CHAPTER

6

Precooling

Atef Mohamed Elansari, Donald L. Fenton†, Christopher W. Callahan‡*

***Department of Agriculture and Bio-systems Engineering, Faculty of Agriculture, Alexandria University, Alexandria, Egypt †Department of Mechanical and Nuclear Engineering, Kansas State University, Manhattan, KS, United States ‡University of Vermont, Bennington, VT, United States**

6.1 INTRODUCTION

Fresh produce (i.e., vegetables, fruits, and cut flowers) are perishable living biological organisms that must stay alive and well following harvest and during the postharvest handling chain until they are either eaten fresh or used for more processing. Perishables are normally exposed to extremes (e.g., solar heat) as well as hostile ambient conditions; therefore they contain much of what is called field heat due that makes them more warmness at harvest than is generally tolerable. Before harvest the mother plant reimburses losses initiated by respiration and transpiration of water, photosynthesis and minerals. After harvesting, separation of the mother plant, field heat must be properly and quickly removed; otherwise, it causes water loss, wilting, and shriveling, which leads to a serious damage in the appearance of produce. If not taken away, field heat will speed up respiratory activity as well as degradation by enzymes. In addition, field heat encourages the growth of decay-producing microorganisms and increases the production of ethylene, which is the natural ripening agent. It is well known that there is a correspondence between produce temperature and the rate of microbial growth. As a rule of thumb a 1-h delay in the precooling process reduces a product's shelf life by one day (Elansari and Yahia, 2012). This is not accurate for all crops, but it is especially so for very highly perishable crops (e.g., strawberries) during hot weather.

Postharvest Technology of Perishable Horticultural Commodities
https://doi.org/10.1016/B978-0-12-813276-0.00006-7

6.2 HISTORY OF PRECOOLING

Postharvest cooling was technically begun by the United States Department of Agriculture in 1904 (Ryall et al., 1982). In 1955 the first commercial precooling structure was erected in California and was applied to the rapid cooling of tables grapes shipped to the Florida market. Then, a simple, light, forced-air cooler was made using a canvas or polyethylene sheet that is rolled over the top and down the back of the pallets set the floor, sealing off the unit and forcing air to be pulled through the vents of the pallet boxes. This unit is designed to be installed within an existing cold room.

6.3 THE DEFINITION OF PRECOOLING

A number of definitions for the precooling process can be used: the removal of field heat from freshly harvested perishable in order to slow down metabolism and lower deterioration prior to transport or storage; the immediate lowering of produce field heat subsequent to harvest; and the quick reduction in temperature of produce. Hence the definition of the cold chain is important, where it means all temperature management steps that perishables must pass through to guarantee they arrive at the end consumer in safe, wholesome and high-quality conditions. The cold chain program must be planned in advance, start immediately after harvest, and continue through all handling processes, including packing, precooling, storage, transportation, cold storage, and display at the receiving market. In other words, cold chain means the progressive removal of field heat from the produce, starting as soon as possible after harvest in the shortest reasonable time cycle. An important aspect of a good cold chain program is its removal of all field heat down to the lowest optimum storage and/or shipping temperature recommended for the produce.

A cold chain program is considered the key element in the advanced supply chain of perishable since it reduces the rate of respiration, slows down ripening, and controls microbial processes.

6.4 THE IMPORTANCE OF THE PRECOOLING AND THE COLD CHAIN

It is well-established fact that temperature is the chief determinant and the most substantial environmental aspect that prompts the deterioration rate of harvested fresh produce. Respiration rates, and subsequently the amount of heat generated by the produce, relies on temperature; the higher the temperature, the higher the rate of generation. Therefore the most critical step for fresh produce, particularly with inherently high respiration rates, is the rapid precooling process to the lowest safe temperature. Rapid precooling enhances keeping nutrition ingredients and freshness, improving coldness, and prevents chilling injury (Yahia and Smolak, 2014). Moreover, precooling minimizes the designed heat load needed for cold rooms and transport equipment, where studies showed that the postharvest losses of commercial fruit and vegetable is almost up to 25%–30% without precooling in the whole storing and transporting chain while it is only 5%–10% through precooling (Yang et al., 2007).

Precooling can be classified as the most essential of the value-added marketing services demanded by increasingly more sophisticated consumers; it provides marketing flexibility, allowing the grower to sell produce at the most proper time. Additionally, precooling is considered an important unit operation for post heat treatment for certain fruits (El-Ramady et al., 2015). Likewise, applying precooling after air shipment can lengthen the shelf life of certain fresh produce for a considerable period of time by lowering the loss of moisture, maintaining a better firmness and texture, and by limiting the increase of fiber content (Laurin et al., 2003, 2005).

6.5 FACTORS INFLUENCING THE OPTIMUM PRECOOLING METHOD

The economic viability of a specific precooling process as an added-value service must recover its cost through selling prices or achieving other economic benefits, considering that the capital investment and the running costs vary significantly among different precooling methods. Several practical tradeoffs can take place regarding the selection of specific method. These procedures may be based on certain circumstances (Becker and Fricke, 2006) such as:

- Type, amount, and mix of produce handled
- Extent of harvesting season
- Regional location
- Scale of the operation
- Produce physical characteristics
- Specific market requirements
- Acceptable pull-down time for final desired temperature
- Sanitation level required
- Packaging applied
- Further storage, shipping conditions
- Skilled labor requirement
- Energy cost and availability
- Interest rates
- Building and equipment capital cost and its maintenance

These factors, if not properly optimized, can lead to precooling systems that do not achieve the required objectives or the cost/benefit associated with the whole process that is not feasible.

The chief task of a well-designed precooling system is to provide a sufficient refrigeration capacity to ensure a rapid pull down to a desired temperature of a pallet load in certain conditions that are required for certain produce within a given space in a specific period of time. Such a system does not only avoid waste of energy, but it also restricts the moisture loss within a permissible limit. An accurate assessment of a cooling load is the heart of designing and operating any type of precooling system where the refrigeration load is the heat removal rate expected to sustain both the space and the produce at the desired conditions in terms of temperature as well as relative humidity. The product cooling load represents about 2/3 of the total refrigeration load during the transient cooling period; this is why it is one of the most important components of the refrigeration load assessment.

Accordingly the significant refrigeration capacity in addition to the cooling medium movement pattern and nature of control of the precooling process makes it different than just storing the produce in a conventional cold storage room. This is why the precooling process must be considered an independent unit operation that requires specially designed equipment (Elansari, 2009). To accomplish this task, equipment of the proper size and type must be selected, installed, and controlled on a 24-h basis, where its size is determined by the actual instantaneous peak load requirements.

The precooling process can be accomplished by several different methods, all of which involve the rapid removal of field heat from the produce to a cooling medium called, such as water, air, or ice. Such methods include the natural air cooling or room cooling method, forced-air cooling, hydrocooling, ice cooling, slurry ice, vacuum cooling, evaporative cooling, liquid nitrogen, transient or mobile cooling, and in-line precooling (optiflow cooling tunnels). Each one of these methods differs in heat removal efficiency, initial capital, and operating cost. One of the main pluses of hydrocooling is that unlike forced air precooling, it removes no water from the produce and may even revive slightly wilted products (Elansari, 2008). However, not all kinds of produce withstand hydrocooling (Tokarskyy et al., 2015). Vacuum cooling has been traditionally used as a precooling treatment for leafy vegetables with a high surface area versus mass that releases water vapor rapidly, allowing them to be cooled quickly. Precooling with top icing is a common practice with green onions and broccoli, where the lakes of ice are placed on top of packed containers. The most regular precooling method utilized for fresh produce is forced-air cooling, which is adapted for many types of vegetables, fruits, and cut flowers. It is one of the few fast-cooling methods used with a wide range of commodities (Defraeye et al., 2015).

These precooling systems commonly use mechanical refrigeration, although there are some low-cost alternatives (e.g., evaporative cooling and night air ventilation) that will be discussed in the storage system chapter.

6.6 PRECOOLING PROCESS FOR FRESH PRODUCE

A proper understanding of the process of precooling is vital for several reasons: design of a reliable system. The careful sizing for all of its elements, the proper operation, efficiency and preventing failures, and ultimately to obtain the best possible quality of the produce with minimum effect on the environment. The following steps explain the cycle of the precooling process (Fig. 6.1) as it is applied to fresh produce:

1. The load of pallets enters the precooling facility either as raw materials or in final packaging. The initial temperature of the produce is significantly higher than the facility temperature. Thus the heat is moving out of the produce to the surrounding air inside the facility because of this temperature difference, which is called the driving force.

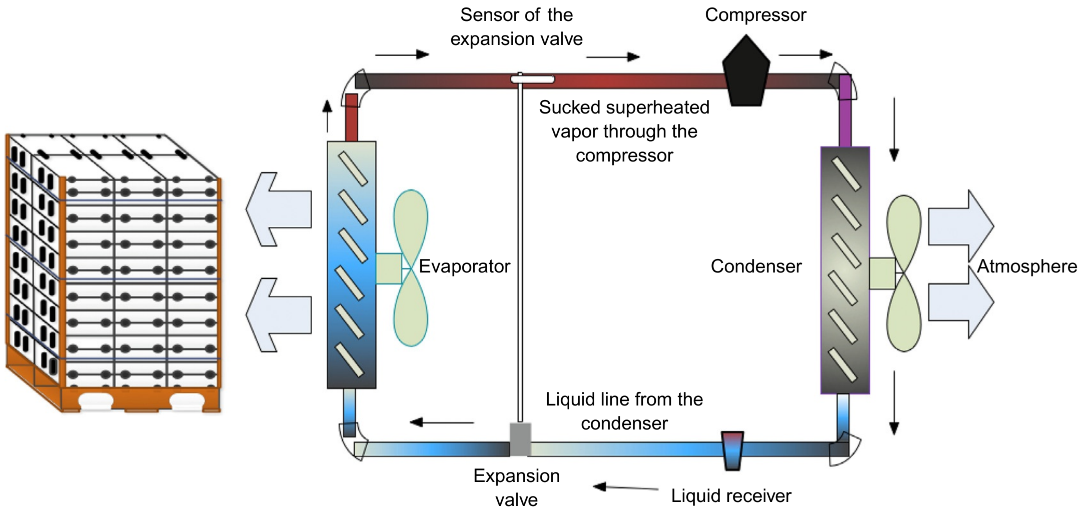

FIG. 6.1 The direct expansion refrigeration cycle.

2. Rapid heat transfer takes place and a temperature gradient develops within the produce, with larger gradients causing fastest cooling. This gradient is a function of produce geometry, physical properties, surface heat transfer parameters, and cooling rates.
3. The system contains a heat exchanger (evaporator or coil) partially filled with a cooling medium (refrigerant) that boils at low pressure and temperature. As this refrigerant boils or evaporates, it absorbs heat. This heat is removed from whatever surrounds that heat exchanger (evaporator or coil), usually air or a secondary refrigerant, and subsequently the produce. This is why the process is called indirect cooling, as there is no direct contact between the produce and the refrigerant.
4. While the refrigerant flows inside the evaporator, it is always colder than the air in the cooling facility; thus the refrigerant is absorbing the heat carried out by the air that is drawn over the evaporator through the fans. The refrigerant is then turned over from the liquid state to the vapor state.
5. As time elapses, heat is removed, and the temperature of the produce is reduced toward its target.
6. The refrigerant is “sucked” from the evaporator as superheated low-pressure gas and is compressed to a higher pressure. This is done through the compressor of the refrigeration system. It should be noticed that compressing the refrigerant gas increases it temperature as well as its enthalpy (total heat content) and does not remove any of the heat transferred from the cooling facility.
7. The high pressure superheated refrigerant vapor flows into the condenser, where it converts from a gas to a liquid and heat is released. This process is the opposite of what is taking place in the evaporator. The cooling of this process is accomplished by using ambient air (air-cooled condenser) or water (water-cooled condenser). Even on a

hot day with a temperature of 45°C the outside ambient air or cooling water temperature from the cooling source is lower than the condenser temperature; thus the heat is transferred from the refrigerant through the pipes and fins of the condenser to the ambient air or water.

8. By now the field heat is pulled out of the produce and discharged to the atmosphere outside the cooling facility, and precooling of the produce has been accomplished.

6.7 TYPES OF AIR PRECOOLING

6.7.1 Small Scale Units

Precooling systems primarily utilize mechanical refrigeration. When there is a ready supply and available electricity, such systems provide the most reliable source of precooling. As mentioned before, there is some low-cost alternatives suitable for a small-scale producer that include evaporative cooling. However, evaporative cooling does not provide the 0–5°C temperatures required for temperate and subtropical produce; in many highly humid areas, it will not even supply the temperatures near 12–13°C, which are recommended for tropical produce. On the other hand, small-scale commercial refrigeration systems are available in most parts of the world and are generally used for restaurants, stores, and other small-scale cold room needs.

Another option for providing refrigeration is to use a modified room air conditioner, a method originally developed by Boyette and Rohrbach (1993). A new controller for air conditioners (CoolBot) allows a low-cost, wall-mounted unit to operate as a low temperature refrigeration unit capable of reaching 1°C without building up ice on the evaporator coil, where such ice buildup restricts airflow and stops cooling.

A variety of portable forced-air coolers have been designed, where a trial-mounted cooling unit equipped with two 10.5 kW packaged air conditioner units, a high-pressure blower and a self-constructed cooling chamber can be used for the precooling process of fresh produce (Talbot and Fletcher, 1993; Boyette and Rohrbach, 1990). The cooling rate reported for previous units were slow and the product load exceeded the design load by 30% apart from the very limited capacity, which is only for one pallet. The water loss was a major concern for both units.

In a further attempt, Elansari et al. (2000) designed a portable forced-air precooling unit using a 40′ high cube bottom air delivery reefer container. The precooling unit was modified by using a bulkhead door, and the floor T-sections were blocked in order to short cycle the cooled air around the precooled pallets. The average pallet table grapes temperature was lowered by 18°C in 8 h. The produce load exceeded the available load for the unit by about 50%, which caused a longer cooling time. The designed refrigeration capacity of the reefer container was to hold and maintain the temperature of the shipment and not to pull down the field heat of the shipment.

Such methods, despite having a relatively low cost, are very slow practices of precooling. These cooling alternatives are best suited to less perishable commodities (e.g., potatoes, onions, apples, sweet potatoes and citrus fruits), as more highly perishable crops will deteriorate before being adequately cooled.

6.7.1.1 Natural Convection Air Cooling (Room Cooling Method)

A conventional refrigerated storage facility is any building or section of a building that achieves controlled storage conditions using thermal insulation and a refrigeration system. Such facilities are classified as coolers, with produce stored at temperatures usually above 0°C. They can be also graded into small, intermediate, and large cold storage rooms, ranging from small ones utilizing prepackaged commercial refrigerator units to a massive cold storage cooler warehouses that are classified as an industrial refrigeration application mainly working with ammonia refrigerant.

Room cooling (Fig. 6.2) occurs when vegetables or fruit cools passively inside a cool room. Temperatures may take hours or days to approach the room setpoint depending on air circulation, produce package, venting, initial temperature, and internal wrapping materials. Unless there is speedy air movement, most cooling will take place by conduction (rather than by convection), with field heat moving out of the product into the surrounding environment. Room cooling can be particularly slow if the room is very full and/or liners are used. The core of a half-tonne bin, for example, can take several days to cool down from a 20°C initial temperature to below 5°C. This can be challenging if the produce has been harvested while hot, is

FIG. 6.2 Room-cooling methods for fresh produce.

subjected to water loss, and/or has a fungal or bacterial infection. Additionally, warm saturated air from the center of the bin can condensate on the produce.

Air is circulated by the existing fans from the evaporator coil in the room, where produce is cooled by exposure to cold air around the produce package. Air within the room is cooled with a direct expansion (DX) refrigeration system or secondary system. Typically the produce is placed on the wall until it is cooled, then it will be moved to another part of the facility for holding or shipping, making space for the warm produce coming in.

This precooling method is the least complicated and also the slowest of the mechanically refrigerated precooling systems. Room cooling minimizes rehandling, as the use of this type of cooling enables the produce to be both cooled and stored in the same space. This decreases the handling steps required and eliminates the capital investment needed for fast cooling, in addition to consuming less power.

The room cooling method is applied for produce sensitive to free moisture or surface moisture and either for very small amounts of produce or produce that does not deteriorate rapidly. However, exposing specific varieties of produce to certain durations of cold storage has been shown to enrich ripening because of increased ethylene synthesis in the tissue (Mworia et al., 2012). For apples the room cooling method is very common in that it stays refrigerated in bins with lateral holes to allow the cool air in; the temperature is mostly kept below 1°C (Russell, 2006). Additionally, citrus is cooled by means of a room cooling method (Defraeye et al., 2015). For cut flowers, room cooling is an adequate method, in which standing flowers are placed in buckets of protective solution. With good circulation of cold air around the flowers, they cool fast. The main drawback with this method is that it is not space efficient. If packaged flowers are being stored in the same area, then the fluctuations in temperature are not ideal; it is generally not a problem unless the storage is for the long term (e.g., weeks rather than days).

Room cooling requires a homogeneous air distribution (at least 60–120 m/min air circulation), spaced stacking for airflow between containers, and well-ventilated packages. As these coolers have less capacity to remove field heat from produce compared with other precooling methods the half-cooling time may be as long as 12–36 h, which means a 7/8 cooling time of 36–108 h (Ross, 1990). The efficiency of a forced-air cooling system compared to a cooling room for grapefruits resulted in a reduction of 6.7°C in 1 h and 14.6°C after 2.5 h, compared to 2°C and 3.5°C for 1 and 2.5 h, respectively, for the cooling room (Barbin et al., 2012). The cooling rate can be enhanced by the use of forced ventilation via a letterbox wall. In this way, some soft fruits may be cooled in less than 2.5 h, however, other crops such as Brussels sprouts or cauliflower may take 24 h or longer.

