Related Commercial Resources

CHAPTER 15

METHODS OF PRECOOLING FRUITS, VEGETABLES, AND CUT FLOWERS

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PRECOOLING is the rapid removal of field heat from freshly harvested fruits and vegetables before shipping, storage, or processing. Prompt precooling inhibits growth of microorganisms that cause decay, reduces enzymatic and respiratory activity, and reduces moisture loss. Thus, proper precooling reduces spoilage and retards loss of preharvest freshness and quality (Becker and Fricke 2002).

Precooling requires greater refrigeration capacity and cooling medium movement than do storage rooms, which hold commodities at a constant temperature. Thus, precooling is typically a separate operation from refrigerated storage and requires specially designed equipment (Fricke and Becker 2003). Precooling can be done by various methods, including hydrocooling, vacuum cooling, air cooling, and contact icing. These methods rapidly transfer heat from the commodity to a cooling medium such as water, air, or ice. Cooling times from several minutes to over 24 hours may be required.

PRODUCT REQUIREMENTS

During postharvest handling and storage, fresh fruits and vegetables lose moisture through their skins through transpiration. Commodity deterioration, such as shriveling or impaired flavor, may result if moisture loss is high. To minimize losses through transpiration and increase market quality and shelf life, commodities must be stored in a low-temperature, high-humidity environment. Various skin coatings and moisture-proof films can also be used during packaging to significantly reduce transpiration and extend storage life (Becker and Fricke 1996a).

Metabolic activity in fresh fruits and vegetables continues for a short period after harvest. The energy required to sustain this activity comes from respiration, which involves oxidation of sugars to produce carbon dioxide, water, and heat. A commodity's storage life is influenced by its respiratory activity. By storing a commodity at low temperature, respiration is reduced and senescence is delayed, thus extending storage life. Proper control of oxygen and carbon dioxide concentrations surrounding a commodity is also effective in reducing the respiration rate (Becker and Fricke 1996a).

Product physiology, in relation to harvest maturity and ambient temperature at harvest time, largely determines precooling requirements and methods. Some products are highly perishable and must begin cooling as soon as possible after harvest; examples include asparagus, snap beans, broccoli, cauliflower, sweet corn, cantaloupes, summer squash, vine-ripened tomatoes, leafy vegetables, globe artichokes, brussels sprouts, cabbage, celery, carrots, snow peas, and radishes. Less perishable produce, such as white potatoes, sweet potatoes, winter squash, pumpkins, and mature green tomatoes, may need to be cured at a higher temperature. Cooling of these products is not as important; however, some cooling is necessary if ambient temperature is high during harvest.

Commercially important fruits that need immediate precooling include apricots; avocados; all berries except cranberries; tart cherries; peaches and nectarines; plums and prunes; and tropical and subtropical fruits such as guavas, mangos, papayas, and pineapples. Tropical and subtropical fruits of this group are susceptible to chilling injury and thus need to be cooled according to individual temperature requirements. Sweet cherries, grapes, pears, and citrus fruit have a longer postharvest life, but prompt cooling is essential to maintain high quality during holding. Bananas require special ripening treatment and therefore are not precooled. Chapter 11 lists recommended storage temperatures for many products.

CALCULATION METHODS

Heat Load

The refrigeration capacity needed for precooling is much greater than that for holding a product at a constant temperature or for slow cooling. Although it is imperative to have enough refrigeration for effective precooling, it is uneconomical to have more than is normally needed. Therefore, heat load on a precooling system should be determined as accurately as possible.

Total heat load comes from product, surroundings, air infiltration, containers, and heat-producing devices such as motors, lights, fans, and pumps. Product heat accounts for the major portion of total heat load, and depends on product temperature, cooling rate, amount of product cooled in a given time, and specific heat of the product. Heat from respiration is part of the product heat load, but it is generally small. Chapter 13 discusses how to calculate the refrigeration load in more detail.

Product temperature must be determined accurately to calculate heat load accurately. During rapid heat transfer, a temperature gradient develops in the product, with faster cooling causing larger gradients. This gradient is a function of product properties, surface heat transfer parameters, and cooling rate. Initially, for example, hydrocooling rapidly reduces the temperature of the exterior of a product, but may not change the center temperature at all. Most of the product mass is in the outer portion. Thus, calculations based on center temperature would show little heat removal, though, in fact, substantial heat has been extracted. For this reason, the product mass-average temperature must be used for product heat load calculations (Smith and Bennett 1965).

The product cooling load can then be calculated as

$$Q = mc_p(t_i - t_{ma}) \tag{1}$$

where m is the mass of product being cooled, c_p is the product's specific heat, t_i is the product's initial temperature, and t_{ma} is the product's final mass average temperature. Specific heats of various fruits and vegetables can be found in Chapter 9.

The preparation of this chapter is assigned to TC 10.9, Refrigeration Application for Food and Beverages.

Precooling Time Estimation Methods

Efficient precooler operation involves (1) proper sizing of refrigeration equipment to maintain a constant cooling medium temperature, (2) adequate flow of the cooling medium, and (3) proper product residence time in the cooling medium. Thus, to properly design a precooler, it is necessary to estimate the time required to cool the commodities from their initial temperature (usually the ambient temperature at harvest) to the final temperature, just before shipping and/or storage. For a specified cooling medium temperature and flow rate, this cooling time dictates the residence time in the precooler that is required for proper cooling (Fricke and Becker 2003).

Accurate estimations of precooling times can be obtained by using finite-element or finite-difference computer programs, but the effort required makes this impractical for the design or process engineer. In addition, two- and three-dimensional simulations require time-consuming data preparation and significant computing time. Most research to date has been in the development of semianalytical/empirical precooling time estimation methods that use simplifying assumptions, but nevertheless produce accurate results.

Fractional Unaccomplished Temperature Difference

All cooling processes exhibit similar behavior. After an initial lag, the temperature at the food's thermal center decreases exponentially (see Chapter 10). As shown in Figure 1, a cooling curve depicting this behavior can be obtained by plotting, on semilogarithmic axes, the fractional unaccomplished temperature difference Y [Equation (2)] versus time (Fricke and Becker 2004).

$$Y = \frac{t_m - t}{t_m - t_i} = \frac{t - t_m}{t_i - t_m} \tag{2}$$

where t_m is the cooling medium temperature, t_i is the initial commodity temperature, and t is the commodity final mass average temperature. This semilogarithmic temperature history curve consists of an initial curvilinear portion, followed by a linear portion. Simple empirical formulas that model this cooling behavior, such as half-cooling time and cooling coefficient, have been proposed for estimating the cooling time of fruits and vegetables.

Half-Cooling Time

A common concept used to characterize the cooling process is the half-cooling time, which is the time required to reduce the temperature difference between the commodity and the cooling medium by half (Becker and Fricke 2002). This is also equivalent to the time required to reduce the fractional unaccomplished temperature difference Y by half.

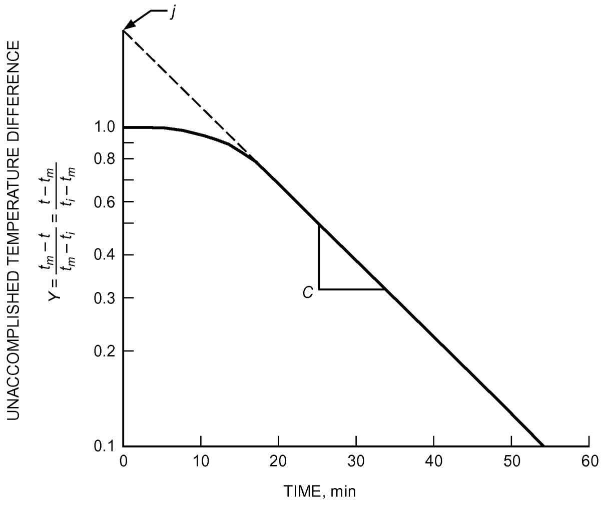


Fig. 1 Typical Cooling Curve

The half-cooling time is independent of initial temperature and remains constant throughout the cooling period as long as the cooling medium temperature remains constant (Becker and Fricke 2002). Therefore, once the half-cooling time has been determined for a given commodity, cooling time can be predicted regardless of the commodity's initial temperature or cooling medium temperature.

