HYDROCOOLING TIME ESTIMATION METHODS

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ABSTRACT

Precooling refers to the rapid removal of field heat from freshly harvested fruits and vegetables prior to shipping, storage or processing. Hydrocooling is a form of precooling in which the product is sprayed with or immersed in an agitated bath of chilled water. The design of hydrocooling systems requires accurate estimation of the hydrocooling times of fruits and vegetables as well as the corresponding refrigeration loads. Numerous methods for predicting the hydrocooling times of fruits and vegetables have been proposed, and the designer is faced with the challenge of selecting an appropriate estimation method from those available. Therefore, this paper reviews selected estimation methods for the hydrocooling times of fruits and vegetables, and quantitatively evaluates the selected hydrocooling time estimation methods by comparing their numerical results to a comprehensive experimental hydrocooling time data set compiled from the literature.

INTRODUCTION

The origin of the refrigeration industry and, by far, its most significant application is the preservation of food. It is known that the cooling of food effectively reduces the activity of micro-organisms and enzymes, thus retarding deterioration. In addition, prompt precooling of fruits and vegetables, that is, the removal of field heat prior to shipping, processing or storage, maintains preharvest freshness and flavor.

Precooling

Product physiology largely determines precooling requirements and methods. Some vegetables are highly perishable and must be precooled as soon as possible after harvest. These include asparagus, snap beans, broccoli, cauliflower, sweet corn, summer squash, vine-ripened tomatoes, leafy vegetables, globe artichokes, Brussels sprouts, cabbage, celery, carrots, snow peas and radishes. Commercially important fruits that need to be precooled immediately after harvest include apricots, avocados, berries, cantaloupes, tart cherries, peaches, nectarines, plums, prunes, guavas, mangos, papayas and pineapples. Thus, precooling systems are essential to the fruit and vegetable industry.

Hydrocooling

Hydrocooling is a form of precooling in which the product is sprayed with or immersed in an agitated bath of chilled water. Commodities which are often hydrocooled include asparagus, snap beans, sweet corn, cantaloupes, celery, snow peas, radishes, tart cherries and peaches. Commodities which are sometimes hydrocooled include cucumbers, peppers, melons and early crop potatoes.

The refrigeration capacity needed for hydrocooling is much greater than that required for holding a product at a constant temperature. Therefore, it is imperative to have an adequate amount of refrigeration for effective hydrocooling, however, it is uneconomical to have more refrigerating capacity available than is needed. Hence, the efficient design of hydrocooling systems requires accurate estimation of the hydrocooling times of fruits and vegetables as well as the corresponding refrigeration loads.

HYDROCOOLING TIME ESTIMATION METHODS

The design of hydrocooling systems and the specification of hydrocooling process parameters requires accurate estimation of the hydrocooling times of fruits and vegetables as well as the corresponding refrigeration loads. Theoretically, the hydrocooling of fruits and vegetables can be described via the Fourier heat conduction equation. For regularly shaped fruits and vegetables with constant thermophysical properties, uniform initial conditions, constant external conditions and a prescribed surface temperature or a convection boundary condition, exact analytical solutions to the Fourier heat conduction equation exist, which allow for the estimation of hydrocooling times of fruits and vegetables. However, for irregularly shaped fruits and vegetables with temperature dependent thermophysical properties or other complicating factors, it is not possible to derive exact analytical solutions for hydrocooling time via the Fourier heat conduction equation.

Accurate numerical estimations of the hydrocooling times of fruits and vegetables can be obtained by using appropriate finite element or finite difference computer programs to solve the Fourier heat conduction equation. 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 which make use of simplifying assumptions, but nevertheless 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 [1]. A cooling curve depicting this behavior can be obtained by plotting, on semilogarithmic axes, the fractional unaccomplished temperature difference versus time. The fractional unaccomplished temperature difference, *Y*, is defined as follows:

$$Y = \frac{t_m - t}{t_m - t_i} = \frac{t - t_m}{t_i - t_m} \tag{1}$$

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 [2, 3, 4, 5, 6, 7]. This is also equivalent to the time required to reduce the fractional unaccomplished temperature difference, *Y*, by one-half.

The half-cooling time is independent of the initial temperature and remains constant throughout the cooling period provided that the cooling medium temperature remains constant [6, 7]. 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 [6], which, when used in conjunction with half-cooling times, can provide estimates of hydrocooling times for fruits and vegetables. In addition, a general nomograph, was constructed to calculate the hydrocooling times of commodities based upon their half-cooling times [6]. The hydrocooling time of fruits and vegetables may be determined without the use of nomographs by using the half-cooling time, Z, and the following equation:

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

Values of half-cooling times, Z, for numerous commodities have been reported by various researchers [2, 6, 8, 9, 10, 11, 12, 13].

