Hydrocooling Fruits & Vegetables

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The effective cooling of food reduces the activity of microorganisms and enzymes, retarding deterioration. Prompt precooling of fruits and vegetables, i.e., the removal of field heat prior to shipping, processing or storage, maintains preharvest freshness and flavor.[1]

Precooling operations require greater refrigeration capacity and cooling medium movement than do storage rooms that hold commodities at a constant temperature. Thus, precooling is typically a separate operation from refrigerated storage and requires the use of specially designed equipment.[2] Precooling can be accomplished by methods including hydrocooling, vacuum cooling, air cooling and contact icing. These various precooling methods rapidly transfer heat from the commodity to a cooling medium such as water, air or ice. Cooling times from several minutes to more than 24 hours may be required for proper precooling of commodities.

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Hydrocooling

Hydrocooling is a form of precooling in which the commodities are sprayed with chilled water or immersed in an agitated bath of chilled water. Hydrocooling is an effective and economical method of precooling. However, hydrocooling has a tendency to produce physiological and pathological effects on certain commodities. Therefore, its use is limited or prohibited with these commodities.[2] In addition, proper sanitation of the hydrocooling water is necessary to prevent bacterial infection. Asparagus, snap beans, sweet corn, cantaloupes, celery, snow peas, radishes, tart cherries and peaches often are hydrocooled. Commodities that are sometimes hydrocooled include cucumbers, peppers, melons and early crop potatoes.

Hydrocooling rapidly cools commodities. The cold water that flows around the commodities causes the surface temperature to be

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essentially equal to that of the water. Thus, the resistance to heat transfer at the surface is negligible and the rate of internal cooling of the commodity is limited by the rate of heat transfer from the interior to the surface. This internal cooling rate depends upon the volume of the commodity in relation to its surface area as well as the thermal properties of the commodity.

In addition to rapid cooling, hydrocooling has the advantage of causing no commodity moisture loss. In fact, hydrocooling even may rehydrate slightly wilted product.[3] Thus, from a consumer standpoint, the quality of hydrocooled commodities is high, while from the producer's standpoint, the salable weight is high. In contrast, other precooling methods, such as vacuum cooling 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. If commodities are to be cooled in packaging, the packaging must allow for adequate water flow from 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, provided that they are wax-dipped to withstand water contact.[3]

Types of Hydrocoolers

Hydrocooler designs generally can be divided into two categories, namely shower-type hydrocoolers and immersion hydrocoolers. In a shower hydrocooler, the commodities pass under a shower of chilled water, as shown in *Figure 1*. Typically, the shower is achieved by flooding a perforated pan with chilled water. Gravity forces the chilled water to pass through the perforated pan and shower over the commodities. Showertype hydrocoolers may incorporate conveyors for continuous product flow or may be operated in batch mode. Water flow rates for shower-type hydrocoolers typically range from 10 to 20 gpm/ft^2 (6.8 to 13.6 L/s per m^2) of cooling area.[4,5]

Immersion hydrocoolers, shown in *Figure 2*, 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. The commodities then travel submerged along the length of the tank, and are removed at the opposite end. For immersion hydrocooling, a water velocity of 15 to 20 fpm (75 to 100 mm/s) is suggested.[4]

In large packing facilities, flooded ammonia refrigeration systems often are used to chill the hydrocooling water. Cooling coils are placed directly in a tank through which water is rapidly circulated. The refrigerant temperature inside the cooling coils is typically 28°F (–2°C), producing a chilled water temperature of about 34°F (1°C). Because of the high cost of acquiring and operating mechanical refrigeration units, they typically are limited to providing chilled water for medium- to high-volume hydrocooling operations.

Smaller hydrocooling 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 water reservoir of the hydrocooler. The initial cost of an ice-cooled hydrocooler is much less than that of a hydrocooler using mechanical refrigeration. However, for an ice-cooled hydrocooler to be economical, a reliable source of ice must be available at a reasonable cost.[5]

Variations on the Hydrocooling Concept

Other concepts that are similar to hydrocooling include hydraircooling as well as chilling and freezing using aqueous solutions. Henry and Bennett[6] describe hydraircooling. In this technique, a combination of chilled water and chilled air is circulated over the commodities. Hydraircooling reduces the water volume required for cooling as compared to conventional hydrocooling, and also reduces the maintenance required to keep the cooling water clean.

Robertson, et al.,[7] 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. However, a shortcoming of the immersion chilling or freezing process with aqueous solutions is the absorption of solutes from the aqueous solution by the food item.