Product-specific nomographs have been developed, which, when used in conjunction with half-cooling times, can provide estimates of cooling times for fruits and vegetables (Stewart and Couey 1963). In addition, a general nomograph (Figure 2) was constructed to calculate hydrocooling times of commodities based on their half-cooling times (Stewart and Couey 1963). In Figure 2, product temperature is plotted along the vertical axis versus time measured in half-cooling periods along the horizontal axis. At zero time, the product temperature is the initial commodity temperature; at infinite time, product temperature equals water temperature. To use Figure 2, draw a straight line from the initial commodity temperature at zero time (left axis) to the commodity temperature at infinite time [i.e., the water temperature (right axis)]. Then draw a horizontal line at the final commodity temperature (left and right axes). The intersection of these two lines determines the number of half-cooling periods required (bottom axis). Multiply the half-cooling time for the particular commodity by the number of half-cooling periods to obtain the hydrocooling time.

The following example illustrates the use of the general nomograph for determining hydrocooling time.

Example 1. Assume that topped radishes with a half-cooling time of 2.2 min are to be hydrocooled using 32°F water. How long would it take to hydrocool the radishes from 80° to 50°F?

Solution. Using the general nomograph in Figure 2, draw a straight line from 80° on the left to 32°F on the right. Then draw a horizontal line at the final commodity temperature, 50°F. These lines intersect at 1.4 half-cooling periods. Multiply this by the half-cooling time (2.2 min) to obtain the total hydrocooling time of 3.1 min.

Using nomographs can be time consuming and cumbersome, however. Cooling time θ of fruits and vegetables may be determined without the use of nomographs by using the half-cooling time Z:

$$\theta = \frac{-Z \ln(Y)}{\ln(2)} \tag{3}$$

Values of half-cooling times for the hydrocooling of numerous commodities have been reported (Bennett 1963; Dincer 1995; Dincer and Genceli 1994, 1995; Guillou 1958; Nicholas et al. 1964; O'Brien and Gentry 1967; Stewart and Couey 1963). Tables 1 to 3 summarize half-cooling time data for a variety of commodities.

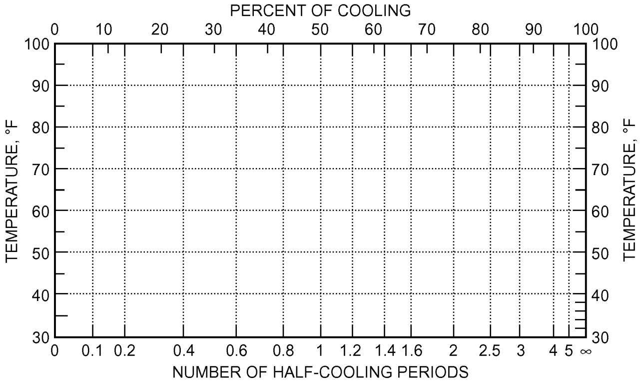


Fig. 2 General Nomograph to Determine Half-Cooling Periods
(Stewart and Couey 1963)

Table 1 Half-Cooling Times for Hydrocooling of Various Commodities

Commodity	Commodity Size	Container	Half-Cooling Time, min.
Artichoke		None (completely exposed)	8
		Crate, lid off, paper liner	12
Asparagus	Medium	Completely exposed	1.1
		Lidded pyramid crate, spears upright	2.2
Broccoli		Completely exposed	2.1
		Crate with paper liner, lid off	2.2
		Crate without liner, lid off	3.1
Brussels sprouts		Completely exposed	4.4
		Carton, lid open	4.8
		Jumble stack (9 in. deep)	6.0
Cabbage		Completely exposed	69
		Carton, lid open	81
		Jumble stack (four layers)	81
Carrots, topped	Large	Completely exposed	3.2
		50 lb mesh bag	4.4
Cauliflower, trimmed		Completely exposed	7.2
Celery	2 Dozen	Completely exposed	5.8
		Crate, lidded, paper liner	9.1
Sweet corn, in husks	5 Dozen	Completely exposed	20
		Wirebound corn crate, lidded	28
Peas, in pod		Completely exposed (flood)	1.9
		1 bushel basket, lid off (flood)	2.8
		1 bushel basket, lidded (submersion)	3.5
Potatoes		Completely exposed	11
		Jumble stack (five layers, 9 in. deep)	11
Radishes		Completely exposed	1.1
		Crate, lid off, three layers of bunches, 9 in. deep	1.9
		Carton, lid open, three layers of bunches, 9 in. deep	1.4
topped		Completely exposed	1.6
		Jumble stack (9 in. deep)	2.2
Tomatoes		Completely exposed	10
		Jumble stack, five layers, 10 in. deep	11

Source: Stewart and Couey (1963).

Cooling Coefficient

Cooling time may also be predicted using the cooling coefficient C. As shown in Figure 1, the cooling coefficient is minus the slope of the $\ln(Y)$ versus time curve, constructed on a semilogarithmic axis from experimental observations of time and temperature (Becker and Fricke 2002). The cooling coefficient indicates the change in the fractional unaccomplished temperature difference per unit cooling time (Dincer and Genceli 1994). The cooling coefficient depends on the commodity's specific heat and thermal conductance to the surroundings (Guillou 1958). Using the cooling coefficient for a particular cooling process, cooling time θ may be estimated as

$$\theta = -\frac{1}{C}\ln\left(\frac{Y}{j}\right) \tag{4}$$

The lag factor j is a measure of the time between the onset of cooling and the point at which the slope of the $\ln(Y)$ versus θ curve becomes constant [i.e., the time required for the $\ln(Y)$ versus θ curve to become linear]. The lag factor j can be found by extending the linear portion of the semilogarithmic cooling curve to the $\ln(Y)$ axis; the intersection is the lag factor j.

By substituting $Y = 0.5$ into Equation (4), which corresponds to the half-cooling time, cooling coefficient C can be related to half-cooling time Z as follows:

$$Z = \frac{\ln(2j)}{C} \tag{5}$$

Cooling coefficients have been reported by Dincer (1995, 1996), Dincer and Genceli (1994, 1995), Henry and Bennett (1973), and Henry et al. (1976) for hydrocooling and hydraircooling (see the Cooling Methods section for discussion of these methods) various commodities, as summarized in Tables 2 to 4.

Other Semianalytical/Empirical Precooling Time Estimation Methods

Chapter 10 discusses various semianalytical/empirical methods for predicting cooling times of regularly and irregularly shaped foods. These cooling time estimation methods are grouped into two main categories: those based on (1) f and j factors (for either regular or irregular shapes), and (2) equivalent heat transfer dimensionality.

Numerical Techniques

Becker and Fricke (1996b, 2001) and Becker et al. (1996a, 1996b) developed a numerical technique for determining cooling rates as well as latent and sensible heat loads caused by bulk refrigeration of fruits and vegetables. This computer model can predict commodity moisture loss during refrigerated storage and the temperature distribution within the refrigerated commodity, using a porous media approach to simulate the combined phenomena of transpiration, respiration, airflow, and convective heat and mass transfer. Using this numerical model, Becker et al. (1996b) found that increased airflow decreases moisture loss by reducing cooling time, which quickly reduces the vapor pressure deficit between the commodity and surrounding air, thus lowering the transpiration rate. They also found that bulk mass and airflow rate were of primary importance to cooling time, whereas relative humidity had little effect on cooling time.

COOLING METHODS

The principal methods of precooling are hydrocooling, forced-air cooling, forced-air evaporative cooling, package icing, and vacuum cooling. Precooling may be done in the field, in central cooling facilities, or at the packinghouse.

HYDROCOOLING

In hydrocooling, commodities are sprayed with chilled water, or immersed in an agitated bath of chilled water. Hydrocooling is effective and economical; however, it tends to produce physiological and pathological effects on certain commodities; therefore, its use is limited (Bennett 1970). In addition, proper sanitation of the hydrocooling water is necessary to prevent bacterial infection of commodities. Commodities that are often hydrocooled include asparagus, snap beans, carrots, sweet corn, cantaloupes, celery, snow peas, radishes, tart cherries, and peaches. Cucumbers, peppers, melons, and early crop potatoes are sometimes hydrocooled. Apples and citrus fruits are rarely hydrocooled. Hydrocooling is not popular for citrus fruits because of their long marketing season; good postharvest holding ability; and susceptibility to increased peel injury, decay, and loss of quality and vitality after hydrocooling.

