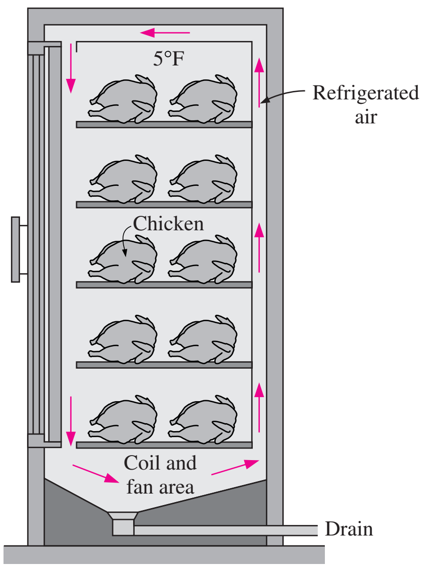

FIGURE P17–97E

17–98 A person puts a few peaches (ρ = 960 kg/m^3, c_p = 3.9 kJ/kg · °C, k = 0.53 W/m · °C, and $\alpha = 0.14 \times 10^{-6}$ m^2/s) into the freezer at −18°C to cool them quickly for the guests who are about to arrive. Initially, the peaches are at a uniform temperature of 20°C, and the heat transfer coefficient on the surfaces is 18 W/m^2 · °C. Treating the peaches as 8-cm-diameter spheres, determine the center and surface temperatures of the peaches in 45 minutes. Also, determine the amount of heat transfer from each peach.
Answers: 7.2°C, −3.7°C, 19.7 kJ

17–99 A refrigeration system is to cool bread loaves with an average mass of 450 g from 22°C to −10°C at a rate of 500 loaves per hour by refrigerated air at −30°C and 1 atm. Taking the average specific and latent heats of bread to be 2.93 kJ/kg · °C and 109.3 kJ/kg, respectively, determine (*a*) the rate of heat removal from the breads, in kJ/h, (*b*) the required volume flow rate of air, in m^3/h, if the temperature rise of air is not to exceed 8°C, and (*c*) the size of the compressor of the refrigeration system, in kW, for a COP of 1.2 for the refrigeration system.

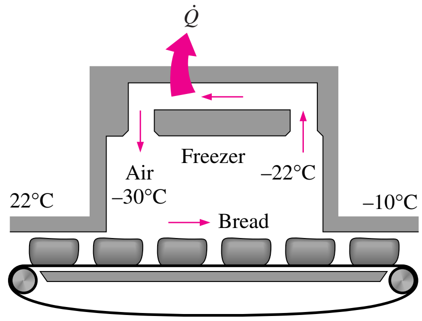

FIGURE P17–99

17–100 A holding freezer whose outer dimensions are 70 m × 22 m × 6 m is maintained at −23°C at a location where the annual mean ambient temperature is 14°C. The construction of the roof is such that it has an *R*-value of 4 m^2 · °C/W (equivalent to *R*-23 in English units of h · ft^2 · °F/Btu), which is well below the recommended value of *R*-8.5. The refrigeration system has a COP of 1.25, and the cost of electricity is \$0.07/kWh. Taking the heat transfer coefficients on the inner and outer surfaces of the walls to be 12 and 30 W/m^2 · °C, respectively, determine the amount of electrical energy and money this facility will save per year by increasing the insulation value of the walls to the recommended level of *R*-8.5. What is the percent error involved in the total thermal resistance of the roof in neglecting the convection resistances on both sides? *Answers:* 50,650 kWh/yr, \$3546/yr, 2.9 percent

17–101 Milk is to be transported from Wyoming to Chicago for a distance of 1600 km in an 8-m-long, 2.2-m-external-diameter cylindrical tank. The walls of the tank are constructed of 3-cm-thick urethane insulation (k = 0.029 W/m · °C) sandwiched between two metal sheets. The milk is precooled to 2°C before loading, and its temperature is not to exceed 5°C on arrival. The average ambient temperature can be as high as 32°C, and the effect of solar radiation and the radiation from hot pavement surfaces can be taken to be equivalent to a 5°C rise in ambient temperature. If the average velocity during transportation is 60 km/h, determine if the milk can be transported without any refrigeration.

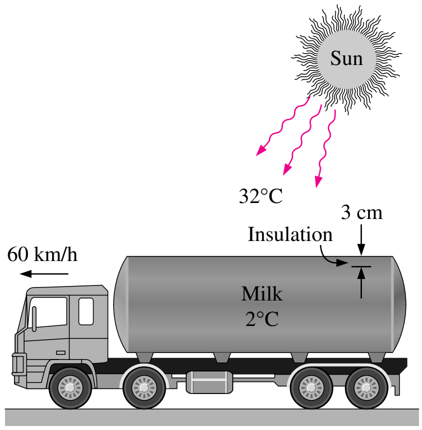

FIGURE P17–101

Computer, Design, and Essay Problems

17–102 Write an essay on the operating principle of thermoelectric refrigerators, and discuss their advantages and disadvantages.