Hydrocooling Time Estimation Methods

Efficient operation of hydrocoolers involves the proper sizing of refrigeration equipment to maintain a constant chilled water temperature, typically about 34°F (1°C); an adequate flow of chilled water; and, a proper product residence time in the chilled water. Thus, to

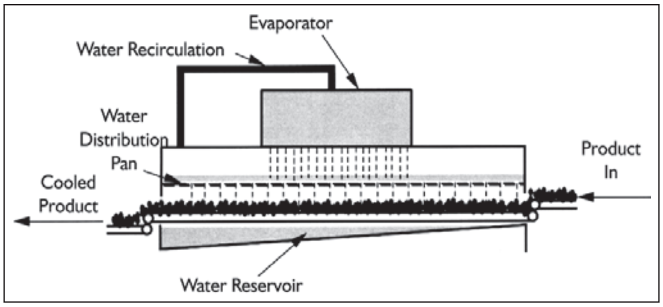

Figure 1: Schematic of a shower-type hydrocooler.[3]

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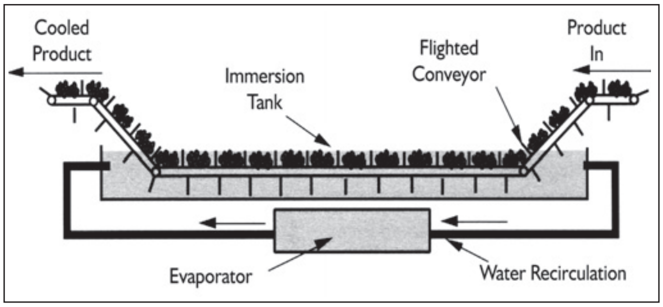

Figure 2: Schematic of an immersion hydrocooler.[3]

properly design a hydrocooler, 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 prior to shipping and/or storage. For a specified hydrocooling water temperature and flow rate, this cooling time would dictate the residence time within the hydrocooler, which is required for proper cooling of the commodities. Thus, for shower or immersion hydrocoolers, the cooling time determines the proper conveyor belt speed and the appropriate length of the hydrocoolers' cooling section.[8]

The design of hydrocooling systems and specification of hydrocooling process parameters require accurate estimation of the hydrocooling times of fruits and vegetables as well as the corresponding refrigeration loads.

Accurate numerical estimations of the hydrocooling times of fruits and vegetables can be obtained by using appropriate finite element or finite difference computer programs. However, the effort required to perform this task makes it impractical for the design or process engineer. In addition, two-dimensional and three-dimensional simulations would require time consuming data preparation and significant computing time. Hence, the majority of the research effort to date has been in the development of semi-analytical/empirical hydrocooling time estimation methods that make use of simplifying assumptions, but neverthless produce accurate results.

Fractional Unaccomplished Temperature Difference

All hydrocooling processes exhibit similar behavior. After an initial lag, the temperature at the thermal center of the food item decreases exponentially. As shown in *Figure 3*, a cooling curve depicting this behavior can be obtained by plotting, on semilogarithmic axes, the fractional unaccomplished temperature difference vs. time.[9] The fractional unaccomplished temperature difference, Y, is defined as follows:

$$Y = \frac{t_m - t}{t_m - t_i} = \frac{t - t_m}{t_i - t_m} \qquad (1)$$

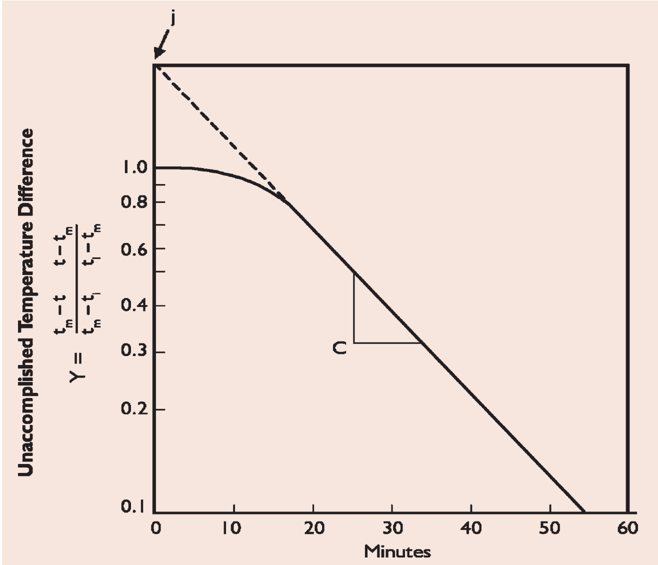

Figure 3: Typical cooling curve.

where

t_m is the hydrocooling water temperature, t_i is the initial commodity temperature and t is the final commodity temperature.