Hydrocooling is rapid because the cold water flowing around the commodities causes the commodity surface temperature to essentially equal that of the water (Ryall and Lipton 1979). Thus, the resistance to heat transfer at the commodity surface is negligible. The rate of internal cooling of the commodity is limited by the rate

Table 2 Lag Factors, Cooling Coefficients, and Half-Cooling Times for Hydrocooling Various Fruits and Vegetables

Commodity and Size	Temperature, °F			Water Flow Rate, ft/min	Crate Load, lb	Lag Factor *j*	Cooling Coefficient *C*, s^{-1}	Half-Cooling Time *Z*, s	Reference
	Initial	Final	Water						
Cucumbers	72	39		9.8	11	1.291	0.001601	546.6	Dincer and Genceli 1994
l = 6.3 in.					22	1.177	0.001567	592.3	
d = 1.5 in.					33	1.210	0.001385	638.2	
					44	1.251	0.001243	737.6	
			33	9.8	11	1.037	0.001684	432.9	Dincer 1995
					22	1.228	0.001675	536.4	
					33	1.222	0.001629	548.5	
					44	1.237	0.001480	612.1	
Eggplant	71			9.8	11	1.077	0.000822	933.9	Dincer 1995
l = 5.6 in.					22	1.109	0.000794	1003	
d = 1.8 in.					33	1.195	0.000870	1011	
					44	1.206	0.000770	1143	
Peaches	70	39		9.8	11	1.067	0.001585		Dincer 1996
d = 2.2 in.					44	1.113	0.001201		
Pears	73	39	34	9.8	11	1.119	0.001434	561.6	Dincer and Genceli 1995
d = 2.4 in.					22	1.157	0.001419	591.0	
					33	1.078	0.001296	592.8	
					44	1.366	0.001151	873.1	
		36		9.8	11	1.076	0.001352		Dincer 1996
					44	1.366	0.001151		
Plums	72	36		9.8	11	1.122	0.003017		Dincer 1996
d = 1.5 in.					44	1.171	0.002279		
Squash	71		33	9.8	11	1.172	0.001272	669.6	Dincer 1995
l = 6.1 in.					22	1.202	0.001186	739.8	
d = 1.8 in.					33	1.193	0.001087	799.9	
					44	1.227	0.001036	866.6	
Tomatoes	70		33	9.8	11	1.209	0.001020	865.4	Dincer 1995
d = 2.8 in.					22	1.310	0.000907	1062	
					33	1.330	0.000800	1222	
					44	1.322	0.000728	1336	
		39		9.8	11	1.266	0.000953		Dincer 1996
					44	1.335	0.000710		

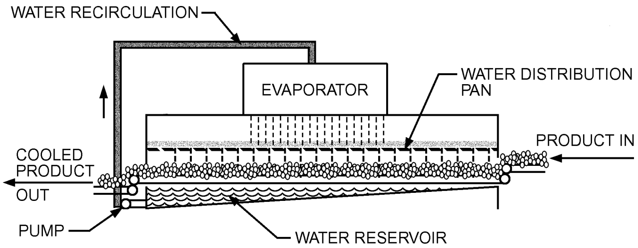


Fig. 3 Schematic of Shower Hydrocooler
(USDA 2004)

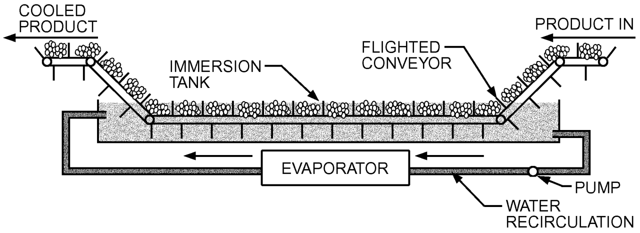


Fig. 4 Schematic of Immersion Hydrocooler
(USDA 2004)

of heat transfer from the interior to the surface, and depends on the commodity's volume in relation to its surface area, as well as its thermal properties. For example, Stewart and Lipton (1960) showed a substantial difference in half-cooling time for sizes 36 and 45 cantaloupes. A weighted average of temperatures taken at different depths showed that 20 min was required to half-cool size 36 melons and only 10 min for size 45.

Hydrocooling also has the advantage of causing no commodity moisture loss. In fact, it may even rehydrate slightly wilted product (USDA 2004). Thus, from a consumer standpoint, the quality of hydrocooled commodities is high; from the producer's standpoint, the salable weight is high. In contrast, other precooling methods such as vacuum or air cooling may lead to significant commodity moisture loss and wilting, thus reducing product quality and salable weight.

Commodities may be hydrocooled either loose or in packaging (which must allow for adequate water flow within and must tolerate contact with water without losing strength). Plastic or wood containers are well suited for use in hydrocoolers. Corrugated fiberboard containers can be used in hydrocoolers, if they are wax-dipped to withstand water contact (USDA 2004).

Types of Hydrocoolers

Hydrocooler designs can generally be divided into two categories: shower-type and immersion. In a **shower hydrocooler**, the commodities pass under a shower of chilled water (Figure 3), which is typically achieved by flooding a perforated pan with chilled

Table 3 Cooling Coefficients and Half-Cooling Times for Hydraircooling Sweet Corn and Celery

Commodity	Crate Type	Spray Nozzle Type	Water Flow Rate, ft^3/min	Airflow Rate, ft^3/min	Cooling Coefficient C, s^{-1}	Half-Cooling Time, s	Reference
Sweet corn	Wirebound	Coarse	12	0	0.000347		Henry and Bennett 1973
			12	0	0.000444		
			7.4	0	0.000642		
			13	0	0.000336		
		Medium	11	0	0.000406		
			6.7	0	0.000406		
			6.7	—	0.000414		
			13	0	0.000492		
			13	—	0.000542		
			13	1000	0.000447		
			13	1600	0.000486		
			13	2760	0.000564		
		Flood pan	33	0	0.000464		
			53	0	0.000567		
		Coarse	13	0		2170	Henry et al. 1976
		Medium	11	0		1730	
			13	1000		1570	
			13	1590		1440	
			13	2770		1220	
		Flood pan	5.3	0		1290	
Celery	Vacuum-cooling		6.1	2000		3710	Henry et al. 1976
			6.1	4200		2360	
			6.1	6470		2310	
	Hydrocooling		6.1	1800		1890	
			6.1	3500		1790	
			6.1	5000		1390	
	Well-ventilated		6.1	1800		2170	
			6.1	4000		1490	
			6.1	5100		1050	

Table 4 Cooling Coefficients for Hydrocooling Peaches

Hydrocooling Method	Water Flow	Water Temp., °F	Fruit Temp., °F		Cooling Coefficient, s^{-1}
			Initial	Final	
Flood, peaches in 3/4 bushel baskets	0.667 $ft^3/min·ft^2$	35	88	47	0.00105
	1.33 $ft^3/min·ft^2$	35	85	44	0.00111
		40	82	49	0.000941
		45	82	49	0.00144
	2.00 $ft^3/min·ft^2$	35	91	39	0.00183
		45	89	51	0.00174
		55	88	58	0.00139
Immersion	2.67 ft^3/min	35	85	44	0.00123
	5.35 ft^3/min	35	85	42	0.00137
	2.67 ft^3/min	45	88	49	0.00168
	5.35 ft^3/min	45	86	49	0.00172
	8.00 ft^3/min	45	86	51	0.00130

Source: Bennett (1963).

water. Gravity forces the water through the perforated pan and over the commodities. Shower hydrocoolers may have conveyors for continuous product flow, or may be operated in batch mode. Water flow rates typically range from 0.17 to 0.33 gal/s per square foot of cooling area (Bennett et al. 1965; Boyette et al. 1992; Ryall and Lipton 1979). **Immersion hydrocoolers** (Figure 4) consist of large, shallow tanks that contain agitated, chilled water. Crates or boxes of commodities are loaded onto a conveyor at one end of the tank, travel submerged along the length of the tank, and are removed at the opposite end. For immersion hydrocooling, a water velocity of 3 to 4 in/s is suggested (Bennett 1963; Bennett et al. 1965).