Unless the room is designed to deliver a high level of relative humidity, slow cooling rates caused by the room cooling method will have sufficient time to remove moisture from the air, and subsequently the dry air will draw moisture out of the product. Produce is largely constituted of water, and so the loss of moisture will degrade its quality, taste, texture, and shelf life. Generally, most of these rooms, notably those in developing countries, are furnished with a direct expansion commercial refrigeration system (DX), which is not ideal for long storage. The mounted evaporators regularly have limited surface area and large ΔT (temperature difference between room air and coil) that increase the water loss from the produce. Furthermore, air velocity declines with increasing distance from the source, causing produce stacked farther from the fans to have less air passage over it.

Defrost is another problem for this type of precooling method. In a typical cold room, fans circulate air over the refrigerator coils. To maintain a storage temperature of 0°C the temperature of the coils will have to be considerably below 0°C. Moisture is therefore removed from the air and accumulates as ice on the coils at that temperature; this is why a defrost system is a basic requirement, because such cold rooms would sometimes run as low as −2°C for certain produce, such as grapes. Electrical defrost presents further heat load to the system and causes great fluctuations in room temperature. It is a very well known fact that any temperature fluctuations may result in condensation, promoting disease development as well as reducing postharvest life.

As mentioned before the nature of the DX refrigeration system has the adverse effect of removing moisture from the air as it passes over the evaporator. This can be minimized by the careful selection of the evaporator surface area; however, some moisture loss and, hence, weight loss is inevitable. Humidification systems provide an alternative to reduce the losses by the introduction of water into the air.

6.7.1.2 Modified Room Cooling Method

The room cooling method is primarily governed by the convective heat transfer mode, which limits the amount of heat transferred from the produce surface to the cooling air. Convective heat transfer is increased as the air velocity increases. The produce that is being precooled are obstacles to air flow, thus heat transfer can be compromised. Therefore the main improvements in the room cooling method are achieved via a precise control of airflow. If the facilities are to be utilized for rapid precooling, then the size of the refrigeration system must be enlarged. The increased refrigeration capacity will be estimated by the daily harvested produce amount, the desired cooling time, and the final temperature required. For an existing mid- to large-sized room, it is expected to have sufficient cooling capacity to precool a predetermined amount of produce according to its conditions. For a small room an essential step is the determining of the capacity of the installed refrigeration system. It is necessary to know the system control in addition to the initial produce temperature, final temperature, thermal properties, and the space requirements to place the tunnel produce load.

Based upon this data and the estimated cooling capacity of the storage space the optimum amount of produce to be precooled can be estimated. An auxiliary cooling fan is put in position after the pallets are placed in the room. Pallets are stacked in even numbers in set positions on the cool room floor (Fig. 6.3). A tarp is rolled down over the bins to direct airflow. The forced air fan is wheeled in position against the pallets. The fan is turned on, which then draws air through the pallets. After the precooling process is complete the fan can be shut off, and the pallets remain in position for room storage.

With regard to the airflow direction, there two options: sucking or blowing air. Barbin et al. (2012) compared these two options using an experimental portable forced-air tunnel built inside an existing cold store. The setup was designed to improve cooling rates inside a storage room without the need for a separate cooling tunnel. Results showed that both the air distribution and the heat transfer occur more uniformly around the products in the suction process than in the blowing system.

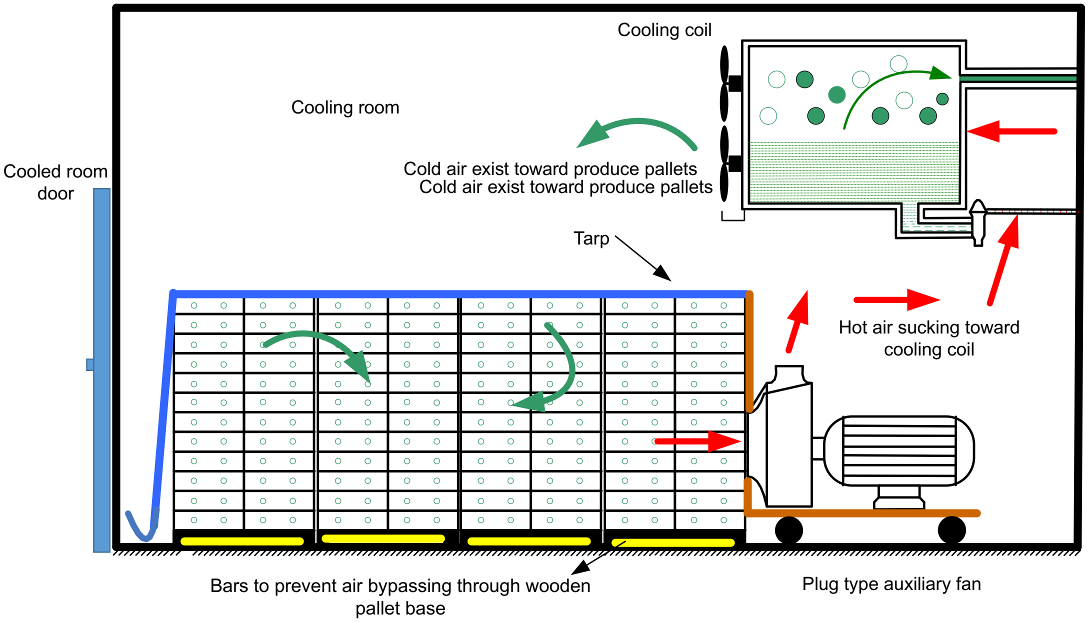

FIG. 6.3 Modified room-cooling method to enhance the precooling process of fresh produce.

6.8 FORCED-AIR COOLING

Forced-air cooling is an improved technique for postharvest fast cooling compared to the room cooling method where cold air is forced through produce packed in boxes or pallet bins passing through its venting areas. In other words, forced-air cooling is the process of swiftly taking away the heat from produce by creating a pressure differential across the product. Forced air or "pressure cooling" essentially increases the surface area being precooled from that of the package to that of the produce inside. Such a system can reduce precooling times by 10 times or even more compared to room cooling method. Forced air systems (Fig. 6.4) pull cold air through vented packages of the produce at rates ranging from 0.1 to 2.0 L/S/kg.

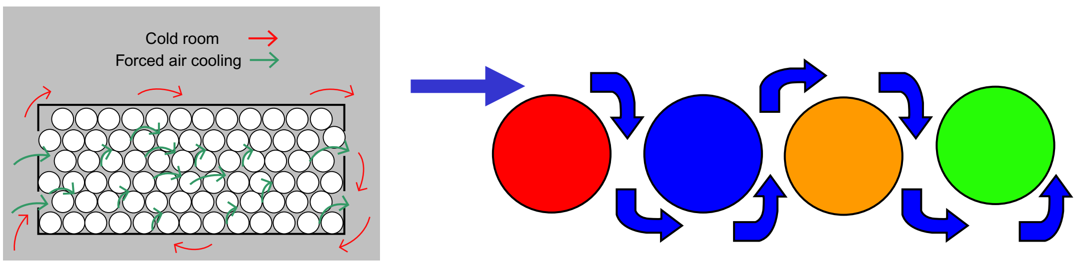

FIG. 6.4 The increased surface area and convective heat transfer during the forced air precooling process.

FIG. 6.5 Forced air precooling system.

A general standard for fan power used is that there should be enough pressure to hold a piece of A4 paper against one of the carton vents.

A number of airflow configurations are available, but the tunnel cooler is the most common (Fig. 6.5). Other air arrangements include cold wall and serpentine flow. Most of the tunnel coolers are designed for two rows of stacked pallets (or bins) to be placed against a central plenum and lined up in front of a fan. A tarpaulin is draped over the top to block the gaps between the pallets, forcing air through the carton side vents and through the produce inside. Therefore when the fan is turned on, it pulls the cold air toward the center section between the pallets. The room air is cooled with a refrigeration coil (evaporator). As the fan generates a negative pressure area between the produce pallets the cold room air outside of the pallets is "forced" to pass through the produce pallets. The fan inside the plenum draws cold air through the cartons, therefore heat is removed from the packed produce and the air is exhausted directly back into the room passing through a cooling system first. Over time the heat is removed through convection and some convective of evaporation. In this system the produce is precooled in batches; cooling cycles range from 1 h for cut flowers to more than 6 h for larger fruit diameters (Thompson, 2004).

A vertical airflow forced air precooler (Fig. 6.6) uses pallet racking so that pallets can be double stacked. If 12 pallets fill a floor space footprint with a tarped tunnel precooler system, then the vertical airflow design permits 24 pallets to be precooled in that same space. One advantage of the vertical design system is that it eliminates the conventional precooling difficulty of the last pallets to cool, which are typically those two pallet positions furthest from the suction fan or fans. The system offers superior cooling speeds with flow rates up to 2.35 L/S/kg compared by 1 L/S/kg for the tarped tunnel precooler. Additionally, flow can be reversed in a vertical cooler. While the design precools faster, it also physically doubles the precooling pallet positions, resulting in a capacity that can actually triple. The design

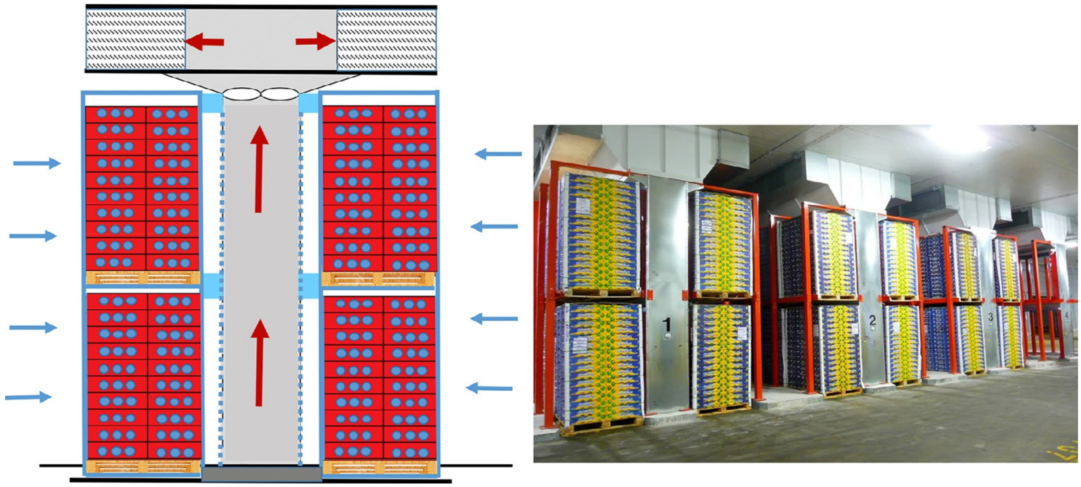

FIG. 6.6 Vertical Airflow forced air precooler.

of such technology presents several advantages, such as faster cooling, increased capacity per unit of floor area, potential for reduced cost per unit cooled, more uniform product temperature, field side operation, and automated process control.

The drawbacks of a vertical airflow forced-air precooler is the high pressure drop across the pallets, where a doubling airflow increases the pressure drop by a factor of about 4. This is also reflected in increased fan electrical power because doubling the airflow increases the electricity demand for fans by a factor of 7 or 8; this also results in an increased heat load because fan heat is added. However, the use of a high venting area reduces the pressure drop across the pallet.

There are some downsides to the traditional tarped-tunnel method. The tunnel setup takes several minutes; each pallet or pair of pallets must be placed manually and accurately to prevent air short cycling and bypass via the in-between pallets gaps and underneath. Room air is naturally mixed with warmer air coming in through the doors. A large space is required to accommodate the tunnels, which means more refrigeration capacity is required to cool "unusable" or wasted space. Of course, once the cooling is completed the tarp must be removed and the pallets transferred to a separate cold room for holding.

The continuous system where produce is carried through a cooler on a conveyer has largely been abandoned in favor of batch cooling due to the high cost of conveyer systems. Recent use of that configuration has been reported for a specific application, such as a production line for fresh-cut produce (Christie, 2007). A new system (Fig. 6.7) is developed where pallets are set on infeed conveyors. Once a full load has been staged the precooling door opens, and the pallets are inserted automatically into the first zone. As the pallets move from the infeed conveyer to the specified zone, they are automatically packed tightly again. Once inside the cooling zone the seals (tarp) are inflated, pressing tightly against the product pallets surfaces, creating the negative pressure zone. The powerful fans draw cold air through the pallets and chill the warm air that comes off of the produce with refrigeration coils in the upper plenum. Because of the compact size of the cooling zone, there is no wasted space to cool. As the produce advances from one precooling zone to the next the seals extend and retract,

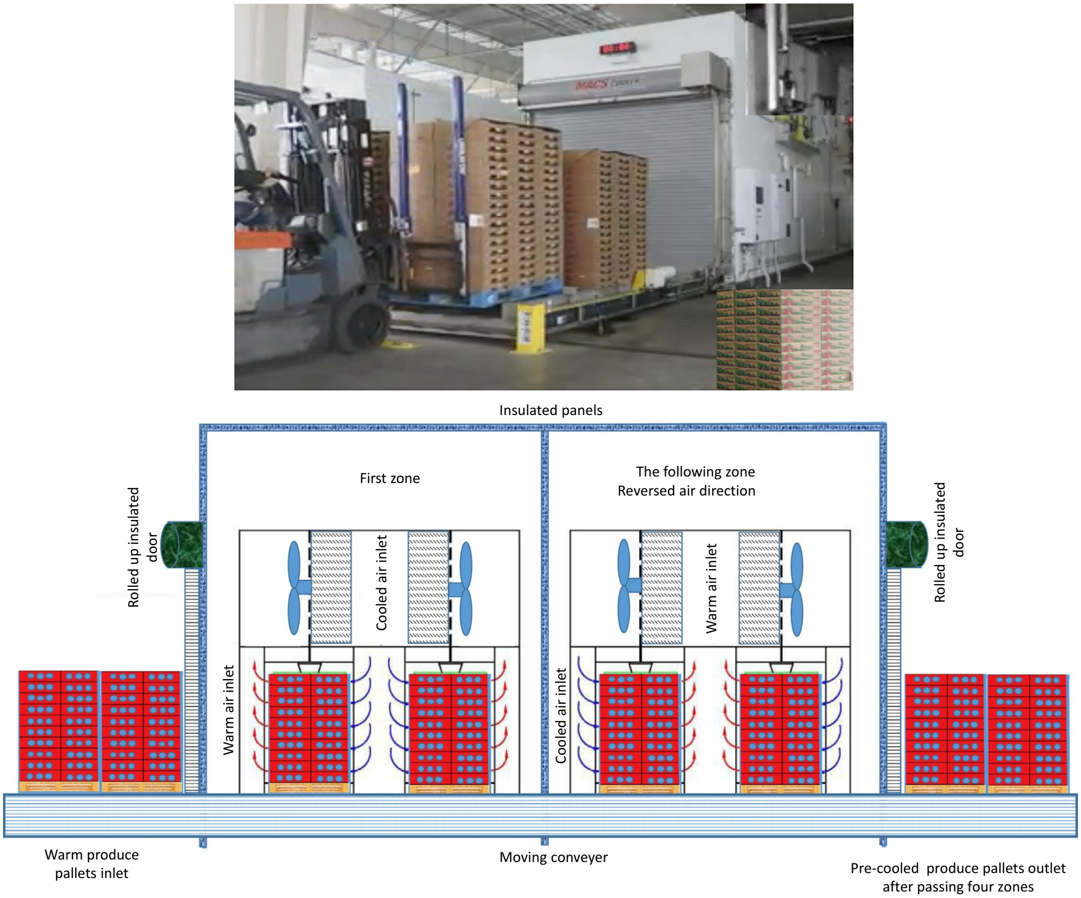

FIG. 6.7 Automated loading forced air precooling system.

and the air direction is reversed automatically to yield even cooling. The system is equipped with an LED display that tells operators and drivers how much time is left before the produce shifts to the following precooling zone. When the produce load has moved through all of the precooling zones, it moves on to the outfeed conveyors, where it can be picked up and transferred either to cold storage or transport. Using that system, strawberry cooling time can be reduced from 1.5–2 h to about 1 h (Thompson et al., 2010).

It should be mentioned that the ventilation of the produce packages should be designed in such a way that they can supply a uniform airflow distribution and consequently even produce precooling. Well-vented sound pallets with good alignment between containers greatly speed room cooling by allowing air movement through containers (Fig. 6.8). Total venting area and opening size, shape, and position show a significant effect on pressure drop, air distribution uniformity, and cooling effectiveness (Pathare et al., 2012). Recent advances in measurement and mathematical modeling techniques, such as CFD, represent powerful tools for developing detailed investigations of local airflow rate and heat and mass transfer processes within complex packaging structures.

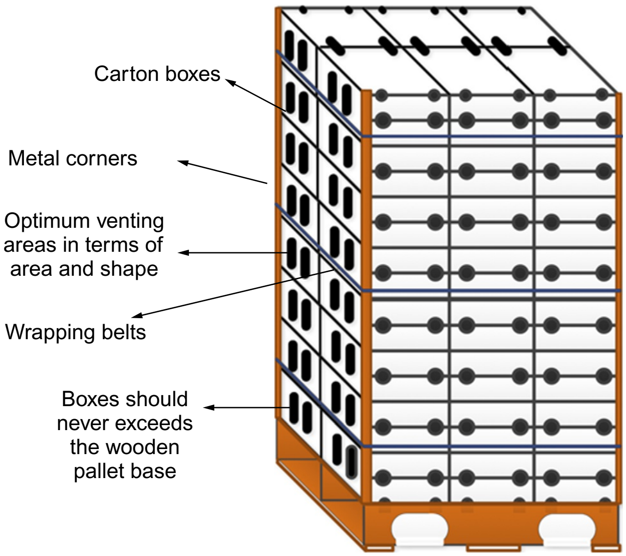

FIG. 6.8 Pallet arrangement for forced air cooling.