17–103 Using a thermometer, measure the temperature of the main food compartment of your refrigerator, and check if it is between 1 and 4°C. Also, measure the temperature of the freezer compartment, and check if it is at the recommended value of −18°C.

17–104 Using a timer (or watch) and a thermometer, conduct the following experiment to determine the predictable heat load of your refrigerator. First, make sure that the door of the refrigerator is not opened for at least a few hours to make sure that steady operating conditions are established. Start the timer when the refrigerator stops running and measure the time Δt_1 it stays off before it kicks in. Then measure the time Δt_2 it stays on. Noting that the heat removed during Δt_2 is equal to the heat gain of the refrigerator during $\Delta t_1 + \Delta t_2$ and using the power consumed by the refrigerator when it is running, determine the average rate of heat gain for your refrigerator, in W. Take the COP (coefficient of performance) of your refrigerator to be 1.3 if it is not available.

Now, clean the condenser coils of the refrigerator and remove any obstacles on the way of airflow through the coils. By repeating the measurements above, determine the improvement in the COP of the refrigerator.

17–105 Design a hydrocooling unit that can cool fruits and vegetables from 30°C to 5°C at a rate of 20,000 kg/h under the following conditions:

The unit will be of flood type that will cool the products as they are conveyed into the channel filled with water. The products will be dropped into the channel filled with water at one end and picked up at the other end. The channel can be as wide as 3 m and as high as 90 cm. The water is to be circulated and cooled by the evaporator section of a refrigeration system. The refrigerant temperature inside the coils is to be −2°C, and the water temperature is not to drop below 1°C and not to exceed 6°C.

Assuming reasonable values for the average product density, specific heat, and porosity (the fraction of air volume in a box), recommend reasonable values for the quantities related to the thermal aspects of the hydro-cooler, including (*a*) how long the fruits and vegetables need to remain in the channel, (*b*) the length of the channel, (*c*) the water velocity through the channel, (*d*) the velocity of the conveyor and thus the fruits and vegetables through the channel, (*e*) the refrigeration capacity of the refrigeration system, and (*f*) the type of heat exchanger for the evaporator and the surface area on the water side.

17–106 Design a scalding unit for slaughtered chicken to loosen their feathers before they are routed to feather-picking machines with a capacity of 1200 chickens per hour under the following conditions:

The unit will be of immersion type filled with hot water at an average temperature of 53°C at all times. Chicken with an average mass of 2.2 kg and an average temperature of 36°C will be dipped into the tank, held in the water for 1.5 min, and taken out by a slow-moving conveyor. The chicken is expected to leave the tank 15 percent heavier as a result of the water that sticks to its surface. The center-to-center distance between chickens in any direction will be at least 30 cm. The tank can be as wide as 3 m and as high as 60 cm. The water is to be circulated through and heated by a natural gas furnace, but the temperature rise of water will not exceed 5°C as it passes through the furnace. The water loss is to be made up by the city water at an average temperature of 16°C. The ambient air temperature can be taken to be 20°C. The walls and the floor of the tank are to be insulated with a 2.5-cm-thick urethane layer. The unit operates 24 h a day and 6 days a week.

Assuming reasonable values for the average properties, recommend reasonable values for the quantities related to the thermal aspects of the scalding tank, including (*a*) the mass flow rate of the make-up water that must be supplied to the tank, (*b*) the length of the tank, (*c*) the rate of heat transfer from the water to the chicken, in kW, (*d*) the velocity of the conveyor and thus the chickens through the tank, (*e*) the rate of heat loss from the exposed surfaces of the tank and if it is significant, (*f*) the size of the heating system in kJ/h, (*g*) the type of heat exchanger for heating the water with flue gases of the furnace and the surface area on the water side, and (*h*) the operating cost of the scalding unit per month for a unit cost of $1.10 therm of natural gas (1 therm = 105,000 kJ).

17–107 A company owns a refrigeration system whose refrigeration capacity is 200 tons (1 ton of refrigeration = 211 kJ/min), and you are to design a forced-air cooling system for fruits whose diameters do not exceed 7 cm under the following conditions:

The fruits are to be cooled from 28°C to an average temperature of 8°C. The air temperature is to remain above −2°C and below 10°C at all times, and the velocity of air approaching the fruits must remain under 2 m/s. The cooling section can be as wide as 3.5 m and as high as 2 m.

Assuming reasonable values for the average fruit density, specific heat, and porosity (the fraction of air volume in a box), recommend reasonable values for the quantities related to the thermal aspects of the forced-air cooling, including (*a*) how long the fruits need to remain in the cooling section, (*b*) the length of the cooling section, (*c*) the air velocity approaching the cooling section, (*d*) the product cooling capacity of the system, in kg · fruit/h, (*e*) the volume flow rate of air, and (*f*) the type of heat exchanger for the evaporator and the surface area on the air side.