In large packing facilities, flooded ammonia refrigeration systems are often used to chill hydrocooling water. Cooling coils are placed directly in a tank through which water is rapidly circulated. Refrigerant temperature inside the cooling coils is typically 28°F, producing a chilled-water temperature of about 34°F. Because of the high cost of acquiring and operating mechanical refrigeration units, they are typically limited to providing chilled water for medium- to high-volume hydrocooling operations.

Smaller operations may use crushed ice rather than mechanical refrigeration to produce chilled water. Typically, large blocks of ice are transported from an ice plant to the hydrocooler, and then crushed and added to the hydrocooler's water reservoir. The initial cost of an ice-cooled hydrocooler is much less than that of one using mechanical refrigeration. However, for an ice-cooled hydrocooler to be economically viable, a reliable source of ice must be available at a reasonable cost (Boyette et al. 1992).

Variations on Hydrocooling

Henry and Bennett (1973) and Henry et al. (1976) describe **hydraircooling**, in which a combination of chilled water and chilled air is circulated over commodities. Hydraircooling requires less water for cooling than conventional hydrocooling, and also reduces the maintenance required to keep the cooling water clean. Cooling rates equal to, and in some cases better than, those obtained in conventional unit load hydrocoolers are possible.

Robertson et al. (1976) describe a process in which vegetables are frozen by **direct contact with aqueous freezing media**. The aqueous freezing media consists of a 23% NaCl solution. Freezing times of less than one minute were reported for peas, diced carrots, snow peas, and cut green beans, and a cost analysis indicated that freezing with aqueous freezing media was competitive to air-blast freezing.

Lucas and Raoult-Wack (1998) note that immersion chilling and freezing using aqueous refrigerating media have the advantage of shorter process times, energy savings, and better food quality compared to air-blast chilling or freezing. The main disadvantage is absorption of solutes from the aqueous solution by food. Immersion chilling or freezing with aqueous refrigerating media can be applied to a broad range of foods, including pork, fish, poultry, peppers, beans, tomatoes, peas, and berries.

As an alternative to producing chilled water with mechanical refrigeration or ice, **well water** can be used, provided that the water temperature is at least 10°F lower than that of the product to be cooled. However, the well water must not contain chemicals and biological pollutants that could render the product unsuitable for human consumption (Gast and Flores 1991).

Hydrocooler Efficiency

Hydrocooling efficiency is reduced by heat gain to the water from surrounding air. Other heat sources that reduce effectiveness include solar loads, radiation from hot surfaces, and conduction from the surroundings. Protection from these sources enhances efficiency. Energy can also be lost if a hydrocooler operates at less than full capacity or intermittently, or if more water than necessary is used (Boyette et al. 1992).

To increase hydrocooler energy efficiency, the following factors should be considered during design and operation (Boyette et al. 1992):

- Insulate all refrigerated surfaces and protect the hydrocooler from wind and direct sunlight.
- Use plastic strip curtains on both the inlet and outlet of conveyor hydrocoolers to reduce infiltration heat gain.
- Operate the hydrocooler at maximum capacity.
- Consider using thermal storage, in which chilled water or ice is produced and stored during periods of low energy demand and is subsequently used along with mechanical refrigeration to chill hydrocooling water during periods of peak energy demand. Thermal storage reduces the size of the required refrigeration equipment and may decrease energy costs.
- Use an appropriately sized water reservoir. Because energy is wasted when hydrocooling water is discarded after operation, this waste can be minimized by not using an oversized water reservoir. On the other hand, it may be difficult to maintain consistent hydrocooling water temperature and flow rate with an undersized water reservoir.

Hydrocooling Water Treatment

The surface of wet commodities provides an excellent site for diseases to thrive. In addition, because hydrocooling water is recirculated, decay-producing organisms can accumulate in the hydrocooling water and can easily spread to other commodities being hydrocooled. Thus, to reduce the spread of disease, hydrocooling water must be treated with mild disinfectants.

Typically, hydrocooling water is treated with chlorine to minimize the levels of decay-producing organisms (USDA 2004). Chlorine (gaseous, or in the form of hypochlorous acid from sodium hypochlorite) is added to the hydrocooling water, typically at the level of 50 to 100 ppm. However, chlorination only provides a surface treatment of the commodities; it is not effective at neutralizing an infection below the commodity's surface.

The chlorine level in the hydrocooling water must be checked at regular intervals to ensure that the proper concentration is maintained. Chlorine is volatile and disperses into the air at a rate that increases with increasing temperature (Boyette et al. 1992). Furthermore, if ice cooling is used, melting in the hydrocooling water dilutes the chlorine in solution.

The effectiveness of the chlorine in the hydrocooling water strongly depends on the pH of the hydrocooling water, which should be maintained at 7.0 for maximum effectiveness (Boyette et al. 1992).

To minimize debris accumulation in the hydrocooling water, it may be necessary to wash commodities before hydrocooling. Nevertheless, hydrocooling water should be replaced daily, or more often if necessary. Take special care when disposing of hydrocooling water, because it often contains high concentrations of sediment, pesticides, and other suspended matter. Depending on the municipality, hydrocooling water may be considered an industrial wastewater and, thus, a hydrocooler owner may be required to obtain a wastewater discharge permit (Boyette et al. 1992). In addition to daily replacement of hydrocooling water, shower pans and/or debris screens should be cleaned daily, or more often if necessary, for maximum efficiency.

FORCED-AIR COOLING

Theoretically, air cooling rates can be comparable to hydrocooling under certain conditions of product exposure and air temperature. In air cooling, the optimum value of the surface heat transfer coefficient is considerably smaller than in cooling with water. However, Pflug et al. (1965) showed that apples moving through a cooling tunnel on a conveyer belt cool faster with air at 20°F approaching the fruit at 600 fpm than they would in a water spray at 35°F. For this condition, they calculated an average film coefficient of heat transfer of 7.3 $\text{Btu/h}\cdot\text{ft}^2\cdot{}^\circ\text{F}$. They noted that the advantage of air is its lower temperature and that, if water were reduced to 34°F, the time for water cooling would be less. Note, however, that air temperatures could be more difficult to manage without specifically fine control below 34°F.

In tests to evaluate film coefficients of heat transfer for anomalous shapes, Smith et al. (1970) obtained an experimental value of 6.66 $\text{Btu/h}\cdot\text{ft}^2\cdot{}^\circ\text{F}$ for a single Red Delicious apple in a cooling tunnel with air approaching at 1570 fpm. At this airflow rate, the logarithmic mean surface temperature of a single apple cooled for 0.5 h in air at 20°F is approximately 35°F. The average temperature difference across the surface boundary layer is, therefore, 15°F and the rate of heat transfer per square foot of surface area is

$$q/A = 6.66 \times 15 = 100\ \text{Btu/h}\cdot\text{ft}^2$$

For these conditions, the cooling rate compares favorably with that obtained in ideal hydrocooling. However, these coefficients are based on single specimens isolated from surrounding fruit. Had the fruit been in a packed bed at equivalent flow rates, the values would have been less because less surface area would have been exposed to the cooling fluid. Also, the evaporation rate from the product surface significantly affects the cooling rate.

Because of physical characteristics, mostly geometry, various fruit and vegetable products respond differently to similar treatments of airflow and air temperature. For example, in a packed bed under similar conditions of airflow and air temperature, peaches cool faster than potatoes.

Surface coefficients of heat transfer are sensitive to the physical conditions involved among objects and their surroundings. Soule et al. (1966) obtained experimental surface coefficients ranging from 9 to 12 $\text{Btu/h}\cdot\text{ft}^2\cdot{}^\circ\text{F}$ for bulk lots of Hamlin oranges and Orlando tangelos with air approaching at 225 to 350 fpm. Bulk bins containing 1000 lb of 2.85 in. diameter Hamlin oranges were cooled from 80°F to a final mass-average temperature of 46.5°F in 1 h with air at 330 fpm (Bennett et al. 1966). Surface heat transfer coefficients for these tests averaged slightly above 11 $\text{Btu/h}\cdot\text{ft}^2\cdot{}^\circ\text{F}$. On the basis of a log mean air temperature of 44°F, the calculated half-cooling time was 0.27 h.