Package design is a subject of ongoing and dynamic research in the fresh produce industry due to its importance in the forced-convective cooling process with its complexity. Optimum package design is very product-specific due to the large variability in size, shape, and thermophysical properties of different fresh produce. Often a compromise has to be made between optimal ventilation (percentage and shape) and mechanical strength of the package, which is required for stacking as well as for protecting the produce. The packaging method and materials should be selected appropriately to avoid any blockage of air vents and passages in order to allow good air flow and to achieve the cooling rate desired. Therefore produce packaging with airflow-restricting materials should be taken into consideration when sizing the system airflow and static head pressure of the fans. Produce boxes should have at least a 5% sidewall vent area to accommodate airflow without an excessive pressure drop across the box (Kader, 2002). For example, packing table grapes for sea shipments requires a lot of packaging and wrapping that cannot be avoided, such as consumer bags and unvented liner. Crisosto et al. (2002) described an airflow rate of 9.35 m^3/h/kg that overcome the heavy internal package of table grape boxes during the precooling process. Luvisi et al. (1995) reported a value of 3.7 h as a 7/8 cooling time of grapes that were bagged and packed in corrugated box with initial and final temperatures of 21.1°C and 1.7°C, respectively. For most forced air precooling systems, fans are being sized to deliver on a maximum static head pressure of 200 Pa (Hugh and Fraser, 1998).

A new packaging design capable of promoting a more uniform and energy-efficient performance during forced-air cooling has been proposed (Ferrua and Singh, 2009). The design was developed using an advanced mathematical models simulation technique called computational fluid dynamics (CFD). For the same airflow conditions the new suggested design significantly improved the uniformity and energy-efficiency of the precooling process. A newly designed pack named Supervent and Ecopack for a citrus fruit precooling process using CFD modeling was analyzed (Defraeye et al., 2013) using CFD process. The optimal cooling performance was determined for Ecopack in terms of the uniformity of fruit cooling as well as the improvements in cooling performance.

6.8.1 Forced-Air Cooling System Classification

While physical properties such as size, shape, and thermal properties are unchanging for a given produce, the precooling rate for a specified system depends principally on the velocity of the refrigerated air flowing through that produce; it is the only governing factor. Additionally the temperature of the forced cold air is not allowed to be reduced beyond a certain safe point in order to avoid chilling or freezing injury. Forced air coolers utilize centrifugal, axial fans to circulate the refrigerated air around the system. Such fans are sized based on the criteria of required airflow rate as well as static head pressure. These conditions are determined by: produce type and productivity of the system; the arrangement applied (bulk, pallet, or stacking); and the cooling rate designed. Therefore, there are two common designs of a forced air precooling system. They are: (1) ice banks (wetted-coil) and (2) dry-coil high humidity style that can be classified into DX system and glycol system (chilled water). The two systems have substantial differences in design concepts and philosophy; each has advantages and disadvantages that should be considered to determine which is the best for a specific commodity.

6.8.1.1 Ice Bank (Wetted-Coil)

In wet cooling systems (Fig. 6.9) the refrigeration is supplied in the front of the water pumped from the ice water tank, which works as a thermal storage unit at the top of the fill pack heat transfer surface (cooling tower), thus cooling the air and warming the water. The development of the ice on the surface of the evaporative coil takes place when the refrigeration load is low and melts when the load goes up. Water drops, which can cause damage to the produce, are stripped from the airstream by directional mist eliminators. The water is not allowed to freeze at all through mechanical agitation, which also provides good heat transfer rates between the refrigerated plates and the water (Tassou and Xiang, 1998). The air leaves the cooler and is supplied to the produce at temperatures as low as 1.5°C, with relative humidities as high as 98%.

Harvested produce is brought into the precooling room and stacked in open crates in order to permit the forced circulation of air through the crates; the cooling unit is usually placed near the end of the room. Cold humidified air is circulated by the power fan of the cooler to the opposite end of the room, where it is drawn through the stacked produce pallets and returns back to the unit. Each cold room may have one or more units operating in parallel based on the total capacity required. The circulation rate is typically 40 air changes per hour (Benz, 1989).

The wet deck system was common in precooling systems that were installed in many packhouse facilities, especially in developing countries (Elansari and Siddiqui, 2016). Wet deck systems have the ability to maintain low temperatures and high relative humidities with lower running costs than conventional systems, making them suitable for long- and medium-term storage of a number of vegetable crops (Farrimond et al., 1979). Wet air cooling has been used successfully for the precooling and/or storage of: grapes, mushrooms, cucumbers, carrots, cauliflowers, tomatoes, strawberries, cut flowers, white and red cabbage, Brussels sprouts, spinach, potted plants and flowers, lettuce chicory, potatoes, celery, and leeks.

As the system recirculates water the water serves as an effective air scrubber and can be very effective in removing airborne contaminations by absorbing them into the water stream. The cooler must be designed to control disease organisms that enter the unit via the coming produce. Chlorine is regularly applied and requires concentrations of 100–150 ppm available chlorine for water near 0°C. However, chlorine is corrosive to many metals, therefore it must

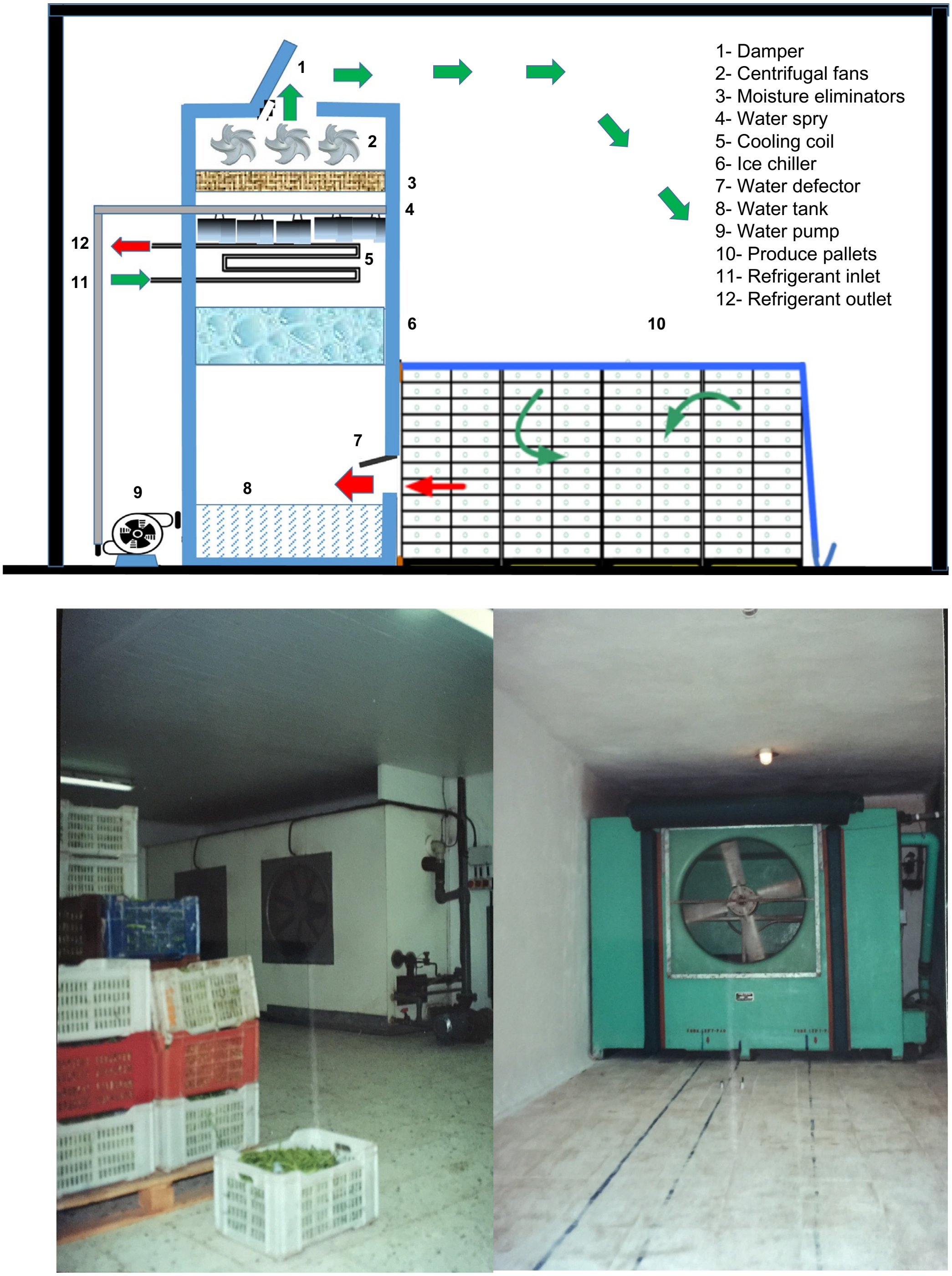

FIG. 6.9 Ice Bank (wetted coil).

be determined in advance whether chlorine can be applied with the cooling equipment installed or not. Other antimicrobial solutions are also available.

Common commercial refrigeration or industrial systems using either semihermetic or screw compressors working with ammonia or halocarbon refrigerant are used to supply the required refrigeration capacity to charge the ice chiller thermal storage unit. The ice can be built at night or when there is no load that is to save energy and capital cost.

Because it can only cool the fruits to 2.5–3°C or above the wet deck system is not the optimum precooling technique for sea shipment produce. In addition the wetting of product surfaces make handling difficult and provides an enhanced environment for microbial growth. Therefore due to the wet air used, packaging must be water resistant, hence waxed face packs or plastic trays are usually required. The ice bank coolers also require a larger space (James, 2013); however, the system offers some economic advantages other than reducing weight loss (Tucker, 2016):

- Smaller refrigeration plant since peak heat loads were met by the reserve of ice. The plant therefore runs for longer periods at full capacity.
- Running a refrigeration plant at a full load (as ice bank systems operate) is more feasible than running at a partial load, therefore the overall efficiency of the plant is greater.
- Energy saving, since smaller plant consumes less power.
- A portion of the refrigeration capacity is utilized to accumulate a reserve of ice during the nighttime, when electrical power is cheaper.

6.8.1.2 Dry-Coil, High-Humidity, Direct Expansion

Fundamentally the dry system is similar to the wet precooling, so it is expected that the coolant coil is sized to operate at a small temperature difference between room air and coil ($\triangle T$), which will maintain a high relative humidity of the leaving air stream without introducing any water. This is why it is called a dry-coil, high-humidity system. Therefore the system can maintain 85%–90% relative humidity during the precooling process if properly designed, operated, and maintained. The coil of this type has a large surface area (Fig. 6.10). Elansari (2009) pointed to different details for the dry-coil system that uses an economical semihermetic condensing unit working with R-134a (DX system) that replaced the wet precooling system (Fig. 6.11). The system has been installed in different locations in

FIG. 6.10 Typical evaporative coil for the dry coil high humidity system with large surface area.

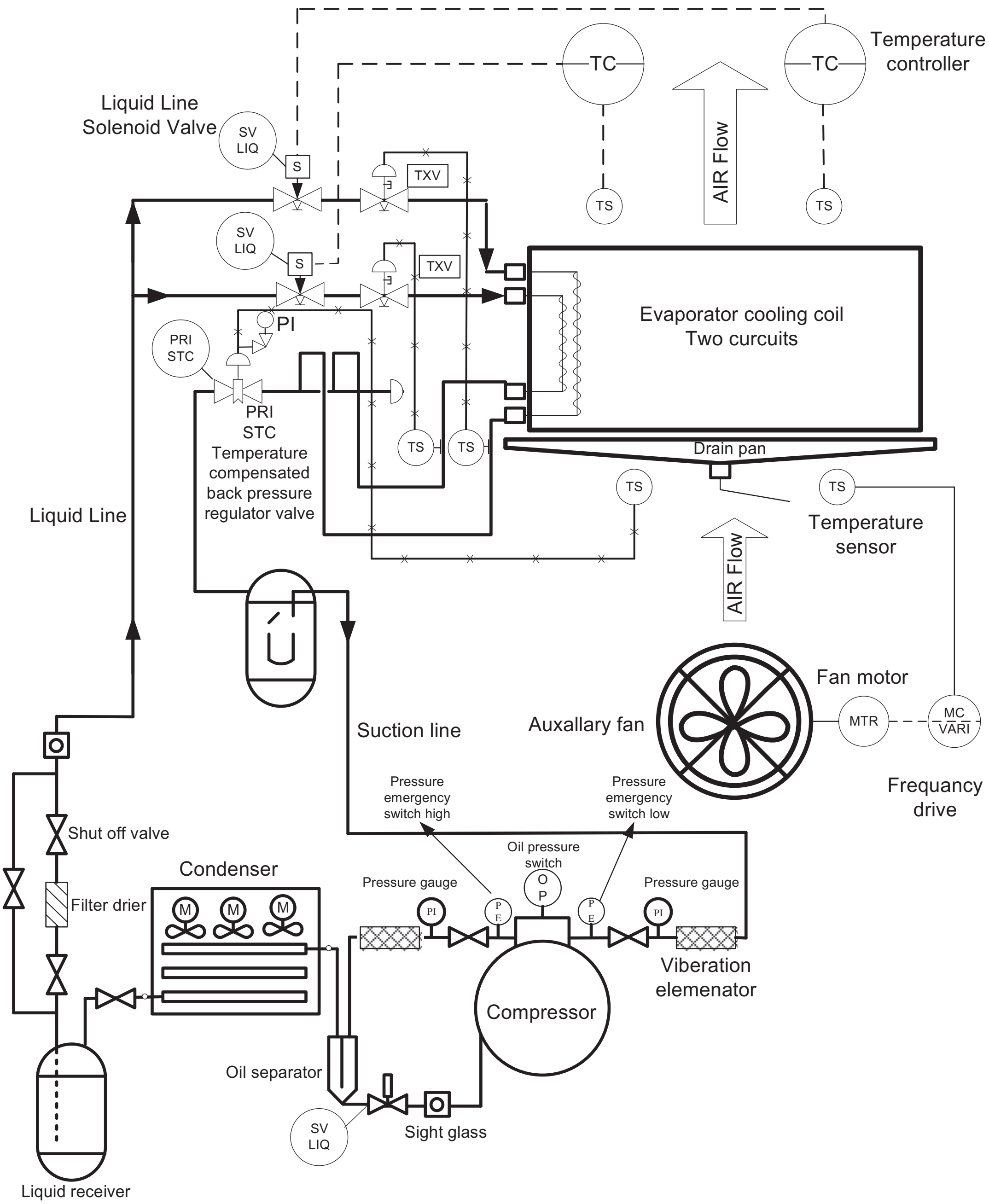

FIG. 6.11 Details of the refrigeration cycle for a dry coil high humidity forced air precooling system.

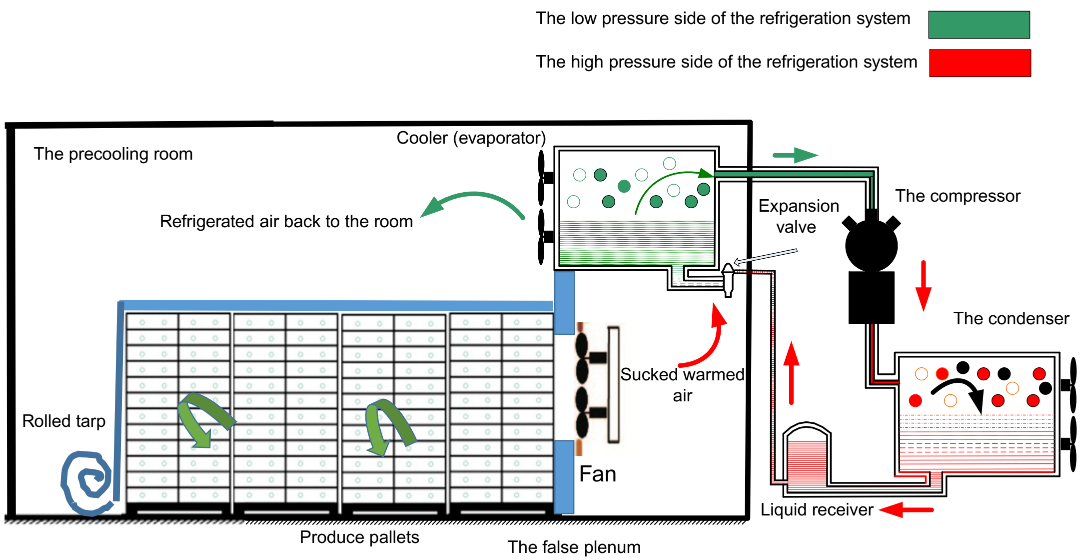

FIG. 6.12 Dry coil high humidity forced air precooling system working with DX.

the Middle East and was proven to be successful (Fig. 6.12). The refrigerant main loop for each precooling tunnel includes a liquid receiver, a thermostatic expansion valve, and a plate-finned tube evaporator coil. The evaporator coil has two circuits and should match the same capacity of the condensing unit. A separate axial auxiliary fan is used to circulate the designed amount of air against 375 Pa static pressure. Each compressor is furnished with a capacity controller that controls the supplied capacity between 50% and 100%. A large fin spacing of evaporators is essential (1.575 cm/fin) in order to ensure a good supply of air through the precooling cycle and to avoid any blocking of the coil by dirt or frost. The system contains a temperature compensated a back pressure regulator valve that maintains the evaporating temperature at the required setup conditions, thus preventing it from decreasing at the end of the precooling cycle. Such installation minimizes the dehydration effect that could happen due to an increase in ΔT. A variable frequency drive (VFD) is used to control the air flow rate supplied by the auxiliary fan in each precooling tunnel. VFDs are an electronic motor controller used to reduce fan speed after the heat field has been partially pulled down. In other words, as the precooling process nears its end, produce water loss should be minimized by reducing air flow, which can be reduced by 50%. The VFDs present a very smart energy savings opportunity because at half fan speed the fans consume only about 15% of full speed power (Morton and McDevitt, 2000). Additionally a safety cutoff system that prevents any freezing of produce being precooled is installed at the front of the air return channel to sense the return air temperature and stop the fan if the temperature is less than 0°C.