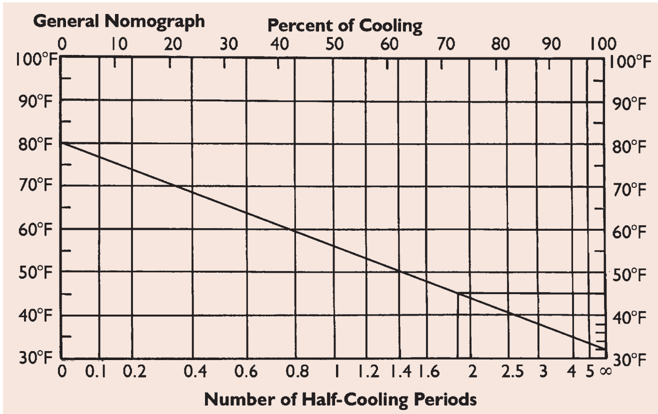

Figure 4: Example hydrocooling time estimation using general nomograph.

This semilogarithmic temperature history curve consists of one initial curvilinear portion, followed by one or more linear portions. Simple empirical formulae, which model this cooling behavior, have been proposed for estimating the hydrocooling time of fruits and vegetables.

Half-Cooling Time

A common concept used to characterize the hydrocooling process is the half-cooling time. The half-cooling time is the time required to reduce the temperature difference between the commodity and the cooling medium by one-half.[8] This is also equivalent to the time required to reduce the fractional unaccomplished temperature difference, Y,

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by one-half.

The half-cooling time is independent of the initial temperature and remains constant throughout the cooling period provided the cooling medium temperature remains constant.[8] Therefore, once the half-cooling time has been determined for a given commodity, the prediction of hydrocooling time is possible, regardless of the initial temperature of the commodity or the temperature of the cooling medium.

Product specific nomographs have been developed that when used in conjunction with half-cooling times, can provide estimates of hydrocooling times for fruits and vegetables.[9] In addition, a general nomograph, shown in *Figure 4*, was constructed to calculate the hydrocooling times of commodities based upon their half-cooling times.[10] To use the nomograph, place a straightedge from the initial commodity temperature at zero time to the water temperature at infinite time. The number of half-cooling periods may be read along the straightedge at any desired final commodity temperature. 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: Assume that topped radishes with a half-cooling time of 2.2 minutes are to be hydrocooled using 32°F (0°C) water. How long would it take to hydrocool the radishes from 80°F to 45°F (27°C to 7°C)?

Solution: As shown on the general nomograph in *Figure 4*, place a straightedge from 80°F (27°C) on the left to 32°F (0°C) on the right. Note that the final commodity temperature, 45°F (7°C), intersects the straightedge at approximately 1.8 half-cooling periods. Multiple the number of half-cooling periods, 1.8, by the half-cooling time, 2.2 minutes, to obtain the total hydrocooling time of 4.0 minutes.

The use of nomographs can be time-consuming and cumbersome. The hydrocooling time of fruits and vegetables may be determined without the use of nomographs by using the halfcooling time and the following equation:

$$q = \frac{-Z\ln(Y)}{In\ (2)} \qquad (2)$$

where

q is the cooling time (min) and

Z is the half-cooling time (min).

A summary of half-cooling time data for a variety of commodities is presented in *Table 1*.[10]