By correlating data from experiments on cooling 2.8 in. diameter oranges in bulk lots with results of a mathematical model, Baird and Gaffney (1976) found surface heat transfer coefficients of 1.5 and 9 $\text{Btu/h}\cdot\text{ft}^2\cdot{}^\circ\text{F}$ for approach velocities of 11 and 412 fpm, respectively. A Nusselt-Reynolds heat transfer correlation representing data from six experiments on air cooling of 2.8 in. diameter oranges and seven experiments on 4.2 in. diameter grapefruit, with approach air velocities ranging from 5 to 412 fpm, gave the relationship $\text{Nu} = 1.17\,\text{Re}^{0.529}$, with a correlation coefficient of 0.996.

Ishibashi et al. (1969) constructed a staged forced-air cooler that exposed bulk fruit to air at a progressively declining temperature

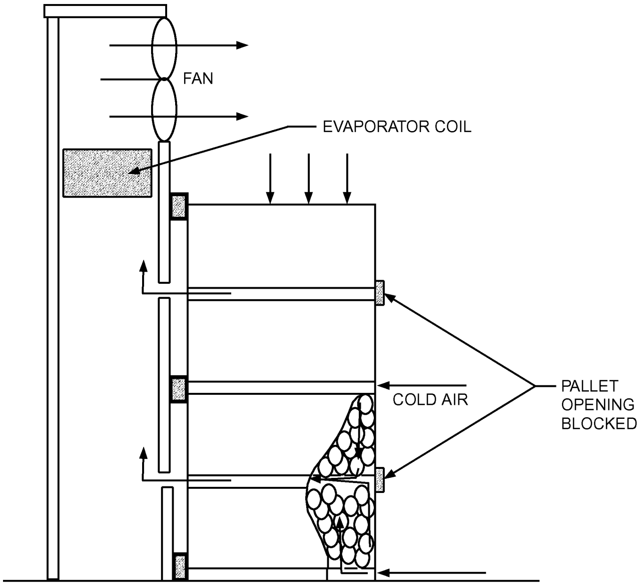


Fig. 5 Serpentine Forced-Air Cooler

(50, 32, and 14°F) as the fruit was conveyed through the cooling tunnel. Air approached at 700 fpm. With this system, 2.5 in. diameter citrus fruit cooled from 77 to 41°F in 1 h. Their half-cooling time of 0.32 h compares favorably with a half-cooling time of 0.30 h for similarly cooled Delicious apples at an approach air velocity of 400 fpm (Bennett et al. 1969). Perry and Perkins (1968) obtained a half-cooling time of 0.5 h for potatoes in a bulk bin with air approaching at 250 fpm, compared to 0.4 h for similarly treated peaches and 0.38 h for apples. Optimum approach velocity for this type of cooling is in the range of 300 to 400 fpm, depending on conditions and circumstances.

Commercial Methods

Produce can be satisfactorily cooled (1) with air circulated in refrigerated rooms adapted for that purpose, (2) in rail cars using special portable cooling equipment that cools the load before it is transported, (3) with air forced through the voids of bulk products moving through a cooling tunnel on continuous conveyors, (4) on continuous conveyors in wind tunnels, or (5) by the forced-air method of passing air through the containers by pressure differential. Each of these methods is used commercially, and each is suitable for certain commodities when properly applied. Figure 5 shows a schematic of a serpentine forced-air cooler.

In circumstances where air cannot be forced directly through the voids of products in bulk, using a container type and load pattern that permit air to circulate through the container and reach a substantial part of the product surface is beneficial. Examples of this are (1) small products such as grapes and strawberries that offer appreciable resistance to airflow through voids in bulk lots, (2) delicate products that cannot be handled in bulk, and (3) products that are packed in shipping containers before precooling.

Forced-air or pressure cooling involves definite stacking patterns and baffling of stacks so that cooling air is forced through, rather than around, individual containers. Success requires a container with vent holes in the direction air will move and a minimum of packaging materials that would interfere with free air movement through the containers. Under these conditions, a relatively small pressure differential between the two sides of the containers results in good air movement and excellent heat transfer. Differential pressures in use are about 0.25 to 3 in. of water, with airflows ranging from 1 to 3 cfm/lb of product.

Because cooling air comes in direct contact with the product being cooled, cooling is much faster than with conventional room cooling. This gives the advantage of rapid product movement through the cooling plant, and the size of the plant is one-third to one-fourth that of an equivalent cold room type of plant.

Mitchell et al. (1972) noted that forced-air cooling usually cools in one-fourth to one-tenth the time needed for conventional room cooling, but it still takes two to three times longer than hydrocooling or vacuum cooling.

A proprietary direct-contact heat exchanger cools air and maintains high humidities using chilled water as a secondary coolant and a continuously wound polypropylene monofilament packing. It contains about 2000 linear feet of filament per cubic foot of packing section. Air is forced up through the unit while chilled water flows downward. The dew-point temperature of air leaving the unit equals the entering water temperature. Chilled water can be supplied from coils submerged in a tank. Build-up of ice on the coils provides an extra cooling effect during peak loads. This design also allows an operator to add commercial ice during long periods of mechanical equipment outage.

In one portable, forced-air method, refrigeration components are mounted on flat bed trailers and the warm, packaged produce is cooled in refrigerated transport trailers. Usually the refrigeration equipment is mounted on two trailers; one holds the forced-air evaporators and the other holds compressors, air-cooling condensers, a high-pressure receiver, and electrical gear. The loaded produce trailers are moved to the evaporator trailer and the product is cooled. After cooling, the trailer is transported to its destination.

Effects of Containers and Stacking Patterns

Accessibility of the product to the cooling medium, essential to rapid cooling, may involve both access to the product in the container and to the individual container in a stack. This effect is evident in the cooling rate data of various commodities in various types of containers reported by Mitchell et al. (1972). Parsons et al. (1972) developed a corrugated paperboard container venting pattern for palletized unit loads that produced cooling rates equal to those from conventional register stacked patterns. Fisher (1960) demonstrated that spacing apple containers on pallets reduced cooling time by 50% compared to pallet loads stacked solidly. A minimum of 5% sidewall venting is recommended.

Palletization is essential for shipment of many products, and pallet stability is improved if cartons are packed closely together. Thus, cartons and packages should be designed to allow ample airflow though the stacked products. Amos et al. (1993) and Parsons et al. (1972) showed the importance of vent sizes and location to obtain good cooling in palletized loads without reducing container strength. Some operations wrap palletized products in polyethylene to increase stability. In this case, the product may need to be cooled before it is palletized.

Moisture Loss in Forced-Air Cooling

The information in this section is drawn from Thompson et al. (2002).

Moisture loss in forced-air cooling ranges from very little to amounts significant enough to damage produce. Factors that affect moisture loss include product initial temperature and transpiration coefficient, humidity, exposure to airflow after cooling, and whether waxes or moisture-resistant packaging is used.

High initial temperature results in high moisture loss; this can be minimized by harvesting at cooler times of day (i.e., early morning or night), and cooling (or at least shading) products immediately after harvest. Keep reheat during packing to a minimum.

The primary advantage of high humidity during cooling is that product packaging can absorb moisture, which reduces the packaging's absorption of moisture from the product itself.