6.8.1.3 Dry-Coil, High-Humidity, Chilled Water

In such systems and as shown in Fig. 6.13, a cooling coil with a large surface area and small deference between room air temperature and coil temperature (ΔT) cools air and

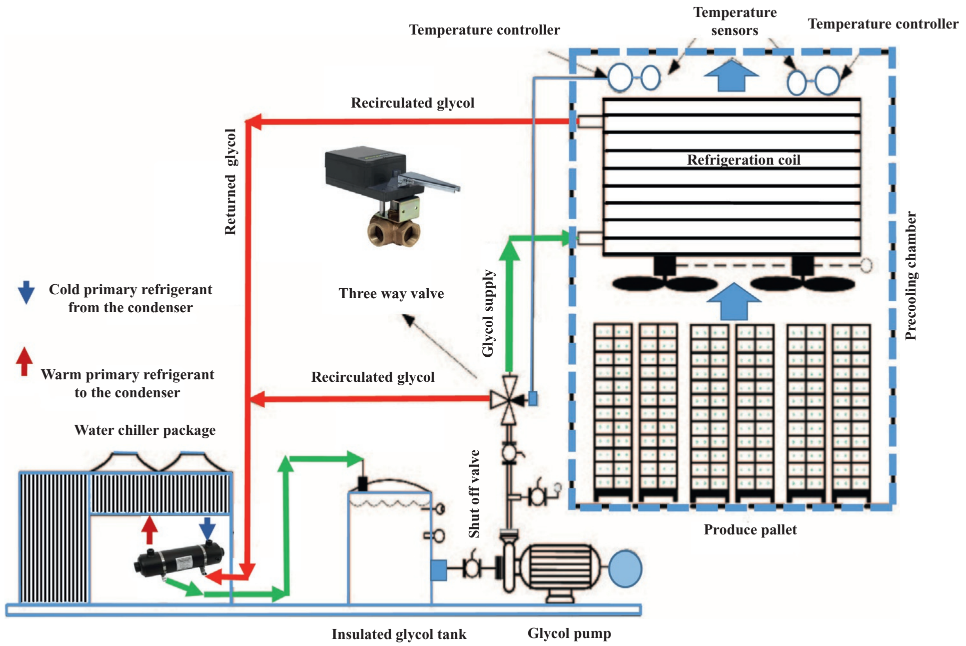

FIG. 6.13 Dry coil high humidity forced air precooling system working with chilled water.

maintains a high humidity level (85%–90%) using chilled water (mixed with propylene glycol) as a secondary coolant that is continuously kept as low as −7°C. Cooling of the water is done in what is called water chiller, where a heat exchanger is used to cool the chilled water (secondary refrigerant) using the primary refrigerant (Fig. 6.13). The chilled water is delivered to a proper sized insulated tank. The chilled water is pumped when needed to the system coils to pick up the heat load conveyed by the air across the cooling coils in each room.

A three-way valve controls water flow in two directions. If the valve is fully open in one position, then the full amount of the chilled water will be moving toward the coil where the full load condition is required. If it is fully opened in the second position, then the water will pass to the other recirculating direction. If the valve is partially open, then a percentage of the water will flow through the first direction and the remaining will pass through the recirculating direction. Therefore the system control adjusts the working conditions for that valve to guarantee maintaining a preset small temperature difference between room air and coil (ΔT) that maintains high humidity level (85%–90%). The dry-coil, high-humidity system offers the following advantages:

- Can maintain high relative humidity up to 85%–90%
- No exposed water for possible cross contamination from recirculated water
- Higher air flow capacity
- Possible to cool produce to 0°C
- Low operating and maintenance cost

On the other hand the chilled water system usually involves more capital cost due to the high surface area of the coils needed in addition to more sophisticated control. The potential of produce freezing exists unless properly operated.

6.9 MOBILE PRECOOLING FACILITIES

A mobile precooler is one that carries out the precooling process on the farm during harvesting season. It can move from one site to another all year round for operations that regularly change harvest locations during or between seasons. The leading advantage of such systems is avoiding delays between harvest and precooling in addition to reducing handling steps.

For the small-scale operation, there are two types of portable precoolers that currently exist, and both have been tested considerably. Both can be self-constructed at a relatively low cost, and complete plans are available (Kitinoja and Thompson, 2010).

Commercial mobile precooling systems (CoolForce Co., USA) have been previously designed, in which three precooling (unit port) container loads of product can be precooled simultaneously. A total of 525 kW of refrigeration is accessible through a high relative humidity air handler. Each port delivers up to 63,000 m^3/h of chilled air at nearly 100% relative humidity at a static head pressure of 375 Pa. Each port can be operated individually, and the unit can simply be repositioned using a standard semitractor truck. The capital investment and running cost of the system are very high due to its capacity that exceeds the production of the average size facilities. It consumes about 30 litter of fuel per hour to run the ammonia screw compressors.

Another system (ColdPICK M1) is a highly mobile precooler developed to be placed in the field next to a picking crew (Fig. 6.14); therefore the speed and efficiency of the unit permits loads to be continually stacked and transferred to the system as they are harvested. The unit processes about one pallet per hour; multiple units can be cross-docked to accommodate larger harvest operations so that several picking crews can work alongside each other. Once the cooling is accomplished the stacks are transferred to a reefer truck where they are

FIG. 6.14 ColdPICK M1mobile precooling system on the left and Cold@Field mobile precooling system on the right.

palletized. As soon as the truck is filled the refrigerated truck transports the produce to the end users or distribution center (ColdPICK International).

Cold@Field systems (American Berry Cooling, Inc) are modular/portable precooler designed to move from district to district as the harvest progresses. It was reported that the system runs very fast and efficiently with high airflow rates for consistent cooling. The system includes automated pallet handling.

It should be noted that there are no published evaluations of any of the above commercial systems to date. The units are being leased from the supplier on an as-needed basis, and fees will vary based upon distance to site, length of lease, and time of year.

Elansari (2009) described the development and performance of a portable forced-air cooling unit that was designed to satisfy different precooling requirements (Fig. 6.15). 2.3 tons of strawberries were precooled from a 22°C initial temperature to a 1–4°C final temperature in 2.5 h. The unit is simple and uses off the shelf refrigeration components. Hermetic scroll compressors have proven to be efficient and reliable with respect to the precooling requirements. The unit is an insulated container (8590 × 2990 × 2940 mm) split into three segments: a machine room, a false wall section, and finally the main precooling space that holds the produce pallets. The unit was designed to comply with road regulations in terms of the outside

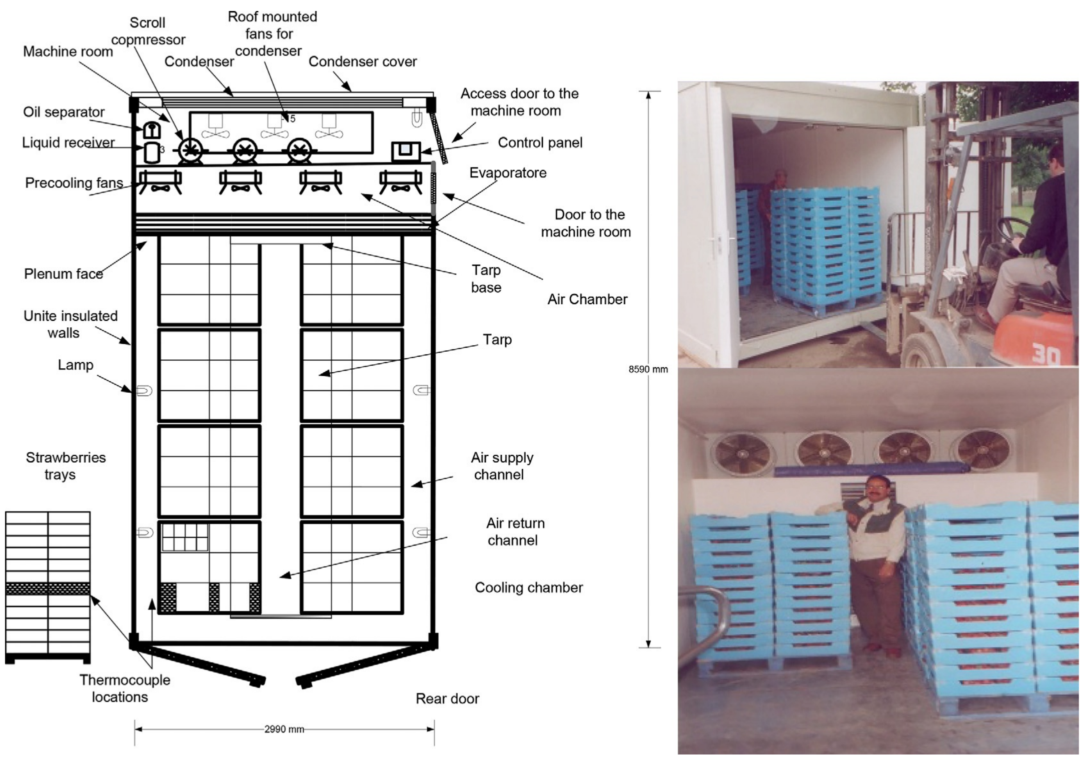

FIG. 6.15 A portable forced air cooling unit.

dimensions as well as weight. The unit can run with a separate motor generator fueled by a diesel/electrical portable power unit to keep it running while off the road.

6.10 HYDROCOOLING

Hydrocooling is the process (Figs. 6.16 and 6.17) of removing field heat from produce after harvesting by exposing it to cold moving water. Hydrocooling is considered one of the fastest precooling techniques. Depending on the hydrocooler type the process can be accomplished by either immersing or flooding products in chilled water or spraying chilled water over the products. One main advantage of the hydrocooling process is that it removes no water from the produce; on the contrary, it may dehydrate wilted produce. This method is an effective way to precool a wide range of fruits and vegetables whether containerized or in bulk. Only

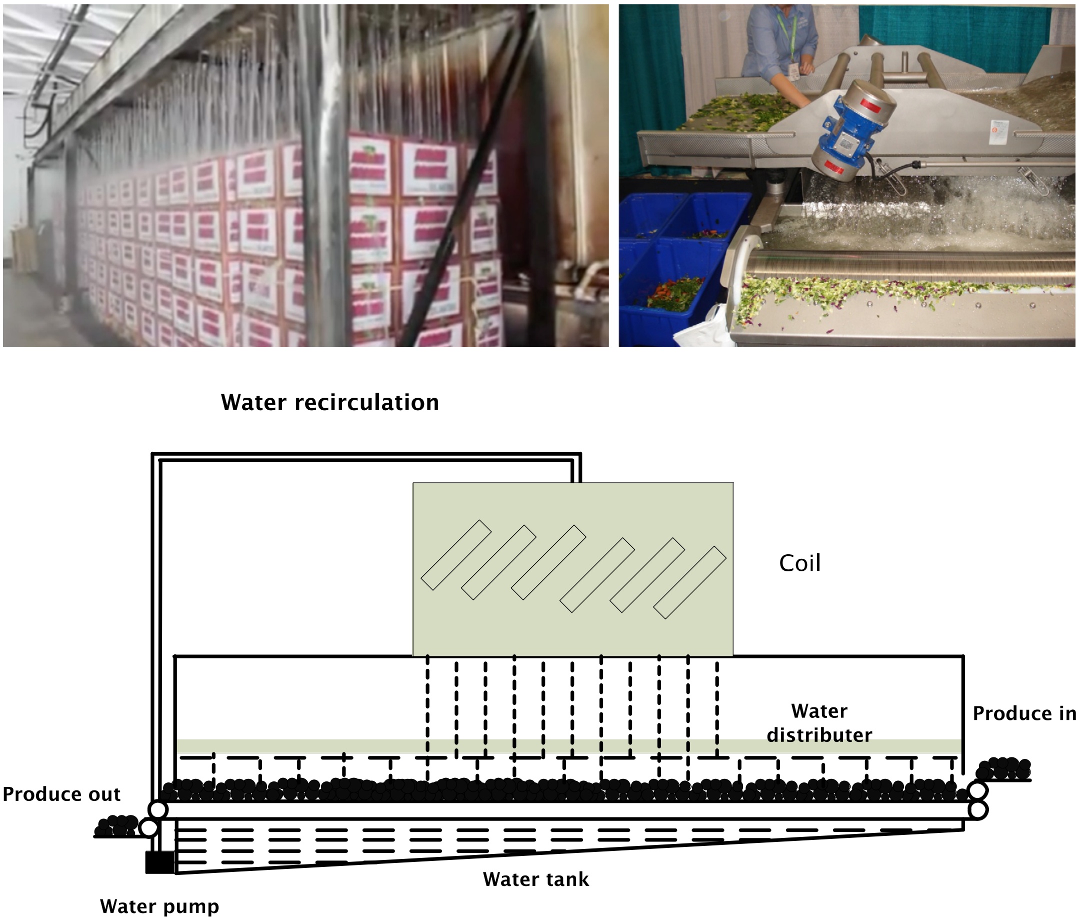

FIG. 6.16 Shower type hydrocooler.

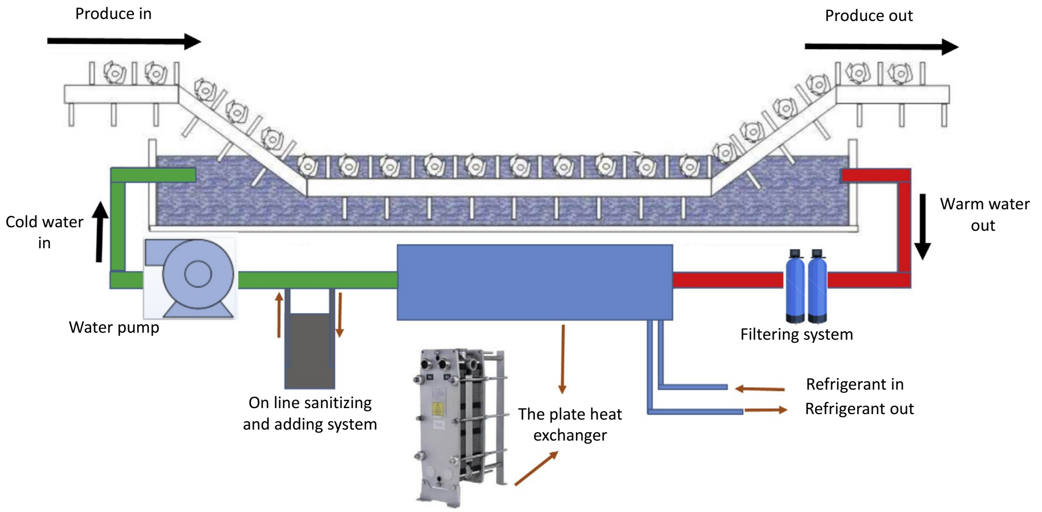

FIG. 6.17 Immersion type hydrocooler.

certain crops (e.g., peach, cherry, avocado, mango, sweet corn, and carrot) can tolerate hydrocooling.

For small-scale operations, well water may be readily available. Because well water is often much cooler than air temperature in most localities of the world, it can be used for hydrocooling. The temperature of deep well water is nearly equal to the average annual air temperature of the same locality at a depth greater than about 2 m below the surface. Therefore well water ranging from 12°C to 15°C can be applied directly for hydrocooling chilling sensitive crops. A mixture of water and ice can be applied for the same purpose (Fig. 6.18). Hydrocooling is very vital for the cherry industry due to the large heat capacity and high rate of heat transfer of agitated water. At typical flow rates and temperature differences, water removes heat about 15 times faster than air, resulting in either a threefold shorter precooling time compared with produce precooled by forced air or a 10-fold shorter time when produce is placed in conventional cold room (Manganaris et al., 2007).

Heat transfer in water is excellent compared to air where the convection coefficient at the produce surface is usually minor. For effective hydrocooling, cold water should be in contact with as much of the surface area of each fruit or vegetable as possible. Therefore, during the hydrocooling process the internal resistance of the produce represents the main resistance to the heat transfer, where the internal heat is removed once it arrives at the surface. The temperature variation between the product surface and the cooling water is normally less than 0.5°C. In ideal circumstances the convective heat transfer coefficient and the cooling rate per unit surface area should be 680 $W/m^2\,°C$ and 300 W/m^2, respectively (Cengel and Ghajar, 2013).

For a successful hydrocooling process, water must be maintained as cold as possible without jeopardizing produce. Therefore, water temperature is regularly sustained around 0.5°C except when chilling delicate produce. The water in a hydrocooling system is cooled by

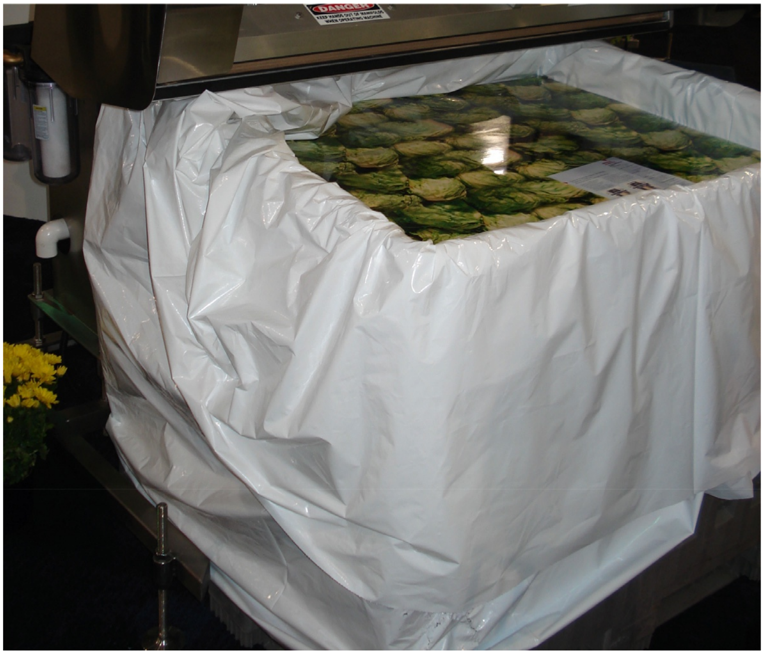

FIG. 6.18 Hydrocooler with water/ice mixture for small scale operation.

passing it through stainless steel cooling coils, where a refrigerant flows at about −2°C. The coil used is usually a plate heat exchanger (PHE) that cools the recirculated water down to 0.5°C, and the plates are refrigerated using R-717 or R-22. The refrigerant is usually supplied from a central equipment room. The PHE is either placed directly over the belt conveyor or on the process floor near the hydrocooler belt. A closed loop is normally used to recirculate the water in order to save water as well as energy.