Commodity	Container	Half-Cooling Time, Z
Artichoke	None (completely exposed)	8 min.
	Crate, Lid Off, Paper Liner	12 min.
Asparagus	Completely Exposed	1.1 min.
	Lidded Pyramid Crate, Spears Upright	2.2 min.
Broccoli	Completely exposed	2.1 min.
	Crate with Paper Liner, Lid Off	2.2 min.
	Crate Without Liner, Lid Off	3.1 min.
Brussels Sprouts	Completely Exposed	4.4 min.
	Carton, Lid Open	4.8 min.
	Jumble Stack (9 in. deep)	6.0 min.
Cabbage	Completely Exposed	69 min.
	Carton, Lid Open	81 min.
	Jumble Stack (Four Layers)	81 min.
Carrots, Topped	Completely Exposed	3.2 min.
	50 lb. Mesh Bag	4.4 min.
Cauliflower, Trimmed	Completely Exposed	7.2 min.
Celery	Completely Exposed	5.8 min.
	Crate, Lidded, Paper Liner	9.1 min.
Sweet Corn (in husks)	Completely Exposed	20 min.
	Wirebound Corn Crate, Lidded	28 min.
Peas (in pod)	Completely Exposed (Flood)	1.9 min.
	One Bushel Basket, Lid Off (Flood)	2.8 min.
	One Bushel Basket, Lidded (Submersion)	3.5 min.
Potatoes	Completely Exposed	11 min.
	Jumble Stack (Five Layers, 9 in. Deep)	11 min.
Radishes	Completely Exposed	1.1 min.
	Crate, Lid Off, Three Layers of Bunches, 9 in. Deep	1.9 min.
	Carton, Lid Open, Three Layers of Bunches, 9 in. Deep	1.4 min.
Radishes, Topped	Completely Exposed	1.6 min.
	Jumble Stack (9 in. Deep)	2.2 min.
Tomatoes	Completely Exposed	10 min.
	Jumble Stack, Five Layers, 10 in. Deep	11 min.

Table 1: **Half-cooling times for hydrocooling of various commodities.**[10]

Cooling Coefficient

Hydrocooling time also may be predicted using the cooling coefficient, C (min $^{-1}$). As shown in *Figure 3*, the cooling coefficient is minus the slope of the ln(*Y*) vs. time curve, constructed on a semi-log axis from experimental observations of time and temperature. The cooling coefficient indicates the change in the fractional unaccomplished temperature difference per unit cooling time. The cooling coefficient depends upon the specific heat of the commodity and the thermal conductance to the surroundings.[8] Using the cooling coefficient for a particular cooling process, the cooling time, q, may be estimated as:

$$q = -\frac{1}{C}\ln\left(\frac{Y}{j}\right) \qquad (3)$$

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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*) vs. q curve becomes constant, i.e., the time required for the ln(*Y*) vs. q curve to become linear. The lag factor, *j*, can be found by extending the linear portion of the semi-logarithmic cooling curve to the ln(*Y*) axis. The intersection of the straight line extension with the ln(*Y*) axis is defined to be the lag factor, *j*.

By substituting *Y* = 0.5 into Equation 3, which corresponds to the half-cooling time, the cooling coefficient, C, can be related to the half-cooling time, *Z*, as follows:

$$Z = \frac{\ln(2j)}{C} \qquad (4)$$

A summary of cooling coefficient data for a variety of commodities is presented in Table 2.[11,12,13]

Hydrocooler Design and Operation

Hydrocooling efficiency is reduced by heat gain to the hydrocooling water from the surrounding air. Other sources of heat that reduce the effectiveness of hydrocoolers include solar loads, radiation from hot surfaces, and conduction from the surroundings. Protecting the hydrocooler from these sources of heat gain will enhance efficiency. Further energy losses occur if a hydrocooler is operated at less than full capacity, if it is operated intermittently, or if more water than necessary is used.[5]

To increase the energy efficiency of a hydrocooler, the following factors should be considered during design and operation:[5]

- 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;
- Because both intermittent operation and operation at reduced capacity wastes energy, operate the hydrocooler at maximum capacity;
- Consider the use of thermal storage in which chilled water or ice is produced and stored during periods of low energy demand. This chilled water or ice subsequently is used along with mechanical refrigeration to chill hydrocooling water during periods of peak energy demand. The use of thermal storage reduces the size of the required refrigeration equipment and may result in decreased energy costs; and
- Use an appropriately sized water reservoir. Since energy will be wasted when the 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 a consistent

Commodity	Commodity Initial Temp.	Commodity Final Temp.	Water Temp.	Water Flow Rate	Crate Load	Lag Factor, j	Cooling Coefficient, C(min–1)	Reference
Cucumbers	72°F		33°F	9.8 fpm	11 lb	1.037	0.10104	11
					22 lb	1.228	0.1005	
					33 lb	1.222	0.09774	
					44 lb	1.237	0.0888	
Eggplant	70°F			9.8 fpm	11 lb	1.077	0.04932	11
					22 lb	1.109	0.04764	
					33 lb	1.195	0.0522	
					44 lb	1.206	0.0462	
Peaches	70°F	39°F		9.8 fpm	11 lb	1.067	0.0951	12
					44 lb	1.113	0.07206	
Pears	73°F	39°F	34°F	9.8 fpm	11 lb	1.119	0.08604	13
					22 lb	1.157	0.08514	
					33 lb	1.078	0.07776	
					44 lb	1.366	0.06906	
Plums	72°F	36°F		9.8 fpm	11 lb	1.122	0.18102	12
					44 lb	1.171	0.13674	
Squash	71°F		33°F	9.8 fpm	11 lb	1.172	0.07632	11
					22 lb	1.202	0.07116	
					33 lb	1.193	0.06522	
					44 lb	1.227	0.06216	
Tomatoes	70°F		33°F	9.8 fpm	11 lb	1.209	0.0612	11
					22 lb	1.310	0.05442	
					33 lb	1.330	0.048	
					44 lb	1.322	0.04368	