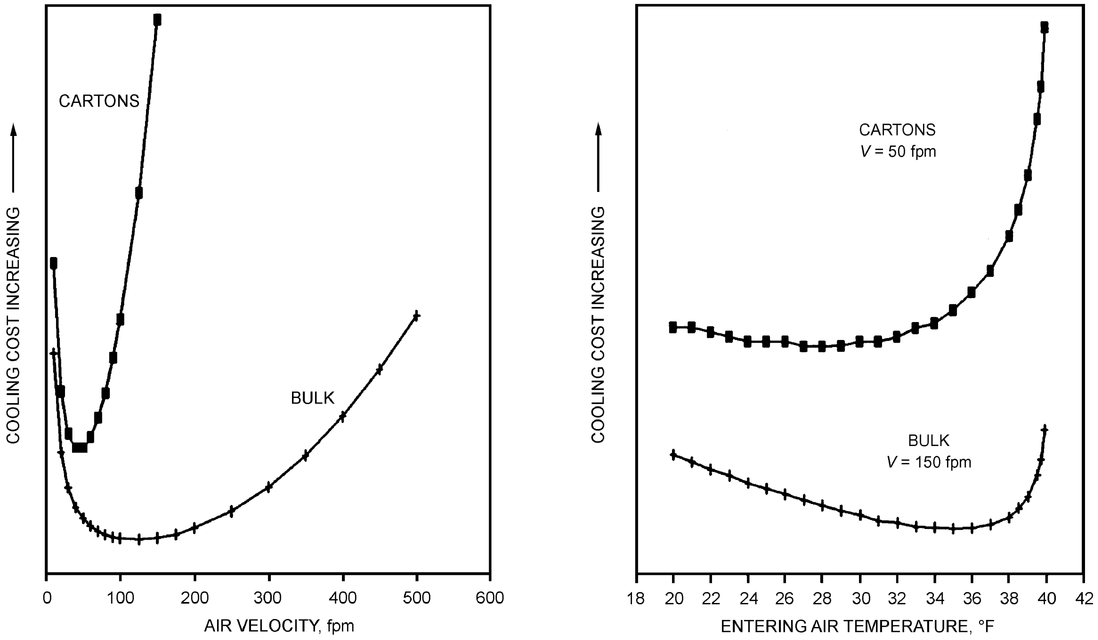


Fig. 6 Engineering-Economic Model Output for a Forced-Air Cooler

High transpiration coefficients also increase moisture loss. For example, carrots, with a high transpiration rate, can lose 0.6 to 1.8% of their original, uncooled weight during cooling. Polyethylene packaging has reduced moisture loss in carrots to 0.08%, although cooling times are about five times longer. Film box liners, sometimes used for packing products with low transpiration coefficients (e.g., apples, pears, kiwifruit, and grapes), are also useful in reducing moisture loss, but they also increase the time required to cool products. Some film box liners are perforated to reduce condensation; liners used to package grapes must also include an SO_2-generating pad to reduce decay.

To prevent exposing product to unnecessary airflow, forced-air coolers should reduce or stop airflow as soon as the target product temperature is reached. Otherwise, moisture loss will continue unless the surrounding air is close to saturation. One method is to link cooler fan control to return air plenum temperature, slowing fan speeds as the temperature of the return air approaches that of the supply air.

Computer Solution

Baird et al. (1988) developed an engineering economic model for designing forced-air cooling systems. Figure 6 shows the type of information that can be obtained from the model. By selecting a set of input conditions (which varies with each application) and varying approach air velocity, entering air temperature, or some other variable, the optimum (minimum-cost) value can be determined. The curves in Figure 6 show that selection of air velocity for containers is critical, whereas selection of entering air temperature is not as critical until the desired final product temperature of 40°F is approached. The results shown are for four cartons deep with a 4% vent area in the direction of airflow, and they would be quite different if the carton vent area was changed. Other design parameters that can be optimized using this program are the depth of product in direction of airflow and the size of evaporators and condensers.

FORCED-AIR EVAPORATIVE COOLING

This approach cools air with an evaporative cooler, passing air through a wet pad before it comes into contact with product and packaging, instead of using mechanical refrigeration. A correctly designed and operated evaporative cooler produces air a few degrees above the outside wet-bulb temperature, at high humidity (about 90% rh), and is more energy-efficient than mechanical refrigeration (Kader 2002). In most of California, for instance, product temperatures of 60 to 70°F can be achieved. This method is suited for products that are best held at moderate temperatures, such as tomatoes, or for those that are marketed soon after harvest.

For more information on evaporative cooling equipment and applications, see Chapter 51 of the 2003 *ASHRAE Handbook—HVAC Applications*, and Chapter 19 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

PACKAGE ICING

Finely crushed ice placed in shipping containers can effectively cool products that are not harmed by contact with ice. Spinach, collards, kale, brussels sprouts, broccoli, radishes, carrots, and green onions are commonly packaged with ice (Hardenburg et al. 1986). Cooling a product from 95 to 35°F requires melting ice equal to 38% of the product's mass. Additional ice must melt to remove heat leaking into the packages and to remove heat from the container. In addition to removing field heat, package ice can keep the product cool during transit.

Pumping **slush ice** or liquid ice into the shipping container through a hose and special nozzle that connect to the package is used for cooling some products. Some systems can ice an entire pallet at one time.

Top icing, or placing ice on top of packed containers, is used occasionally to supplement another cooling method. Because corrugated containers have largely replaced wooden crates, use of top ice has decreased in favor of forced-air and hydrocooling. Wax-impregnated corrugated containers, however, allow icing and hydrocooling of products after packaging.

Flaked or crushed ice can be manufactured on site and stored in an ice bunker for later use; for short-season cooling requirements with low ice demands (e.g., a few tons a day), it may be more economical to buy block ice and crush it on site. Another option is to rent liquid ice equipment for on-site production.

The cooling capacity of ice is 144 Btu/lb; 1 lb of ice will reduce the temperature of 3 lb of produce by approximately 50°F. However, commercial ice-injection systems require significantly more ice beyond that needed for produce cooling. For example, 20 lb of broccoli requires about 32 lb of manufactured ice (losses occur in product cooling, transport, and equipment heat gain; also, a remainder of ice is required in the box on delivery to the customer). The high ice requirement makes liquid icing energy-inefficient and expensive (Thompson et al. 2002). Other disadvantages of ice cooling include (1) weight of the ice, which decreases the net product weight in a vehicle; and (2) the need for water-resistant packaging to prevent water damage to other products; and (3) safety hazards during storage. These disadvantages can be minimized if ice is used for temperature maintenance in transit rather than for cooling, or by using gel-pack ice (often used for flowers), which is sealed in a leakproof bag.

VACUUM COOLING

Vacuum cooling of fresh produce by rapid evaporation of water from the product works best with vegetables having a high ratio of surface area to volume and a high transpiration coefficient. In vacuum refrigeration, water, as the primary refrigerant, vaporizes in a flash chamber under low pressure. Pressure in the chamber is lowered to the saturation point corresponding to the lowest required temperature of the water.

Vacuum cooling is a batch process. The product to be cooled is loaded into the flash chamber, the system is put into operation, and the product is cooled by reducing the pressure to the corresponding saturation temperature desired. The system is then shut down, the product removed, and the process repeated. Because the product is normally at ambient temperature before it is cooled, vacuum cooling can be thought of as a series of intermittent operations of a vacuum refrigeration system in which water in the flash chamber is allowed to come to ambient temperature before each start. The functional relationships for determining refrigerating capacity are the same in each case.

Cooling is achieved by boiling water, mostly off the surface of the product to be cooled. The heat of vaporization required to boil the water is furnished by the product, which is cooled accordingly. As pressure is further reduced, cooling continues to the desired temperature level. The saturation pressure for water at 212°F is 760 mm Hg; at 32°F, it is 4.58 mm Hg. Commercial vacuum coolers normally operate in this range.

Although the cooling rate of lettuce could be increased without danger of freezing by reducing the pressure to 3.8 mm Hg, corresponding to a saturation temperature of 27°F, most operators do not reduce the pressure below that which freezes water because of the extra work involved and the freezing potential.

Pressure, Volume, and Temperature

In vacuum cooling, the thermodynamic process is assumed to take place in two phases. In the first phase, the product is assumed to be loaded into the flash chamber at ambient temperature, and the temperature in the flash chamber remains constant until saturation pressure is reached. At the onset of boiling, the small remaining amount of air in the chamber is replaced by the water vapor, the first phase ends, and the second phase begins simultaneously. The second phase continues at saturation until the product has cooled to the desired temperature.

If the ideal gas law is applied for an approximate solution in a commercial vacuum cooler, the pressure/volume relationships are

$$\begin{array}{lll} \text{Phase 1} & pv & = 29{,}318 \text{ ft}\cdot\text{lb/lb} \\ \text{Phase 2} & pv^{1.056} & = 66{,}370 \text{ ft}\cdot\text{lb/lb} \end{array}$$

where p is absolute pressure and v is specific volume.