In order to minimize the potential risk of spreading any contamination because water recirculation can cause cross contamination for produce, water treatment with an antimicrobial solution is a must. Otherwise, water recirculation can result in the buildup of microorganisms in the water, resulting in increased spoilage and potential foodborne illness. Chemicals such as active chlorine (or ozone) are usually added at a rate of 50–100 mg/kg water in order to reduce bacteria buildup (Suslow, 1997).

Container design and the stacking pattern of the produce are vital. Water distribution within the produce containers, in addition to the amount of water flowing out of the container through the sidewalls, influence the effectiveness of the hydrocooling process. Hence containers should be compatible with water in addition to providing an efficient and uniform cooling throughout the entire volume of the individual container as well as throughout an entire stack of containers. In terms of uniform water distribution the width of the openings on the bottom side of containers is also essential (Pathare et al., 2012). Vigneault et al. (2004) investigated the nonuniform water supply within plastic collapsible containers for three types of produce through the hydrocooling process. The results recommended to use a container base opening that covers approximately 5.2% of the bottom surface, which will permit a more even water distribution and insure the fastest hydrocooling rate by obtaining a higher flow rate in each section of the container.

Traditionally, forced-air cooling is the most common technique applied for the fast precooling of strawberries in packhouse facilities, where the typical cooling times for the pulp temperature to reach 3°C ranges from 60 to 90 min. Nevertheless, the final pulp temperature can fluctuate widely depending on the location within the precooling tunnel, leading to uneven cooling and a delay in accomplishing the desired final temperature. In addition, water loss has been associated with the forced-air cooling process, influencing shelf life and the quality of the strawberries. The application of hydrocooling was extended to strawberries leading to an overall better quality compared with forced-air cooled and resulted in significant differences in epidermal color, weight loss, incidence, and severity of decay (Ferreira et al., 2006; Jacomino et al., 2011). Hydrocooling did not affect the quality during cold storage in terms of physical and chemical analyses, freshness, or decay. Use of this method resulted in fruit that was 2%–3% heavier than those that were forced-air cooled by the end of the storage time. For strawberries, hydrocooling is an alternate method that has several advantages compared to forced-air cooling, including a faster cooling time (12–13 min), reduced dirt/field debris, and overall microbial load (Jacomino et al., 2011).

Based on the current practice, strawberries are unwashed and field packed for fresh market, which expands the risk of microbial contamination during the subsequent handling chain. Fresh and frozen strawberries have been associated with several reported foodborne illness outbreaks in the United States, which draw attention to the need for better sanitation and process control programs. It was reported that compared to forced-air cooling, hydrocooling significantly reduced salmonella survival on inoculated intact strawberries, with levels below the enumerable limit (1.5 log CFU/berry) by Day 8 (Sreedharan et al., 2015). Furthermore, hydrocooling reduced the initial salmonella levels by 1.9 log CFU/berry, while the addition of 100 or 200 ppm HOCl reduced levels by 3.5 and 4.4 log CFU/berry, respectively. Applying both antimicrobials sodium hypochlorite (HOCl, 100 mL/L) and peroxyacetic acid (PAA, 80 mL/L) were effective in lowering surface contamination on strawberries while being hydrocooled (Tokarskyy et al., 2015).

In the immersion type hydrocooler for strawberry using sanitized water, the fruit were uniformly cooled in approximately 13 min, and the throughput was increased by four- to eightfold compared with forced air cooling (Tokarskyy et al., 2015). Hydrocooling of strawberries in clamshells cooled at the same rate as those in bulk and resulted in quality equal to or better than those forced-air precooled after 14 days of storage at 2°C. For blueberries the current practice is forced-air cooling for 60–90 min to a 2–3°C pulp temperature. Carnelossi et al. (2014) compared the cooling efficiency and the effect of forced-air cooling with hydrocooling as well as with hydrocooling plus forced-air cooling on fruit (Emerald and Farthing varieties) quality. It was concluded that the Emerald variety is more sensitive to hydrocooling compared to the Farthing variety. Several fruits from the former showed skin breaks while both cultivars had no decay during storage. For sweet cherries, it has been reported that hydrocooling shortly after harvest (4 h) and directly transporting fruit in a cold water flume during packing will maximize postharvest quality, though it can reduce fruit splitting (Wang and Long, 2015).

The effectiveness of hydrocooling treatment in minimizing delay after harvest to suppress decay and prolong the storage life of produce is still being evaluated. Liang et al. (2013)

studied the influence of hydrocooling at 1, 2, 4, and 6 h after harvest on the shelf life and quality of litchi. The results indicate that hydrocooling for 30 min lowered the temperature of the pericarp by 6.2 ± 0.3°C and delayed the increase in electrolyte leakage and polyphenol oxidase as well as peroxidase activity in the pericarp.

It can be concluded that hydrocooling, when appropriately designed, provides a fast, reliable, and efficient means of cooling water-tolerant produce such as sweet corn, broccoli, artichokes, asparagus, avocados, green beans, beets, Brussels sprouts, cantaloupes, carrots, celery, cherries, strawberries, endive, greens, kale, leeks, nectarines, parsley, peaches, radishes, romaine lettuce, spinach, turnips, watercress, and more.

6.11 VACUUM COOLING

Vacuum cooling (Fig. 6.19) is a batch process in which the produce is precooled by vaporizing water under low-pressure conditions. It was developed by the University of California in the mid 20th century (Tragethon, 2011). In this method the warm produce is placed into an airtight chamber and the pressure is lowered inside the chamber to the point where water boils at the desired cooling temperature. Vacuum pumps are used to evacuate air from the chamber. As the pressure within the chamber is lowered to the saturation pressure corresponding to the initial temperature of the produce, water evaporates. The latent heat required for the evaporation is furnished by the product itself. In this way the sensible heat of the produce is reduced and precooling is accomplished. The bulk volume of vapor generated during the process is taken away by the vacuum pump and/or through a refrigeration coil that condenses the vapor back into the water (Fig. 6.20). In other words, by reducing the pressure the boiling point of water will be lowered so that the water from the surface of the produce can boil at 0°C, which corresponds to an ambient absolute pressure of 613.3 Pa.

Vacuum cooling is the most rapid method used to precool horticultural commodities where the product can be cooled down within 20–40 min. The first commercial vacuum cooling facility precooled five pallets of produce in a batch and reduced the product temperature below 4.4°C immediately following harvest. Since then, it has been broadly applied for the precooling process of leafy vegetables, such as lettuce and mushrooms.

Any produce with free water and whose structure will not be damaged by water removal can be vacuum cooled. However, the produce must have a porous structure in order to enable the diffusion of water vapor generated out of it to the surrounding atmosphere. The principle

FIG. 6.19 Vacuum precooler during operation.

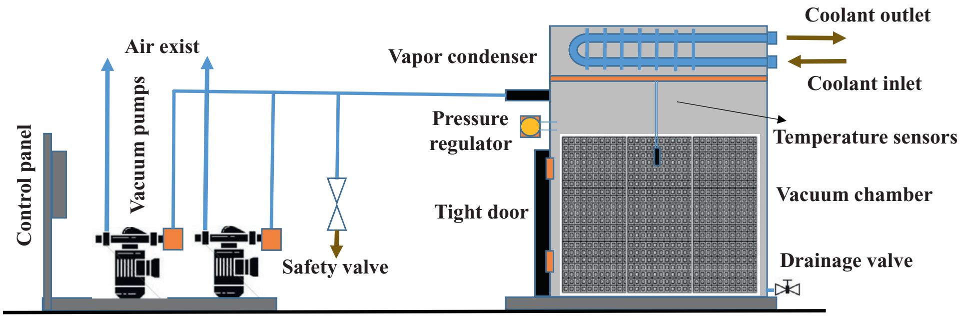

FIG. 6.20 The components of the vacuum precooler.

behind the vacuum cooling technology is the latent heat of vaporization, which is a thermodynamic property of water. This heat is removed from the produce during the evaporation process and results in a reduced temperature. Water is considered a natural refrigerant with a commercial name of R718. Liquid water as a refrigerant will boil at 100°C, though it is well established that boiling water at higher elevations, such as in the mountains, causes the water to boil at a temperature lower than 100°C. Therefore the vacuum cooling of leafy vegetables (e.g., lettuce) is based on lowering the pressure of the air-tight (sealed) cooling tube to the saturation pressure that meets the desired final low temperature required and evaporates some water from the products to be cooled. During this process, free water evaporates at the temperature corresponding to the boiling (flash) point, and as the saturation pressure of water at 0°C is 613.3 Pa the product can be cooled to 0°C by lowering the pressure to that level. With the continual reduction of the pressure of the vacuum chamber, progressive cooling of the produce takes place. Thus the cooling rate can be increased by lowering the pressure below 613.3 Pa, but this is not desirable because of the danger of freezing and the added cost to the system. When a product is subjected to a gradual vacuum the flash point of the water goes down and some of the water boils until new equilibrium conditions are attained (Alibas and Koksal, 2014).

The advantages of vacuum precooling are well proven. Because produce can be precooled in a tremendously short period of time, vacuum cooling has been demonstrated to provide many benefits to the fresh produce industry, including shortening produce dwell time, increasing productivity throughout, minimizing energy consumption, and reducing microbial growth. Vacuum cooling leads to uniform internal temperature distribution when compared with produce cooled using other precooling methods. Precise produce temperature control is easily achievable. Additionally, unlike other precooling techniques, vacuum cooling rate is not directly affected by produce shape or size, which makes itself a much more valuable technology for bulk produce. Vacuum cooling precools vegetables in any unsealed package or container. Additionally, vacuum cooling is considered a more hygienic process in which air only is allowed to enter the chamber at the end of the cooling process when the chamber is open to discharge the vacuum.

By analyzing the vacuum cooling process (Fig. 6.21), two stages can be distinguished. First, produce having an initial temperature of 25°C is brought into the vacuum tube and the operation is started. The chamber temperature remains unchanged until the saturation

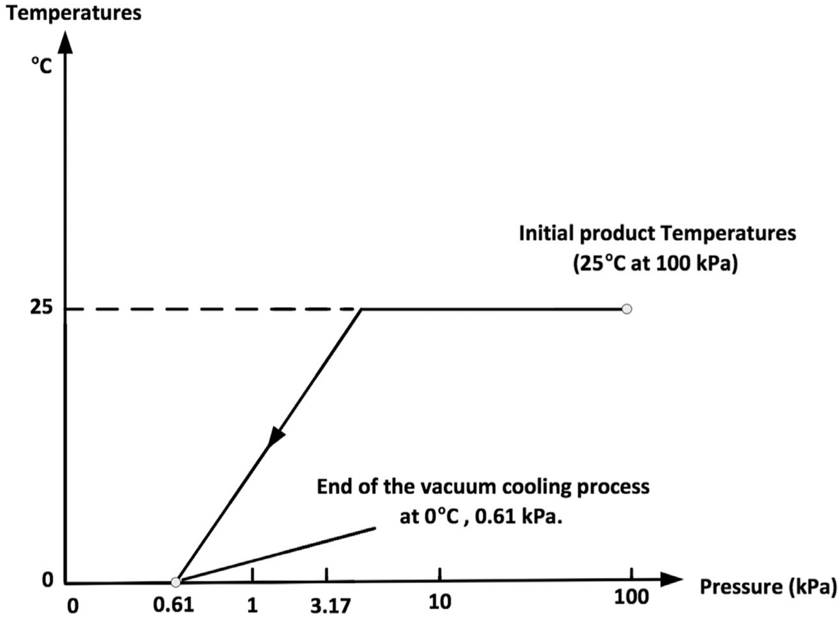

FIG. 6.21 Analysis of the vacuum precooling process.

pressure is achieved, which is 3.17 kPa at 25°C. Secondly, saturation conditions are sustained inside at gradually lower pressures and, consequently, lower temperatures until the desired final temperature is reached, which is commonly slightly above 0°C.

Vacuum cooling is the most expensive alternative when compared to the other precooling techniques. One of the reasons is its limited application specifically to produce with large surface areas per unit mass and a high tendency to liberate moisture. Produce with limited ratios of surface area to mass are not suitable for vacuum cooling, particularly those that have somewhat water-resistant peels, such as tomatoes and cucumbers. Hence the efficiency of cooling and the usefulness of vacuum cooling are mainly linked to the ratio between the crop's evaporation surface area and its mass in addition to the density of the produce and the amount of temperature drop required. Mushrooms and green peas can be vacuum cooled effectively by wetting them first.

The main drawback of the vacuum cooling process is the removal of some water vapor from the produce. However, it is possible to stop the cooling process at a predetermined pressure and temperature in addition to minimizing this water loss by spraying the produce with water before cooling. Some vacuum coolers are equipped with water spray systems that are activated in the course of the cooling cycle; such systems are called hydrovacuum methods. This water must potable and should be treated if it is recirculated. Typical cooling times range from 20 to 40 min at a temperature drop from 27°C to 2°C degrees, where the average moisture loss is 1% for each 11° temperature drop. Because produce is sold by weight a hydro-vacuum system can help reduce moisture loss and support improved economics.

In recent years, vacuum-cooling technology has drawn much attention, and its application has been broadened to the precooling of cut flowers. In 2013, FlowerForce of Netherland started to use the vacuum cooler to quickly cool their product. Using vacuum cooling substantially extends the shelf life of the flowers and reduce postharvest pathogens growth.

Generally, most of the existing precooling facilities and systems have been designed to use halogenated hydrocarbons (CFCs and HCFCs) whose emissions to the atmosphere are depleting the ozone layer and contributing significantly to global warming. The refrigerant leakage rates of the vapor compression systems to the environment is about 15% of the total refrigerant charge per annum (Elansari and Bekhit, 2017). Manufacturing and handling of CFCs is prohibited in most of the world, and many HCFC refrigerants are only a short-term substitute that is becoming more expensive and inefficient. With the phase-out of R22, vacuum cooling machines have a large potential market. In this method the refrigerant is water, which is more widely used and more environmentally friendly.

Cauliflower heads, whose initial temperature was 23.5 ± 0.5°C, were precooled until the temperature reached at 1°C by applying different methods (Alibas and Koksal, 2014). It was found that the most suitable cooling method to precool cauliflower in terms of cooling time and energy consumption is vacuum cooling. Precooling of mushrooms is a major traditional application of vacuum cooling due to the porous structure and high moisture content of mushrooms. For mushrooms, it was reported that the cooling time of 25 minutes from 25.1°C initial temperature to 2.4°C final temperature were achieved, while the weight loss was 5.3% (He et al., 2013). When cabbage is vacuum cooled a pressure of 0.7 kPa reduces the cooling time by 17% and 39%, compared with 1 and 1.5 kPa, respectively (Rahi et al., 2013). The effect of vacuum precooling on leaf lettuce was investigated where the structure of lettuce is complex in terms of heat and mass transfers (Liu et al., 2014). Based on the characteristics of leaf lettuce in vacuum precooling process an unsteady computation model was structured to analyze the aspects affecting vacuum precooling. Various factors such as the precooling temperature, pressure, and quantity of the spray-applied water were confirmed throughout the experiment. It was concluded that the measured and simulated values were basically the same, and the overall trend was comparable; that is the lower the vacuum pressure, the greater the cooling rate of lettuce and water loss rate.

It can be concluded that vacuum cooling machines have a large potential market in the fresh produce industry because its refrigerant is water, which is more widely used and more environmentally friendly. Vacuum cooling is applicable to fruits and vegetables harvested on rainy days, when it can quickly take away surplus moisture on their surface to achieve the cooling effect. Hydrovacuum cooling designed with an additional water circuit meets the rapid cooling while avoiding excessive moisture loss.

6.12 ICE LIQUID WATER MIX

Icing is a precooling technique that involves adding crushed ice on top of the produce in the container (Figs. 6.22 and 6.23). This can be done either manually or via a machine application. When using the machine, ice slurry is injected into produce packages through the side vents or handles without moving the packages from the produce pallets or having to open the tops of it. The slurry also can be quickly injected into each carton as it travels along a conveyor belt.

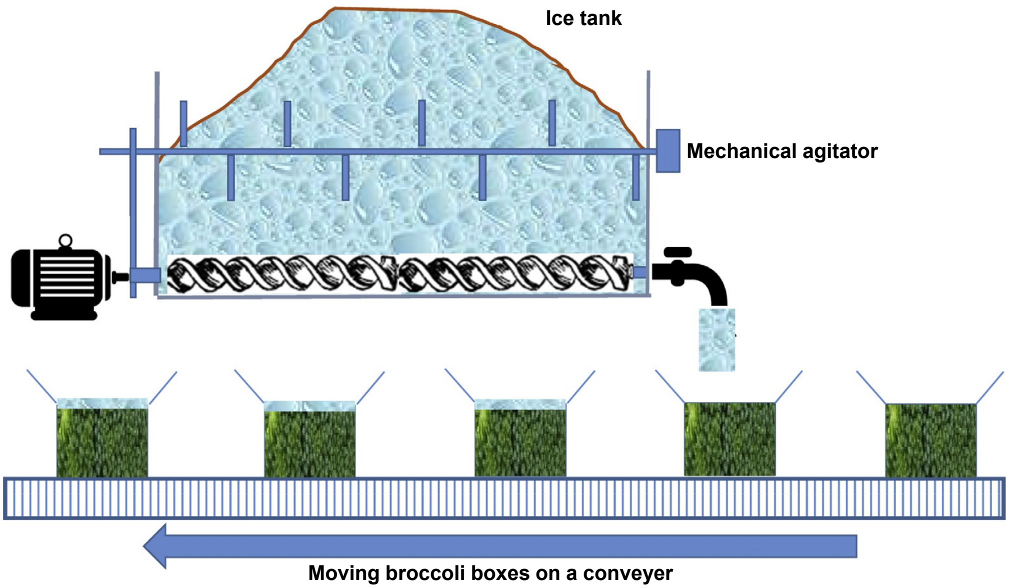

FIG. 6.22 Continuous application of ice to produce cartons.