Table 2: Lag factors and cooling coefficients for hydrocooling of various fruits and vegetables.

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hydrocooling water temperature and flow rate if an undersized water reservoir is used.

Hydrocooling Water Treatment

The surface of wet commodities provides an excellent site for diseases to thrive. In addition, since hydrocooling water is recirculated, decay-producing organisms can accumulate in the hydrocooling water, and thus, these organisms can be spread easily 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.[3] Chlorine in the form of hypochlorous acid from sodium hypochlorite or gaseous chlorine is added to the hydrocooling water, typically at the level of 50 to 100 ppm. However, chlorination of hydrocooling water only provides a surface treatment of the commodities. Chlorine will not neutralize an infection if it has developed below the surface of a commodity.

The chlorine level in the hydrocooling water must be checked at regular intervals to ensure the proper concentration is maintained. Chlorine is volatile and will disperse into the air. The dispersion rate of chlorine into air increases with increasing temperature, and thus, as the temperature of the hydrocooling water increases, the rate of dispersion of chlorine increases.[5] Furthermore, if ice cooling is used, the melting of ice in the hydrocooling water dilutes the chlorine in solution.

The effectiveness of the chlorine in the hydrocooling water strongly depends upon the pH of the hydrocooling water. The pH of hydrocooling water should be maintained at 7.0 to achieve the maximum effectiveness from the chlorine.[5]

To minimize the accumulation of debris in the hydrocooling water, it may be necessary to prewash the commodities prior to hydrocooling. Nevertheless, hydrocooling water should be replaced daily, or more often if necessary.

Special care should be taken when disposing of hydrocooling water since this water often contains high concentrations of sediment, pesticides and other suspended matter. Depending upon the municipality, hydrocooling water may be considered an industrial wastewater and thus, a hydrocooler owner may be required to obtain a wastewater discharge permit.[5] In addition to the daily replacement of hydrocooling water, hydrocooler shower pans and/or debris screens should be cleaned daily, or more often if necessary, to provide maximum efficiency.

Regulations developed by the U.S. Food and Drug Administration and U.S. Environmental Protection Agency (EPA) should be consulted when designing and operating hydrocooling equipment to ensure that the hydrocooling water is safe and properly disposed of after use. It is recommended that the quality of the water used in hydrocooling applications meet the EPA requirements for drinking water. In particular, hydrocooling water quality should conform to the Total Coliform Rule[14] and the Enhanced Surface Water Treatment Rule.[15] In addition, hydrocooling operations should follow the Good Manufacturing Practices (GMPs) found in Title 21 of the Code of Federal Regulations, Part 110,[16] regarding use of water for food and food contact surfaces in processing facilities.

Conclusions

For many fruits and vegetables, rapid precooling immediately after harvest is essential to preserving quality. When commodities are precooled promptly after harvest, shelf-life is extended, appearance is improved, preharvest freshness and flavor are maintained, and deterioration is reduced.

Hydrocooling is an effective method of precooling. In addition to rapid cooling, hydrocooling has the advantage of causing no commodity moisture loss. Thus, quality and salable weight of hydrocooled commodities is high. In contrast, other precooling methods, such as vacuum cooling or air cooling, may lead to significant commodity moisture loss and wilting, thus reducing product quality and salable weight.

In general, hydrocooling is economically viable for only large packing facilities since hydrocooling has relatively high initial and operating costs. However, smaller operations may benefit from hydrocooling since it can provide harvesting and marketing flexibility and can reduce losses that occur during transit.

Consumers may be willing to pay a premium for high-quality commodities, especially if the commodities are perceived to be succulent and full of flavor. Thus, commodities that have been hydrocooled may have a market advantage over commodities that have not been precooled or have been precooled by other means.

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