The pressure/temperature relationship is determined by the value of ambient and product temperature. Based on 90°F for this value, the temperature in the flash chamber theoretically remains constant at 90°F as the pressure reduces from atmospheric to saturation, after which it declines progressively along the saturation line. These relationships are illustrated in Figure 7. Product temperature responds similarly, but varies depending on where temperature is measured in the product, physical characteristics of the product, and amount of product surface water available. Although it is possible for some vaporization to occur in intercellular spaces beneath the product surface, most water is vaporized off the surface. The heat required to vaporize this water is also taken off the product surface, where it flows by conduction under the thermal gradient produced. Thus, the rate of cooling depends on the relation of surface area to volume of product and the rate at which the vacuum is drawn in the flash chamber.

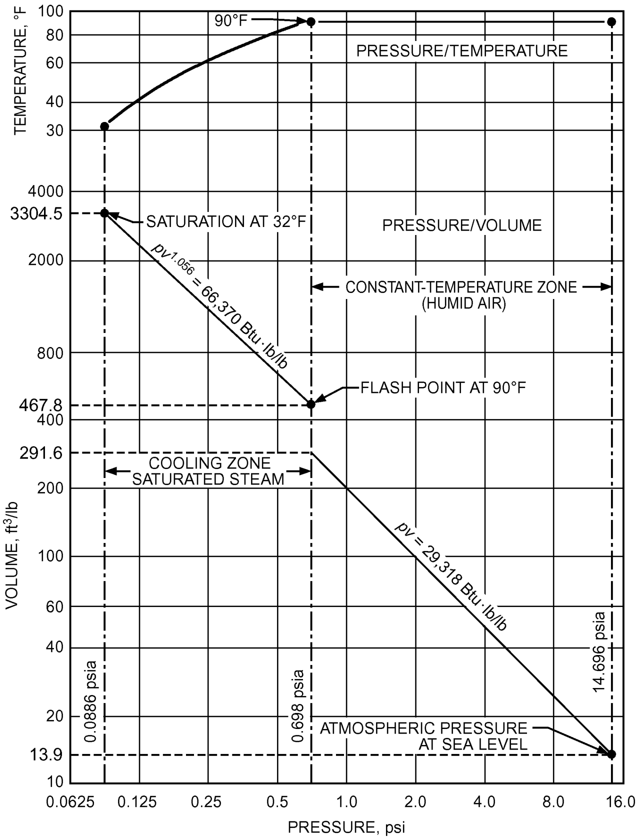


Fig. 7 Pressure, Volume, and Temperature in a Vacuum Cooler Cooling Product from 90 to 32°F

Because water is the sole refrigerant, the amount of heat removed from the product depends on the mass of water vaporized m_v and its latent heat of vaporization L. Assuming an ideal condition, with no heat gain from surroundings, total heat Q removed from the product is

$$Q = m_v L \tag{6}$$

The amount of moisture removed from the product during vacuum cooling, then, is directly related to the product's specific heat and the amount of temperature reduction accomplished. A product with a specific heat capacity of 0.95 Btu/lb·°F theoretically loses 1% moisture for each 11°F reduction in temperature. In a study of vacuum cooling of 16 different vegetables, Barger (1963) showed that cooling of all products was proportional to the amount of moisture evaporated from the product. Temperature reductions averaged 9 to 10°F for each 1% of weight loss, regardless of the product cooled. This weight loss may reduce the amount of money the grower receives as well as the turgor and crispness of the product. Some vegetables are sprayed with water before or during cooling to reduce this loss.

Commercial Systems

The four types of vacuum refrigeration systems that use water as the refrigerant are (1) steam ejector, (2) centrifugal, (3) rotary, and

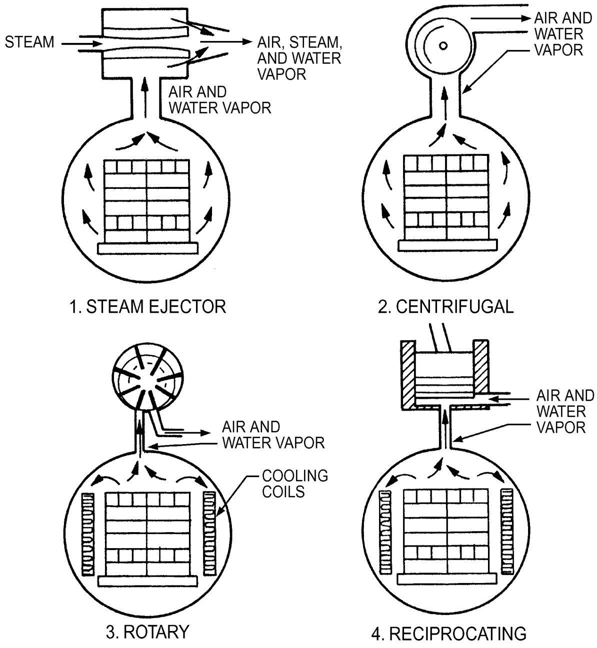
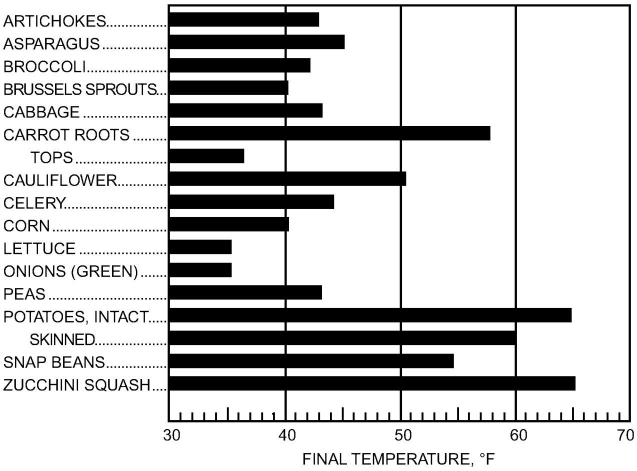


Fig. 8 Schematic Cross Sections of Vacuum-Producing Mechanisms



Vacuum Cooling Conditions

Initial Product Temperature	= 68 to 72°F
Minimum Pressure	= 4 to 4.6 mm Hg
Condenser Temperature	= 29 to 32°F
Time in Vacuum Tank	= 0.42 to 0.5 h

Fig. 9 Comparative Cooling of Vegetables Under Similar Vacuum Conditions

(4) reciprocating. A schematic of the vacuum-producing mechanism of each is illustrated in Figure 8.

Of these, the steam ejector type is best suited for displacing the extremely high volumes of water vapor encountered at the low pressures needed in vacuum cooling. It also has the advantage of having few moving parts, thus requiring no compressor to condense the water vapor. High-pressure steam is expanded through a series of jets or ejectors arranged in series and condensed in barometric condensers mounted below the ejectors. Cooling water for condensing is accomplished by means of an induced-draft cooling tower. In spite of these advantages, few steam ejector vacuum coolers are used today, because of the inconvenience of using steam and the lack of portability. Instead, vacuum coolers are mounted on semitrailers to follow seasonal crops.

The centrifugal compressor is also a high-volume pump and can be adapted to water vapor refrigeration. However, its use in vacuum cooling is limited because of inherent mechanical difficulties at the high rotative speeds required to produce the low pressures needed.

Both rotary and reciprocal vacuum pumps can produce the low pressures needed, and they also have the advantage of portability. Being positive-displacement pumps, however, they have low volumetric capacity; therefore, vacuum coolers using rotary or reciprocating pumps have separate refrigeration systems to condense much of the water vapor that evaporates off the product, thus substantially reducing the volume of water vapor passing through the pump. Ideally, when it can be assumed that all water vapor is condensed, the required refrigeration capacity equals the amount of heat removed from the product during cooling.

The condenser must contain adequate surface to condense the large amount of vapor removed from the produce in a few minutes. Refrigeration is furnished from cold brine or a direct-expansion system. A very large peak load occurs from rapid condensing of so much vapor. Best results are obtained if the refrigeration plant is equipped with a large brine or icemaking tank having enough stored refrigeration to smooth out the load. A standard three-tube plant, with capacity to handle three cars per hour, has a peak refrigeration load of at least 250 tons.