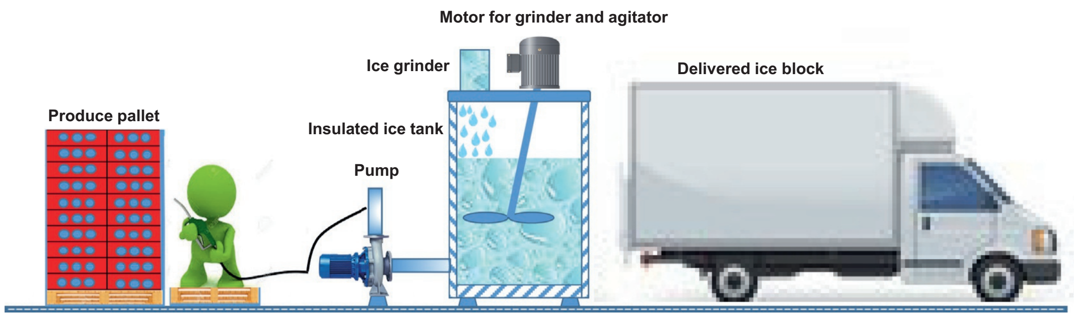

FIG. 6.23 Manual injection system for icing produce cartons.

Top icing is different than slurry in that top icing is a technique of applying a 5–10 cm layer of crushed ice to the top of the product packaging. This method can help maintain cooling for the top few layers of the produce once packed for transport. On the other hand, this method usually does not lead to the even cooling of produce. It is also inefficient, as a large amount of energy is needed to remove the sensible heat from water in order to make ice. Furthermore the method is not cost effective, as it takes 5 min or more for two devoted workers to ice a produce pallet of 30 cartons (Boyette and Estes, 2000), making it only marginally reasonable for small-scale operations. Additionally, crushed ice doesn't effectively cool all of the produce pallets; it only serves to maintain a low temperature. Crushed ice has razor-sharp ends and is quite coarse, which may harm the fresh product's surface. The ice slurry resolves most of these disadvantages because it has a high-energy storage density due to its large latent heat of fusion, and it also has a large heat transfer surface area created by its numerous particles that leads to rapid cooling effect. Therefore the leading advantage of slurry is the much greater contact with produce in addition to being cost effective and environmentally friendly.

Ice slurry is commonly used for fresh produce that can tolerate water such as asparagus, cauliflower, green onions, broccoli, cantaloupes, leafy greens, carrots and sweet corn, spinach, Brussels sprouts, parsley, artichokes, beets, endive, radishes, and watermelon. (El-Ramady et al., 2015). For example, broccoli undergoing rapid chilling by liquid ice of the field-packed waxed broccoli cartons—immediately after harvesting-demonstrated minimal wilting, suppressed enzymatic degradation and reduced respiratory activity. Also, it reduces ethylene production and slows down the progression of decay producing microorganisms. The use of liquid ice with broccoli guarantees that broccoli heads are kept fresh and attractive in appearance throughout the supply chain, right to the end consumer.

Some products that are not compatible with icing include berries, tomatoes, squash, green beans, cucumbers, onions, Romaine lettuce and herbs. Such products should not be precooled using any icing technique. Icing these sensitive products can cause damage, making them unacceptable for sale as well as consumption.

Liquid ice, as shown in Fig. 6.24, is a heterogeneous mixture of fine ice particles and carrier liquid that can be either pure freshwater or a binary solution comprising water and a freezing point food grade depressant, such as propylene glycol. Over the last two decades an interest in applying phase-change liquid ice as a coolant has developed substantially. The leading advantage of the liquid ice is its total heat content for liquid ice, which is approximately eight times higher than that of any traditional heat transfer fluid (secondary refrigerant) based on water, such as propylene glycol (Rhiemeier et al., 2009).

Kauffeld et al. (2010) described an automatic pallet icing chamber that can significantly increase the icing efficiency. The design includes an enclosed stainless steel space capable of icing a 48 cases pallet (9 kg broccoli per carton) for each icing cycle, in which only a single operator is needed to transport the produce pallet to that enclosure.

The liquid ice slurries range in a water-to-ice ratio from 1:1 to 1:4, in which the liquid nature of the slurry allows the ice to travel throughout the produce carton, filling the whole volume of the container, touching all the crevices and voids around and through the individual product. Additionally, slurry ice may be mixed with ozone as an additive in order to prevent microbial growth, extend shelf life, and preserve sensory quality (Keys, 2015). The slurry keeps a

FIG. 6.24 Liquid or slurry ice.

stable low temperature throughout the precooling process and supplies an excellent heat transfer coefficient compared with water or any other single-phase liquids. These features of the liquid ice contribute to its use as a fast cooling technique in fresh produce handling. For example, liquid ice, which is considered a thermal storage medium, can be generated during nighttime hours when power is cheap. During the daytime working hours the cold energy can then be rapidly discharged by melting the ice slurry for produce precooling when power might be several times more expensive.

Recently, Rawung et al. (2014) used a tropical ice cooler with cabbage in order to evaluate air circulation, cooling rate, storage periods, and cabbage loss. Results indicated that the highest cooling rate of ice at room temperature was 0.64°C/h, whereas the weight loss of cabbage was reduced to only 0.83%. In another study for Broccoli, four cooling methods were tested: room cooling, forced-air cooling, hydrocooling and package icing (Kochhar and Kumar, 2015). The temperatures of all four cooling mediums ranged from 0°C to 1°C. Based on the obtained results, it was concluded that package icing and hydrocooling were better methods of cooling than forced air precooling and hydrocooling.

A Canadian company (Sunwell Technologies Inc, 2015) has a newly built ice slurry system for fresh produce, in which the slurry ice is formed inside an ice generator and then transported to an insulated storage-dispenser tank, where they remain suspended in water (Fig. 6.25). Solid ice crystals from the top of the tank are then mixed with a small amount of water. The mixture is then discharged with a positive displacement pump via a network of piping to the packhouse, where it is spread over the produce or injected through the produce packs with a flexible hose. The complete pallet is swiftly chilled in 36 s. The excess water is drained away, leaving the produce pallet uniformly packed in slurry ice and ready for storage and dispatching. Different from other icing systems, this system eliminates the shipping weight by selecting the amount of slurry ice packed in each carton, where the amount of water with the ice slurry can vary according the temperature wanted to be attained and it could be ranged from 65% to 80% where the diameter of ice crystals is as low as 50–500 μm.

6.13 COOLING TIME ESTIMATION

All precooling processes display analogous performances. Following an initial "lag" period the temperature at the thermal center of the produce item decreases exponentially. A typical precooling curve (Fig. 6.26) illustrating this behavior can be obtained by plotting the ratio of the unaccomplished temperature difference, Y, against time on semilogarithmic axes in relation to the total temperature change possible for the cooling condition. The fractional unaccomplished temperature difference, Y, is expressed as follows:

$$Y = \frac{T_m - T}{T_m - T_i} = \frac{T - T_m}{T_i - T_m} \tag{6.1}$$

where T is the temperature at a given time, °C; T_i is the initial temperature, °C; and T_m is the cooling medium temperature, °C.

This semilogarithmic temperature history curve involves one initial curvilinear portion, followed by one or more linear portions. Empirical expressions that represent this cooling

FIG. 6.25 SUNWELL slurry ice system.

curve include two factors, C and j. C is the slope while j is the intercept of the temperature history curve on the semilogarithmic scale. C is called the cooling coefficient and indicates the change in the fractional unaccomplished temperature difference per unit cooling time. Hence C is the minus slope of the linear portion of the cooling curve. C depends upon the thermal properties of the produce mainly specific heat of the produce as well as the thermal conductance to the surroundings.

The j factor is a measure of the lag between the onset of cooling and the exponential decrease in the temperature of the produce; in other words the point at which the slope of the ln (Y) versus time becomes constant (the time needed for the ln (Y) versus time to become linear). Graphically, j corresponds to the time essential for the linear segment of the

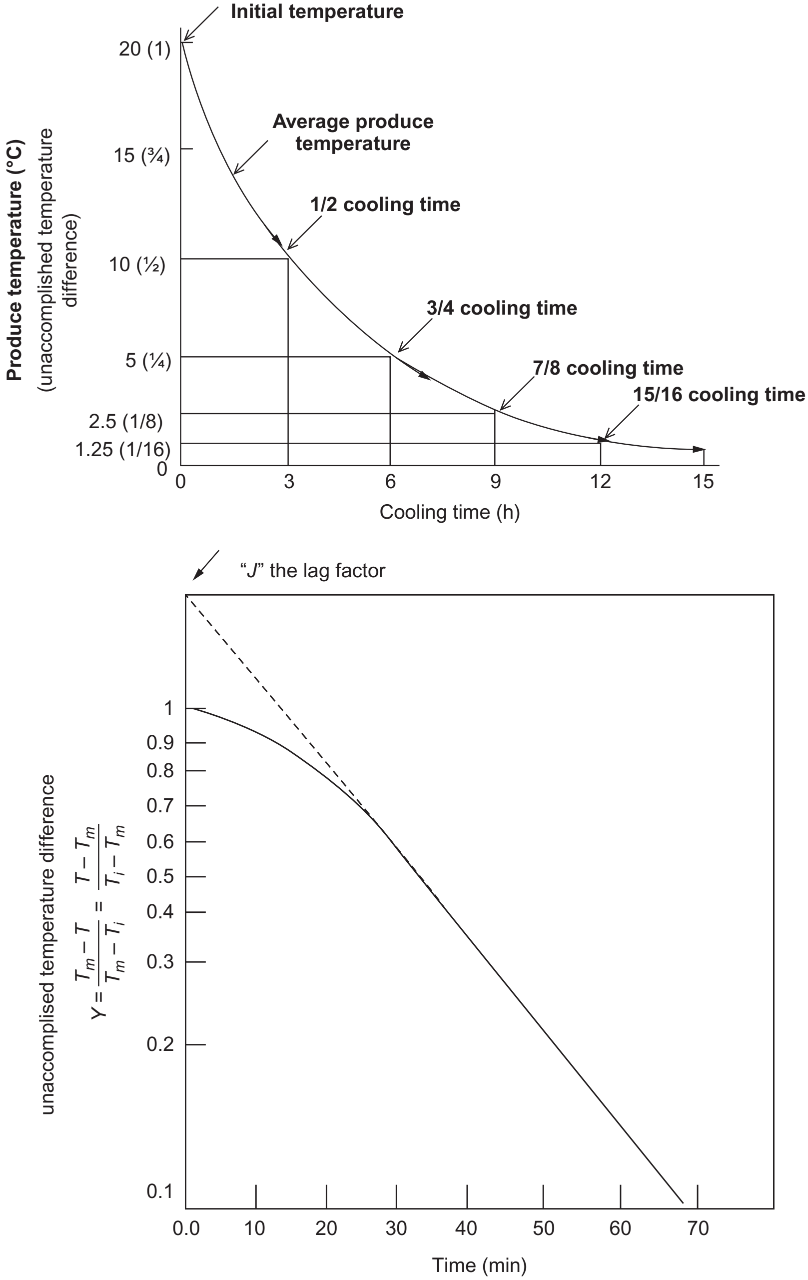

FIG. 6.26 Typical precooling curve and an example for the 7/8 cooling time in 9 h and its representation on a semilogarithmic scale.

temperature history curve to pass throughout one log cycle. Therefore the j factor represents the time required to obtain 90% fall in the nondimensional temperature difference.

The required cooling time for any precooling operation can be obtained explicitly as follows (Becker and Fricke, 2002):

$$\theta = \frac{1}{-C} \ln\left(\frac{y}{j}\right) \tag{6.2}$$

where C is the cooling coefficient, $1/S$. θ is the time elapsed during cooling, min.

A general concept used to characterize the hydrocooling process is the half-cooling (1/2) time, and for forced air precooling it is the 7/8 cooling time. Both are shown in Fig. 6.26. The half-cooling and the 7/8 cooling time is the time required to reduce the differences between the initial and the cooling medium temperature by half and 7/8, respectively. They are also equivalent to the time required to reduce the fractional unaccomplished temperature difference, Y, by half and 7/8 respectively. Both the half-cooling time and 7/8 cooling time are independent of the initial temperature and remain constant throughout the cooling period, provided that the cooling medium temperature remains constant and the produce temperature is uniform throughout the load. However, this assumption may not be valid for forced-air precooler, as poor air distribution may cause nonuniformity in produce temperature.

For example, if after 40 min in a cooler the temperature of the produce has dropped from 30°C to 15°C (the difference is 15°C) and the cooling air temperature is held constant at 0°C, therefore the product is half cooled. In other words the half-cooling time for this specific conditions is 40 min.

$$Y = \frac{T_m - T}{T_m - T_i} = \frac{0-15}{0-30} = \frac{1}{2} \tag{6.3}$$

To determine the 7/8 cooling time, we multiply the half-cooled time by three. Therefore it will take 120 min to reach 7/8 cooling. In other words, after 120 min the temperature of the produce will be:

$$T_i - \frac{7}{8}(T_i - T_m) = 30°\text{C} - \frac{7}{8}(30°\text{C} - 0°\text{C}) = 3.75°\text{C} \tag{6.4}$$

Examples for how to use these models and for the Berhee date fruit where the data collected are shown in Fig. 6.27 and Table 6.1, (Elansari, 2008). The table shows the lag factor (j), the cooling coefficient (C), and the half-cooling time obtained from experimental data. Assuming again that the temperature is to be lowered from 10°C to 4°C using 2°C cold water and for the small size fruit where the lag factor is 0.84 and the cooling coefficient is 0.31 1/S as shown in Table 6.1, the following general expression is applied:

$$\theta = \frac{1}{-C} \ln\left(\frac{Y}{j}\right)$$

$$Y = \frac{2-4}{2-10} = 0.25$$

$$= \frac{-0.31}{2.303} \ln\left(\frac{0.25}{0.84}\right) = 3.9\,\text{min}$$

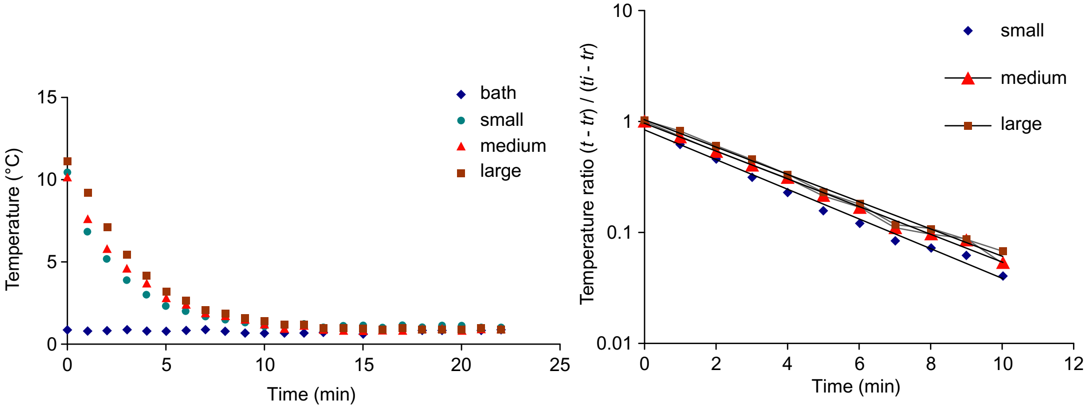

FIG. 6.27 Temperature history curve for Berhee date during hydrocooling.

TABLE 6.1 Values for Cooling Parameters for Barhee Dates With Different Sizes and Initial Temperatures for Hydrocooling (Elansari, 2008)

Treatment	Initial Temperature, T_i (°C)	Size of Barhee	Lag Factor (J)	Cooling Coefficient, C (s^{-1})	HCT ($Z_{1/2}$) (min)	7/8 Cooling Time ($Z_{7/8}$) (min)	R^2
1	10	Small	0.84	0.31	1.68 a	6.18 a	0.98
2		Medium	0.96	0.29	2.27 bc	7.10 ab	0.99
3		Large	1.02	0.28	2.53 cd	7.47 bc	0.99
4	15	Small	1.23	0.35	2.59 cd	6.59 ab	0.99
5		Medium	1.12	0.26	2.92 de	8.15 c	0.99
6		Large	1.08	0.27	3.08 e	8.35 c	0.98
7	25	Small	0.70	0.21	1.61 a	8.37 c	0.98
8		Medium	0.71	0.18	1.97 ab	9.67 d	0.98
9		Large	0.94	0.20	3.19 e	10.23 d	0.99
LSD					0.409	0.938	

Values followed by the same alphabetical letter(s) through a particular column in each treatment of means are not significantly different, using revised LSD test at $P \leq 0.05$.

Therefore it is expected to take 3.9 min to reach a final temperature of 4°C when using hydrocooling water with a 2°C constant temperature for the small size of Berhee date having an initial temperature of 10°C.

For the hydrocooling process the cooling time of fruits and vegetables may be determined using the half-cooling time, Z, as in the following equation (Becker and Fricke, 2002):

$$\theta = \frac{-Z \ln(Y)}{\ln(2)} \tag{6.5}$$

As an example for predicting the cooling time based on the last equation using the same case discussed before where the half-cooling time as shown in Table 6.1 is 1.68 minutes for the small fruit having an initial temperature of 10°C, applying the last equation leads to:

$$\theta = \frac{-Z\ \ln(Y)}{\ln(2)} = \frac{-1.68(\ln 0.25)}{0.693} = 3.36\,\text{min}$$

Both results for the expected cooling time (3.9 and 3.36 min) match the experimental results obtained, as shown in Fig. 6.26. Results obtained by the general model gave more accurate results because it contains both the cooling coefficient and the lag factor, which were obtained using the experimental data directly.

Produce detailed nomographs are available, that in conjunction with half-cooling times, can provide estimates of hydrocooling times. The discrepancy of the mass–average produce temperature with time is shown (Fig. 6.28) for some produce (ASHRAE, 1994; Elansari and Hobani, 2002). It is clear that lowering the temperature difference between the produce and the water to 10% of the initial value takes about 0.4 h for peaches, while it takes 0.7 h for citrus fruits. Therefore the size and density of the produce is an important factor influencing the hydrocooling rate in addition to other variables such as water temperature, produce orientation and water flow pattern.

Once the cooling data has been determined for a given produce the prediction of precooling process time is possible, apart from of the initial temperature of the produce or the temperature of the cooling medium. The half-cooling times, 7/8 cooling times, cooling coefficients, and lag factor have all been published for numerous commodities (ASHRAE, 2010). The 7/8 cooling time is very important for the cooling load calculations.

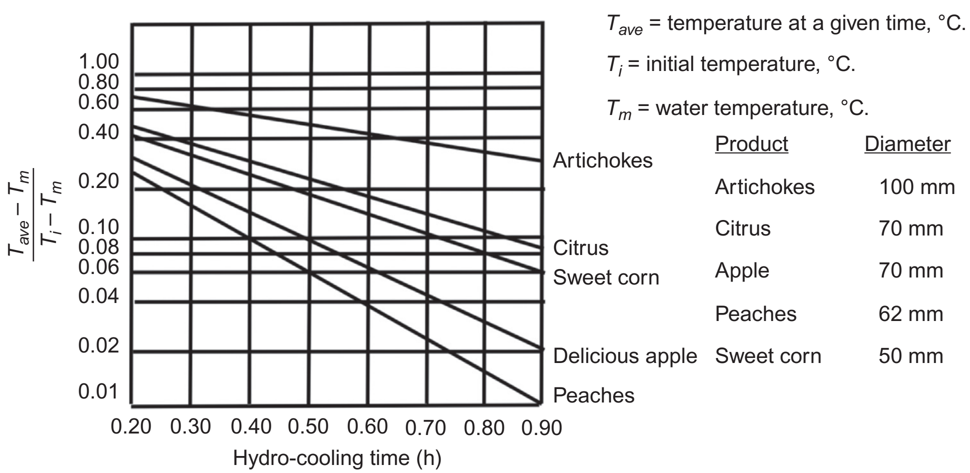

FIG. 6.28 Time-temperature response of various sizes produces during the hydrocooling process.

6.14 COOLING LOAD CALCULATIONS

6.14.1 Forced-Air Cooling

For forced-air cooling the refrigeration capacity requirements are much greater than simply storing products in a typical cold storage room, and they might be as much as 5 or 6 times greater than the requirements for a standard cold room design. Therefore the refrigeration requirements for obtaining fast, uniform cooling must be considered independently from cold storage. Appropriate cooling capacity permits room air temperature to be constant through the precooling process and avoids air temperature increases that slow down cooling rates. In forced-air coolers, precooling rates are determined by supplied cooling capacity in addition to volumetric airflow rate and product size. Wade (1984) developed an equation for the estimation of the refrigeration capacity required in terms of the rate of heat loss needed to cool produce. The developed model uses the seven-eighths cooling times as well as the lag factor. However, the developed model was not practically tested. Thompson and Gordon (1998) reported a calculation method for the estimation of the peak refrigeration capacity associated with product cooling based on certain assumptions where heat from miscellaneous sources such as fan motors was taken as a percentage of the product load.

In warm countries the initial temperature of table grapes at harvest, for example, may exceed 35°C, where the final required precooling temperature is 0.0°C and a condensing temperature of 47°C is very much expected in the outside surroundings. Such circumstances will be reflected in higher refrigeration capacity demands in order to meet these harsh environmental conditions.

Furthermore, fan load is considered the most significant factor in the forced air precooling process, as it contributes about 37% of the heat that must be removed from an average cooler (Thompson et al., 2010). The designed airflow rate considered for sizing the precooling fan is 7.2 m^3/h/kg with a static head pressure value of 375 Pa. The use of this value results in faster precooling rates and reduces the cooling time by about 40% (Castro et al., 2004; Thompson and Gordon, 1998). It is often difficult to predict the total static pressure that the fan must operate against because it is affected by many variables, such as carton side vents, the number and location of vent openings, alignment of vent holes between boxes, and the type of packing materials.

The total heat load for a forced-air cooling system is the sum of the product load, fan load, and extraneous heat conduction through walls, floors, and roof, air infiltration through doors, lights, motors, equipment, and personnel. The miscellaneous load can be averaged to be 20% of the product load. Therefore a simplified formula for heat load calculations per produce package is expressed as follows:

$$Q_t = \text{Product}\,load \times (1.2) + Fan\,load$$

$$Q_t = \left[\frac{W \times C_p \times \Delta T \times 1.2}{\frac{7}{8} \times CT \times 3600}\right] + \left[\frac{q \times W \times P}{\varepsilon \times 3600 \times 1000}\right] \tag{6.6}$$

Q_t is the total heat load, kW; W is the weight of product package, kg; C_p is the specific heat, 3.59, 3.84, 3.90, 3.92, and 3.8 kJ/kg °C for table grapes, strawberries, cantaloupe, mango, and green beans, respectively; ΔT is the cooling range ($T_1 - T_2$), °C; T_1 is the maximum expected

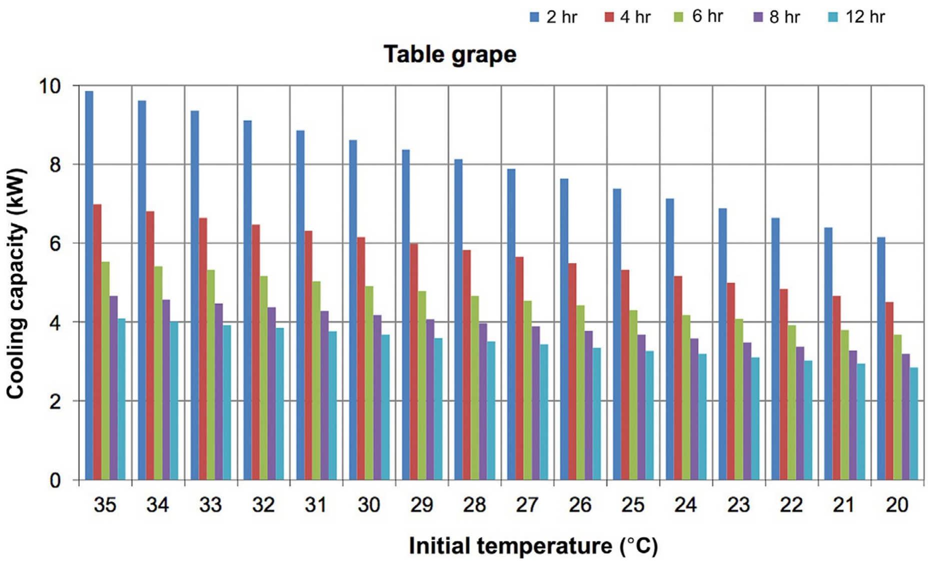

FIG. 6.29 Cooling capacity for table grapes per pallet (95 cartons, 5 kg/carton) at different initial temperature and different precooling duration.

initial temperature for the product, °C; T_2 is the Final recommended cooling temperature, °C; CT is the time to achieve the final recommended product temperature (T_2), h; q is the airflow, 7.2 $m^3\,h^{-1}\,kg^{-1}$; P is the fan pressure, 375 Pa; ε is the fan efficiency, assumed to be 0.5.

Figs. 6.29–6.33 are for table grapes, strawberries, cantaloupes, mangoes, and green beans, respectively, and were developed based on the previous equation for estimating cooling capacity (kW)/pallet. Using these curves, the cooling capacity required for any forced-air cooling project for the mentioned products can be determined considering all the factors listed above.

6.15 HYDROCOOLING AND ICE COOLING

The refrigeration capacity required for the hydrocooling process is much larger than that required for keeping produce at a constant temperature in a cold store (as much as 5 or 6 times) and it is essential to have sufficient refrigeration capacity for effective hydrocooling. However, it is wasteful to have more refrigerating capacity than is needed. Hence the optimum design of hydrocooling systems requires a wise estimate of the hydrocooling times of fruits and vegetables, as well as the parallel refrigeration loads for cold storage. Once the half-cooling time has been finalized for a given produce, the projection of hydrocooling time is feasible despite the initial temperature of the produce or the temperature of the cooling medium (water).

For example, melons, like other perishables, require proper precooling, whereas different varieties require different cooling and storage temperatures. For example, cantaloupes (Galia melons) and other similar categories of melons are cooled and stored at 2°C; Honeydew and similar varieties are cooled and stored at 7°C; while mixed melons are cooled and stored between 10°C and 13°C, depending on specific type. Melons require the relative humidity

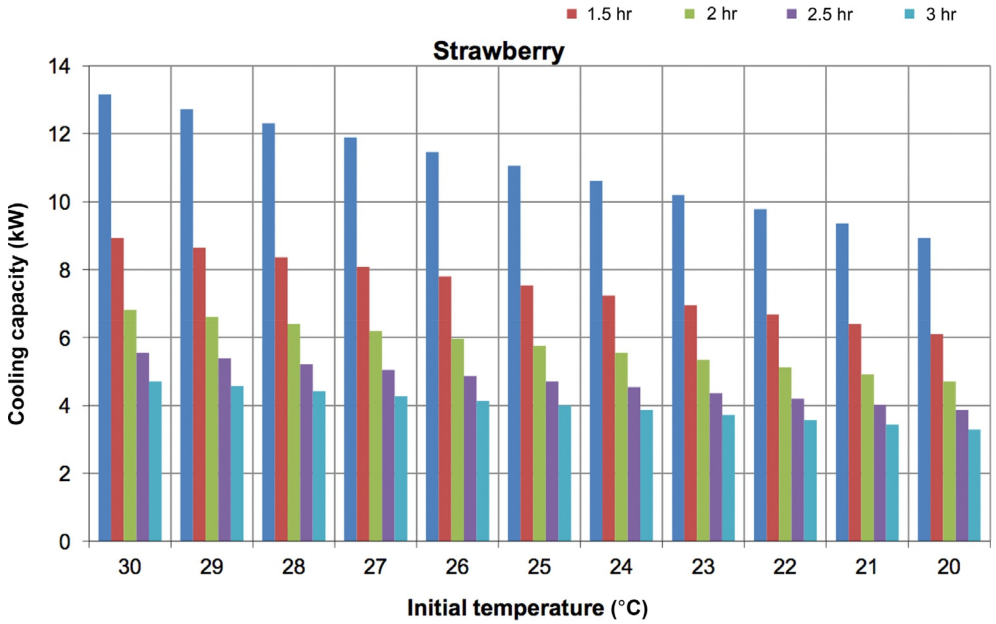

FIG. 6.30 Cooling capacity for strawberries per pallet (95 cartons, 5 kg/carton) initial temperature and different precooling duration.

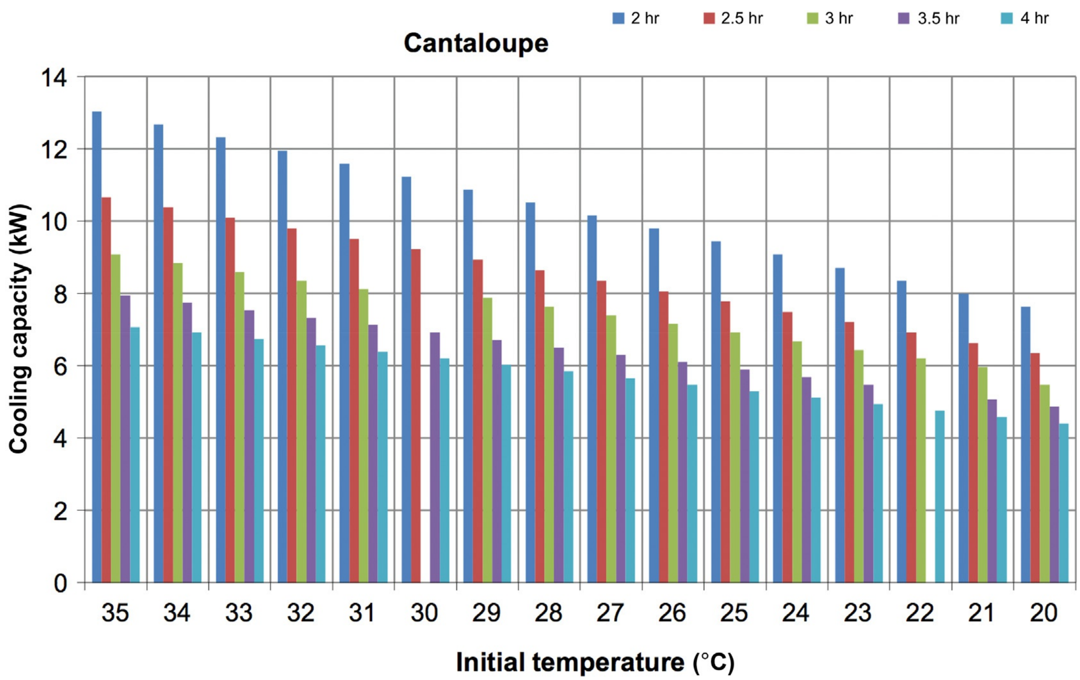

FIG. 6.31 Cooling capacity for cantaloupe per pallet (95 cartons, 5 kg/carton) initial temperature and different precooling duration.

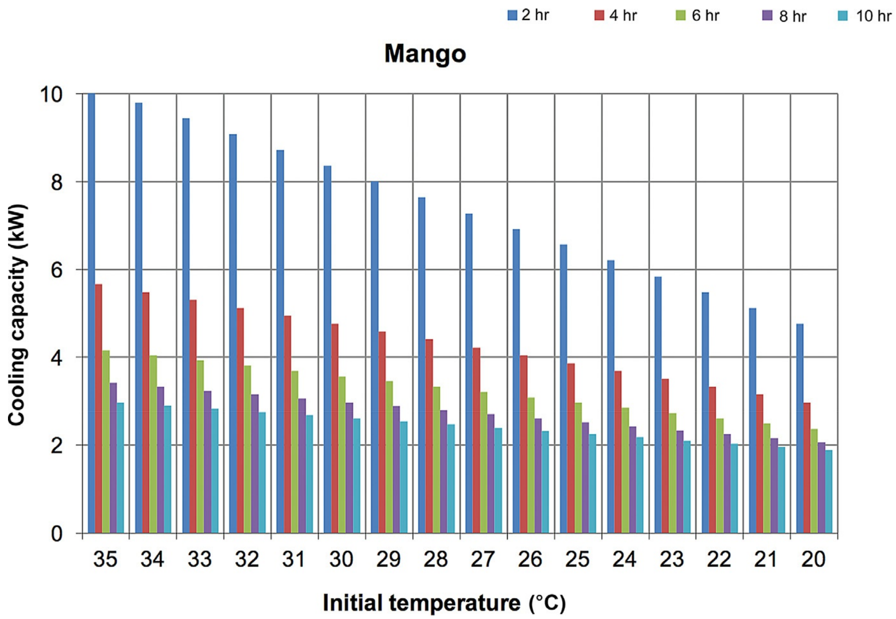

FIG. 6.32 Cooling capacity for mangoes per pallet (95 cartons, 4.5 kg/carton) initial temperature and different precooling duration.

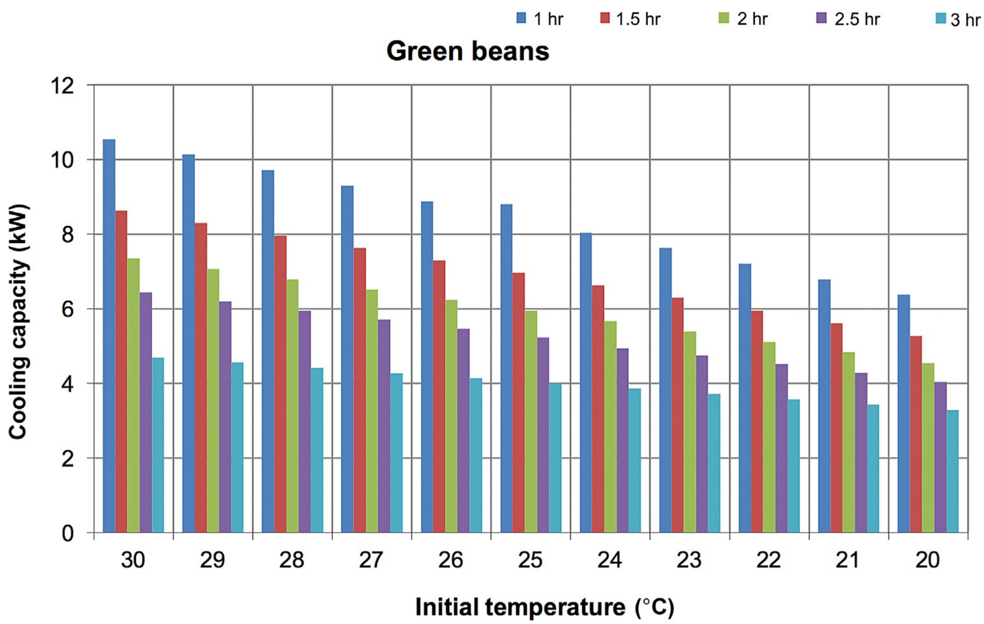

FIG. 6.33 Cooling capacity for green beans per pallet (95 cartons, 4 kg/carton) initial temperature and different precooling duration.

during cooling and storage to be between 85% and 90% RH; this applies for almost all varieties of melons. Refrigeration capacities are greater than that of forced-air cooling. This is due to the faster heat transfer rate caused by direct water contact with the fruit, therefore the average cooling time is less than forced-air cooling. The refrigeration capacity needed for the hydrocooling of melons, as an example, is based on the following model:

$$Q = (W \times C_p \times TR \times CF)/(CT \times 60) \tag{6.7}$$

Q is the product heat load, kW; W is the weight of produce, kg; C_p is the specific heat, 3.90 kJ/(kg °C); TR is the cooling rate, $T_1 - T_2$; T_1 is the initial product temperature before cooling, °C; T_2 is the initial product temperature before cooling, °C; CF is the cooling factor is based on a 30% ancillary heat load; CT is the cooling time, minutes.