To increase cooling effectiveness and reduce product moisture loss, the product is sometimes wetted before cooling begins. However, iceberg lettuce is rarely prewetted. A modification of vacuum cooling circulates chilled water over the product throughout the cooling process. Among the chief advantages are increased cooling rates and residual refrigeration that is stored in the chilled water after each vacuum process. It also prevents water loss from products that show objectionable wilting after conventional vacuum cooling.

Applications

Because vacuum cooling is generally more expensive, particularly in capital cost, than other cooling methods, its use is primarily restricted to products for which vacuum cooling is much faster or more convenient. Lettuce is ideally adapted to vacuum cooling. The numerous individual leaves provide a large surface area and the tissues release moisture readily. It is possible to freeze lettuce in a vacuum chamber if pressure and condenser temperatures are not carefully controlled. However, even lettuce does not cool entirely uniformly. The fleshy core, or butt, releases moisture more slowly than the leaves. Temperatures as high as 43°F have been recorded in core tissue when leaf temperatures were down to 33°F (Barger 1961).

Other leafy vegetables such as spinach, endive, escarole, and parsley are also suitable for vacuum cooling. Vegetables that are less suitable but adaptable by wetting are asparagus, snap beans, broccoli, brussels sprouts, cabbage, cauliflower, celery, green peas, sweet corn, leeks, and mushrooms. Of these vegetables, only cauliflower, celery, cabbage, and mushrooms are commercially vacuum cooled in California. Fruits are generally not suitable, except some berries. Cucumbers, cantaloupes, tomatoes, dry onions, and potatoes cool very little because of their low surface-to-mass ratio and relatively impervious surface. The final temperatures of various vegetables when vacuum cooled under similar conditions are illustrated in Figure 9.

The rate of cooling and final temperature attained by vacuum cooling are largely affected by the commodity's ratio of surface area to its mass and the ease with which it gives up water from its tissues. Consequently, the adaptability of fruits and vegetables varies tremendously for this method of precooling. For products that have a low surface-to-mass ratio, high temperature gradients occur. To prevent the surface from freezing before the desired mass-average temperature is reached, the vacuum pump is switched off and on (“bounced”) to keep the saturation temperature above freezing.

Mechanical vacuum coolers have been designed in several sizes. Most installations use cylindrical or rectangular retorts. For portability, some vacuum coolers and associated refrigeration equipment have been placed on flat-bed trailers.

SELECTING A COOLING METHOD

Packing house size and operating procedures, response of product to the cooling method, and market demands largely dictate the cooling method used. Other factors include whether the product is packaged in the field or in a packing house, product mix, length of cooling season, and comparative costs of dry versus water-resistant cartons. In some cases, there is little question about the type of cooling to be used. For example, vacuum cooling is most effective on lettuce and other similar vegetables. Peach packers in the southeastern United States and some vegetable and citrus packers are satisfied with hydrocooling. Air (room) cooling is used for apples, pears, and citrus fruit. In other cases, choice of cooling method is not so clearly defined. Celery and sweet corn are usually hydrocooled, but they may be vacuum cooled as effectively. Cantaloupes may be satisfactorily cooled by several methods. *Note*: sweet cherries are often hydrocooled in packing houses but are air cooled if orchard packed.

When more than one method can be used, cost becomes a major consideration. Although rapid forced-air cooling is more costly than hydrocooling, if the product does not require rapid cooling, a forced-air system can operate almost as economically as hydrocooling. In a study to evaluate costs of hypothetical precooling systems for citrus fruit, Gaffney and Bowman (1970) found that the cost for forced-air cooling in bulk lots was 20% more than that for hydrocooling in bulk and that forced-air cooling in cartons costs 45% more than hydrocooling in bulk.

Table 5 summaries precooling and cooling methods suggested for various commodities.

COOLING CUT FLOWERS

Because of their high rates of respiration and low tolerance for heat, deterioration in cut flowers is rapid at field temperatures. Refrigerated highway vans do not have the capacity to remove the field heat in sufficient time to prevent some deterioration from occurring (Farnham et al. 1979). Forced-air cooling is commonly used by the flower industry. As with most fruits and vegetables, the cooling rate of cut flowers varies substantially among the various types. Rij et al. (1979) found that the half-cooling time for packed boxes of gypsophila was about 3 min compared to about 20 min for chrysanthemums at airflows ranging from 80 to 260 cfm per box. Within this range, cooling time was proportional to the reciprocal of airflow but varied less with airflow than with flower type.

SYMBOLS

A = product surface area, ft^2
c_p = specific heat of product, Btu/lb·°F
C = cooling coefficient, reciprocal of hours
j = lag factor
L = heat of vaporization, Btu/lb
m = mass of product, lb
m_v = mass of water vaporized, lb
p = pressure, lb/ft^2
q = cooling load or rate of heat transfer, Btu/h
Q = total heat, Btu
t = temperature of any point in product, °F
t_i = initial uniform product temperature, °F
t_m = temperature of cooling medium, °F
t_o = surrounding temperature, °F
t_{ma} = mass-average temperature, °F
v = specific volume of water vapor, $\text{ft}^3\text{/lb}$

Table 5 Cooling Methods Suggested for Horticultural Commodities

Commodity	Size of Operation	
	Large	**Small**
Tree fruits		
Citrus	R	R
Deciduous [a]	FA, R, HC	FA
Subtropical	FA, R	FA
Tropical	FA, R	FA
Berries	FA	FA
Grapes [b]	FA	FA
Leafy vegetables		
Cabbage	VC, FA	FA
Iceberg lettuce	VC	FA
Kale, collards	VC, R, WV	FA
Leaf lettuces, spinach, endive, escarole, Chinese cabbage, bok choy, romaine	VC, FA, WV, HC	FA
Root vegetables		
With tops [c]	HC, PI, FA	HC, FA
Topped	HC, PI	HC, PI, FA
Irish potatoes, sweet potatoes [d]	R w/evap coolers, HC	R
Stem and flower vegetables		
Artichokes	HC, PI	FA, PI
Asparagus	HC	HC
Broccoli, Brussels sprouts	HC, FA, PI	FA, PI
Cauliflower	FA, VC	FA
Celery, rhubarb	HC, WV, VC	HC, FA
Green onions, leeks	PI, HC	PI
Mushrooms	FA, VC	FA
Pod vegetables		
Beans	HC, FA	FA
Peas	FA, PI, VC	FA, PI
Bulb vegetables		
Dry onions [e]	R	R, FA
Garlic	R	
Fruit-type vegetables [f]		
Cucumbers, eggplant	R, FA, FA-EC	FA, FA-EC
Melons		
Cantaloupes, muskmelons, honeydew, casaba	HC, FA, PI	FA, FA-EC
Crenshaw	FA, R	FA, FA-EC
Watermelons	FA, HC	FA, R
Peppers	R, FA, FA-EC, VC	FA, FA-EC
Summer squashes, okra	R, FA, FA-EC	FA, FA-EC
Sweet corn	HV, VC, PI	HC, FA, PI
Tomatillos	R, FA, FA-EC	FA, FA-EC
Tomatoes	R, FA, FA-EC	
Winter squashes	R	R
Fresh herbs		
Not packaged [g]	HC, FA	FA, R
Packaged	FA	FA, R
Cactus		
Leaves (nopalitos)	R	FA
Fruit (tunas or prickly pears)	R	FA
Ornamentals		
Cut flowers [h]	FA, R	FA
Potted plants	R	R

R = Room cooling
HC = Hydrocooling
FA = Forced-air cooling
VC = Vacuum cooling
WV = Water spray vacuum cooling
PI = Package icing
FA-EC = Forced-air evaporative cooling

[a] Apricots cannot be hydrocooled.
[b] Grapes require rapid cooling facilities adaptable to sulfur dioxide fumigation.
[c] Carrots can be vacuum cooled.
[d] With evaporative coolers, facilities for potatoes should be adapted to curing.
[e] Facilities should be adapted to curing onions.
[f] Fruit-type vegetables are sensitive to chilling but at varying temperatures.
[g] Fresh herbs can be easily damaged by water beating in hydrocooler.
[h] When cut flowers are packaged, only use forced-air cooling.

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V = air velocity, fpm
Y = temperature ratio $(t - t_o)/(t_i - t_o)$
Z = half-cooling time, h
θ = cooling time, h

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