For calculating the amount of ice required, the following assumptions are used:

Specific heat of ice $C_{pi} = 1.94$ kJ/(kg °C)
Specific heat of water $C_{pw} = 4.186$ kJ/(kg °C)
Latent heat of fusion of ice = 335 kJ/kg

Table 6.2 shows the refrigeration capacity required for melon hydrocooled with the chilled water pump and calculated using the above mentioned model. There is also a column in the developed table that shows the amount of ice required per kilogram (kg) of melon cooled (in the case of a small scale operation). The table shows the refrigeration capacity for hydrocooling the melon to one-half (1/2) cooling based on a nominal 20 minutes and 30 minutes retention time in the hydrocooler. These numbers include a 30% ancillary heat load factor with a good insulated cooler (Thompson and Chen, 1988).

6.16 VACUUM COOLING

The amount of vacuum cooling is equivalent to the amount of heat removed from the produce. It is therefore proportional to the weight of water evaporated, w_v, and the latent heat of vaporization of water at the average temperature, h_{fg}. It can be estimated as:

$$Q_{\text{vacuum}} = w_v h_{fg} \text{ (kJ)} \tag{6.8}$$

As:

$$Q_{\text{vacuum}} = m_P C_p \Delta T \text{ (kJ)} \tag{6.9}$$

where m_p is the produce weight, kg; C_p is the specific heat of the produce (kJ/kg·°C); ΔT is the temperature difference between the produce initial temperature and the final desired temperature (°C).

Therefore during vacuum cooling the amount of water vapor generated (also cooling loss) can be calculated by:

$$w_v = m_P C_p \Delta T / h_{fg} \text{ (kg)} \tag{6.10}$$

Example: If the initial temperature of the produce to be vacuum-cooled is 25°C and the desired final temperature is 0°C, then the average heat of vaporization can be taken to be

TABLE 6.2 Refrigeration Capacity for Hydrocooling Melons to 1/2 Initial Temperature for a 5 kg Box of Melon

				Amount of Ice Required (kg) at −5°C Up To 10°C Use of Meted Ice	
Initial Temperature (°C)	**Final Temperature (°C)**	**20 min Cooling Time (kW)**	**30 min Cooling Time (kW)**	**20 min Cooling Time**	**30 min Cooling Time**
35	18	0.359	0.239	1.11	0.74
34	17.5	0.349	0.232	1.08	0.72
33	17	0.338	0.225	1.05	0.70
32	16.5	0.327	0.218	1.02	0.68
31	16	0.317	0.211	0.98	0.66
30	15.5	0.306	0.204	0.95	0.63
29	15	0.296	0.197	0.92	0.61
28	14.5	0.285	0.190	0.89	0.59
27	14	0.275	0.183	0.85	0.57
26	13.5	0.264	0.176	0.82	0.55
25	13	0.254	0.169	0.79	0.52
24	12.5	0.243	0.162	0.75	0.50
23	12	0.232	0.155	0.72	0.48
22	11.5	0.222	0.148	0.69	0.46
21	11	0.211	0.141	0.66	0.44
20	10.5	0.201	0.134	0.62	0.42

2472 kJ/kg, which corresponds to the average temperature of 12.5°C (this is adapted from the properties of saturated water tables by interpolation). Assuming that the specific heat of produce is about 4.12 kJ/kg·°C, we need to estimate the temperature decrease for each 0.01 kg water evaporation per kg of produce. Therefore:

$$0.01\,\text{kg} = 1\,(\text{kg of produce}) \times 4.12\,(\text{kJ/kg°C}) \times \Delta T/2472\,(\text{kJ/kg})$$

$$\Delta T = 6.00°\text{C}$$

Hence, 0.01 kg of evaporated water will cool down 1 kg of produce by 6°C. In other words the vacuum-cooled produce, with no bulk water on its surface, will lose 1% moisture for each 6°C drop in their temperature. This means the products will experience a weight loss of 4% for a temperature drop of about 24°C. To minimize the product moisture loss and enhance the effectiveness of vacuum cooling the products are often wetted prior to cooling; also a hydrovacuum can be applied.

6.17 CONCLUSION

Different precooling techniques are presented along with theory, components, and recent applications. Cooling capacity and cooling time estimation methods were analyzed. To capitalize on the benefits of each individual system, careful design and selection of components is essential in order to optimize the capital investment needed, as well as the running and maintenance costs.

References

Alibas, I., Koksal, N., 2014. Forced-air, vacuum, and hydro precooling of cauliflower (*Brassica oleracea* L. var. botrytis cv. Freemont). Part I. Determination of precooling parameters. Food Sci. Technol. (Campinas) 34 (4), 730–737.

ASHRAE, 1994. Methods of precooling fruits, vegetables and cut flowers. In: Refrigeration Systems and Applications Handbook, Chapter 10. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA.

ASHRAE, 2010. Handbook of Fundamentals. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA.

Barbin, D.F., Neves Filho, L.C., Silveira, V., 2012. Portable forced-air tunnel evaluation for cooling products inside cold storage rooms. Int. J. Refrig. 35 (1), 202–208.

Becker, B.R., Fricke, B.A., 2002. Hydro-cooling time estimation methods. Int. Commun. Heat Mass Transfer 29, 165–174.

Becker, B.R., Fricke, B.A., 2006. Best practices in the design, construction, and management of refrigerated storage facilities. In: International Institute of Ammonia Refrigeration Annual Meeting, vol. 28, pp. 341–388.

Benz, S.M., 1989. Wet air-cooling. In: International Institute of Ammonia Refrigeration Annual Meeting, vol. 11, pp. 85–94.

Boyette, M.D., Estes, E.A., 2000. Crushed and Liquid Ice Cooling. Postharvest Technology Series AG-414-5. Carolina Cooperative Extension Service. https://content.ces.ncsu.edu/crushed-and-liquid-ice-cooling.

Boyette, M.D., Rohrbach, R.P., 1990. A low-cost, portable, forced-air pallet cooling system. Appl. Eng. Agric. 9, 97–104.

Boyette, M.D., Rohrbach, R.P., 1993. A low-cost, portable, forced-air pallet cooling system. Appl. Eng. Agric. 9 (1), 97–104.

Carnelossi, M.A.G., Sargent, S.A., Berry, A.D., 2014. Hydrocooling, Forced-Air-Cooling and Hydrocooling Plus Forced-Air-Cooling. American Society for Horticultural Science, ASHS Annual Conference, Salon.

Castro, L.R., Vigneault, C., Cortez, L.A.B., 2004. Effect of container opening area on air distribution during precooling of horticultural produce. Trans. ASAE 47 (6), 2033–2038.

Cengel, Y.A., Ghajar, A.J., 2013. Heat and Mass Transfer: Fundamentals and Applications, fifth ed. McGraw-Hill Higher Education, New York.

Christie, S., 2007. Pre-Cooling Fresh-Cuts; Cold Chain Begins Before Processing Starts. Fresh Cut. Great American Publishing.

Crisosto, C.H., Thompson, J.F., Garner, D., 2002. Table Grapes Cooling. Central Valley Postharvest Newsletter. Cooperative Extension. vol. 11 University of California, Kearney Agriculture Center, pp. 5–13.

Defraeye, T., Lambrecht, R., Tsige, A.A., Delele, M.A., Opara, U.L., Cronjé, P., Verboven, P., Nicolai, B., 2013. Forced-convective cooling of citrus fruit: package design. J. Food Eng. 118 (1), 8–18.

Defraeye, T., Verboven, P., Opara, U.L., Nicolai, B., Cronjé, P., 2015. Feasibility of ambient loading of citrus fruit into refrigerated containers for cooling during marine transport. Biosyst. Eng. 134, 20–30.

Elansari, A.M., 2008. Hydrocooling rates of Barhee dates at the Khalal stage. Postharvest Biol. Technol. 48 (3), 402–407.

Elansari, A.M., 2009. Design of portable forced—air precooling system. J. Saudi Soc. Agric. Sci. 2, 38–48.

Elansari, A.M., Bekhit, A.E.D., 2017. Freezing/thawing technologies. In: Bekhit, A.E.-d. (Ed.), Advances in Meat Processing. CRC Press, pp. 219–265.

Elansari, A.M., Hobani, A.I., 2002. Hydro-Cooling of Artichokes Heads. vol. 115. Agricultural Research Center, King Saud University, Saudi Arabia, pp. 5–15.

Elansari, A.M., Shokr, A.Z., Hussein, A.M., 2000. The use of sea-shipment container as a portable pre-cooling facility. Misr J Agric Eng 17, 401–411.
Elansari, A.M., Siddiqui, M.W., 2016. Recent recent advances in postharvest cooling of horticultural produce. In: Siddiqui Wasim, M.W. (Ed.), Postharvest Management of Horticultural Crops Practices for Quality Preservation. Chapter 1. Apple Academic Press.
Elansari, A.M., Yahia, E.M., 2012. Cold Chain for Perishable Foods (In Arabic). FAO Regional Office for the Near East and North Africa, http://neareast.fao.org.
El-Ramady, H.R., Domokos-Szabolcsy, É., AAbdalla, N., Taha, H.S., Fári, M., 2015. Postharvest Management of Fruits and Vegetables Storage. Sustainable Agriculture Reviews. Springer International Publishing, Switzerland, pp. 65–152.
Farrimond, A., Lindsay, R.T., Neale, M.A., 1979. The ice bank cooling system with positive ventilation. Int. J. Refrig. 2 (4), 199–205.
Ferreira, M.D., Brecht, J.K., Sargent, S.A., Chandler, C.K., 2006. Hydrocooling as an alternative to forced-air-cooling for maintaining fresh-market strawberry quality. Hort. Technol. 16, 659–666.
Ferrua, M.J., Singh, R.P., 2009. Modeling the forced-air-cooling process of fresh strawberry packages. Part I. Numerical model. Int. J. Refrig. 32 (2), 335–348.
He, S.Y., Yu, Y.Q., Zhang, G.C., Yang, Q.R., 2013. Effects of vacuum pre-cooling on quality of mushroom after cooling and storage. Adv. Mater. Res. 699, 189–193.
Hugh, W., Fraser, P., 1998. Tunnel forced—air-coolers. Canadian Plan Service 98031, 1–10.
Jacomino, A.P., Sargent, S.A., Berry, A.D., Brecht, J.K., 2011. Potential for grading, sanitizing, and hydrocooling fresh strawberries. Proc. Fla. State Hort. Soc. 124, 221–226.
James, S.J., 2013. Refrigeration systems. In: Baker, C.G.J. (Ed.), Handbook of Food Factory Design. Springer International Publishing AG.
Kader, A.A., 2002. Postharvest Technology of Horticultural Crops. Coop. Ext. Service. University of California. Special Pubi. 3311. Agr., & Nat. Resources Pubi, Berkley, CA.
Kauffeld, M., Wang, M.J., Goldstein, V., Kasza, K.E., 2010. Ice slurry applications. Int. J. Refrig. 33 (8), 1491–1505.
Keys, D.R., 2015. Cooling Characterizations and Practical Utilization of Sub-micron Slurry Ice for the Chilling of Fresh Seafood. MSc Thesis, Oregon State University.
Kitinoja, L., Thompson, J.F., 2010. Precooling systems for small scale producers. Stewart Postharvest Rev. 2(2).
Kochhar, V., Kumar, S., 2015. Effect of different pre-cooling methods on the quality and shelf life of Broccoli. J. Food Process. Technol. 6 (3), 1–7.
Laurin, E., Nunes, M.C.N., Emond, J.P., 2003. Forced-air-cooling after air-shipment delays asparagus deterioration. J. Food Qual. 26 (1), 43–54.
Laurin, E., Nunes, M.C.N., Emond, J.P., 2005. Re-cooling of strawberries after air shipment delays fruit senescence. Acta Hortic. (682), 1745–1751.
Liang, Y.S., Wongmetha, O., Wu, P.S., Ke, L.S., 2013. Influence of hydrocooling on browning and quality of litchi cultivar Feizixiao during storage. Int. J. Refrig. 36 (3), 1173–1179.
Liu, E., Hu, X., Liu, S., 2014. Experimental study on effect of vacuum pre-cooling for post-harvest leaf lettuce. Res. Crops 15 (4), 907–911.
Luvisi, D., Shorey, H., Thompson, J.F., Hinsch, T., Slaughter, D., 1995. Packaging California Grapes. University of California, DANR, Publication # 1934.
Manganaris, G.A., Ilias, I.F., Vasilakakis, M., Mignani, I., 2007. The effect of hydro- cooling on ripening related quality attributes and cell wall physicochemical proper- ties of sweet cherry fruit (*Prunus avium* L.). Int. J. Refrig. 30 (8), 1386–1392.
Morton, R.D., McDevitt, M.L., 2000. Evaporator fan variable frequency drive effects on energy and fruit quality. In: 16th Annual Postharvest Conference, Yakima, WA, 14–15.
Mworia, E.G., Yoshikawa, T., Salikon, N., Oda, C., Asiche, W.O., Yokotani, N., Abe, D., Ushijima, K., Nakono, R., Kubo, Y., 2012. Low-temperature-modulated fruit ripening is independent of ethylene in 'Sanuki Gold' kiwi fruit. J. Exp. Bot. 63 (2), 963–971.
Pathare, P.B., Opara, U.L., Vigneault, C., Delele, M.A., Al-Said, F.A.J., 2012. Design of packaging vents for cooling fresh horticultural produce. Food Bioprocess Technol. 5 (6), 2031–2045.
Rahi, S., Bahrami, H., Shaeikhdavoodi, M., 2013. Using vacuum cooling method of precooling process of cabbage. J. Life Sci. Biomed. 3 (1), 56–59.

Rawung, H., Ubis, S., Kairupan, S., Wullur, H., Tooy, D., 2014. Analysis of a cooling system for cabbage in a box cooler. International Conference on Food, Agriculture and Biology (FAB, 2014), Kuala Lumpur (Malaysia).
Rhiemeier, J.M., Harnisch, J., Ters, C., Kauffeld, M., Leisewitz, A., 2009. Comparative assessment of the climate relevance of supermarket refrigeration systems and equipment. Environmental Research of the Federal Ministry of the Environment, Nature Conservation and Nuclear Safety Research Report # 20644300.
Ross, D.S., 1990. Postharvest Cooling Basics. vol. 178 Facts Agricultural Engineering/University of Maryland, Cooperative Extension Service, pp. 1–8.
Russell, K., 2006. Refrigeration for controlled atmosphere storage of apples in the 21st century. In: International Institute of Ammonia Refrigeration Annual Meeting. vol. 28, pp. 275–314.
Ryall, A.L., Lipton, W.J., Pentzer, W.T., 1982. Handling, Transportation and Storage of Fruits and Vegetables. vol. 1. AVI Pub. Co, Westport, CT.
Sreedharan, A., Tokarskyy, O., Sargent, S., Schneider, K.R., 2015. Survival of *Salmonella* spp. on surface-inoculated forced-air-cooled and hydrocooled intact strawberries, and in strawberry puree. Food Control 51, 244–250.
Sunwell Technologies Inc, 2015. http://www.sunwell.com.
Suslow, T., 1997. Postharvest Chlorination: Basic Properties and Key Points for Effective Disinfection. University of California, Division of Agriculture and Natural Resources.
Talbot, M.T., Fletcher, J.H., 1993. Design and development of a portable forced-air-cooler. In: Proceedings-Florida State Horticultural Society. vol. 106, p. 249.
Tassou, S.A., Xiang, W., 1998. Modeling the environment within a wet air-cooled vegetable store. J. Food Eng. 38 (2), 169–187.
Thompson, J.F., 2004. The commercial storage of fruits, vegetables, and florist and nursery stocks. In: Agriculture Handbook Number 66. USDA, ARS.
Thompson, J.F., Chen, Y.L., 1988. Comparative energy for use of vacuum, hydro and forced air coolers for fruits and vegetables. ASHRAE Trans. 94 (1), 1427–1432.
Thompson, J.F., Gordon, M.F., 1998. In: Rumsey, T.R., Kasmire, R.F., Crisosto, C. (Eds.), Commercial Cooling of Fruits, Vegetables and Flowers. University of California Division of Agricultural and Natural Resources. Publication No. 21567.
Thompson, J.F., Mejia, D.C., Singh, R.P., 2010. Energy use of commercial forced-air-coolers for fruit. Appl. Eng. Agric. 26 (5), 919–924.
Tokarskyy, O., Schneider, K.R., Berry, A., Sargent, S.A., Sreedharan, A., 2015. Sanitizer applicability in a laboratory model strawberry hydrocooling system. Postharvest Biol. Technol. 101, 103–106.
Tragethon, D., 2011. Vacuum Cooling—The Science and Practice. Industrial Refrigeration Conference and Heavy Equipment Show Caribe Royale, Orlando, FL.
Tucker, G.S., 2016. Food Preservation and Biodeterioration. John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, UK.
Vigneault, C., Markarian, N.R., Da Silva, A., Goyette, B., 2004. Pressure drop during forced-air ventilation of various horticultural produce in containers with different opening configurations. Trans. ASAE 47 (3), 807–814.
Wade, N.L., 1984. Estimation of the refrigeration capacity required to cool horticultural produce. Int. J. Refrig. 7 (6), 358–366.
Wang, Y., Long, L.E., 2015. Physiological and biochemical changes relating to post-harvest splitting of sweet cherries affected by calcium application in hydrocooling water. Food Chem. 181, 241–247.
Yahia, E.K., Smolak, J., 2014. Developing the Cold Chain for Agriculture in the Near East and North Africa (NENA). FAO Regional Office for the Near East and North Africa, http://neareast.fao.org.
Yang, Z., Z. Ma, C. Zha, and Y. Chen. 2007. Study on forced-air pre-cooling of Longan. American Society of Agricultural and Biological Engineers, Paper No. 076267. St. Joseph.

Further Reading

Sahar, R., Bahrami, H., Sheikhdavoodi, M.J., 2013. Using vacuum cooling method of precooling process of cabbage. J. Life Sci. Biomed. J. Life Sci. Biomed. 3 (1), 56–59.
Yunus, A.C., Ghajar, A.J., 2013. Refrigeration and freezing of foods. Chapter 17In: Heat and Mass Transfer: Fundamentals and Applications. McGraw-Hill.
Yunus, C., Michael, B., 2014. Thermodynamics: An Engineering Approach. McGraw-Hill.