Cooling Coefficient

Hydrocooling time may also be predicted using the cooling coefficient, C. 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 [2]. The cooling coefficient indicates the change in the fractional unaccomplished temperature difference per unit cooling time [9]. The cooling coefficient depends upon the specific heat of the commodity and the thermal conductance to the surroundings [2]. Using the cooling coefficient for a particular cooling process, the cooling time may be estimated as:

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

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. θ curve becomes constant, i.e., the time required for the ln(Y) vs. θ 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.

Cooling coefficients have been reported by Dincer and Genceli [9], Dincer [10, 11, 14], Henry and Bennett [3] and Henry et al. [4] for a variety of commodities and cooling conditions.

Factors *f* and *j*

Another hydrocooling time prediction model incorporates two factors, f and j, which represent the slope and intercept, respectively, of the semi-logarithmic temperature history curve [5]. As noted above, the j factor is a measure of the lag between the onset of cooling and the exponential decrease in the temperature of the food. The f factor represents the time required to obtain a 90% reduction in the unaccomplished temperature difference. The f factor is a function of the Biot number while the j factor is a function of the Biot number and the location within the food item.

The general form of the factors f and j cooling time model is:

$$\theta = \frac{-f}{2.303}\ln\left(\frac{Y}{j}\right) \quad (4)$$

From analytical solutions, Pflug et al. [15] developed charts for determining *f* and *j* factors for food items shaped either as infinite slabs, infinite cylinders or spheres. Lacroix and Castaigne [16] presented expressions for estimating the *f* and *j* factors for the thermal center temperature of infinite slabs, infinite cylinders and spheres. In an effort to determine *f* and *j* factors for irregularly shaped food items, Smith et al. [17] developed, for the case of Biot number approaching infinity, a shape factor called the "geometry index." This geometry index is used in conjunction with the Biot number and a nomograph to obtain a characteristic value, M_1^2, which in turn, is used to calculate the *f* and *j* factors.

Analytical Solutions

For simple geometric shapes such as infinite slabs, infinite cylinders and spheres, there exists infinite series, analytical solutions to the Fourier heat conduction equation. Generally, the cooling time is modeled using only the first term of the infinite series solutions, since for $Fo > 0.2$, the higher order terms become negligible, which is typical for most cooling processes. Numerous researchers have applied these series solutions to the cooling and heating of foods [5, 9, 18, 19, 20, 21, 22, 23, 24].

Equivalent Heat Transfer Dimensionality

More recently, cooling time prediction models have been developed which include a shape factor called the "equivalent heat transfer dimensionality" [25]. The "equivalent heat transfer dimensionality" compares the total heat transfer to the heat transfer through the shortest dimension. Cleland and Earle [25] developed an expression for estimating the equivalent heat transfer dimensionality of irregularly shaped food items as a function of Biot number. However, the cooling time estimation method developed by Cleland and Earle, which incorporates the equivalent heat transfer dimensionality, requires the use of a nomograph. Therefore, Lin et al. [26, 27, 28] expanded upon the work of Cleland and Earle [25] to eliminate the need for a nomograph.

In the method of Lin et al. [26, 27, 28], the cooling time of a fruit or vegetable is estimated by a first term approximation to the analytical solution for convective cooling of a sphere:

$$\theta = \frac{3\rho c L^2}{\omega^2 k E}\ln\left(\frac{j}{Y}\right) \quad (5)$$

where ω is the first root of the following transcendental function:

$$\omega \cot\omega + Bi - 1 = 0 \quad (6)$$

In Equation (5), the equivalent heat transfer dimensionality, E, is given as a function of Biot number, Bi.

PERFORMANCE OF HYDROCOOLING TIME ESTIMATION METHODS

The performance of each of the previously discussed hydrocooling time estimation methods was analyzed by comparing calculated cooling times with empirical hydrocooling time data available from the literature. The data set, which consists of 109 data points, is composed of hydrocooling times for nine different fruits and vegetables, including, apples, apricots, cucumbers, eggplant, peaches, pears, plums, squash and tomatoes [9, 10, 12, 20, 21, 30, 31, 32, 33, 34, 35, 36]. The thermal properties of the food items used in this study were either obtained from the source which provided the hydrocooling time data or calculated from equations reported in ASHRAE [29].

Table 1 summarizes the statistical analysis which was performed on the hydrocooling time estimation methods identified in this project. For each of the methods, the following information is given in Table 1: the average absolute prediction error (%) and its standard deviation (%), as well as the minimum and maximum absolute prediction error (%).

Table 1. Statistical Analysis of Hydrocooling Time Estimation Methods.

Hydrocooling Time Estimation Method	Average Absolute Prediction Error (%)	Standard Deviation (%)	Minimum Absolute Prediction Error (%)	Maximum Absolute Prediction Error (%)
Half-Cooling Time Method	16.9	5.84	6.95	26.1
Cooling Coefficient Method	17.1	8.82	2.30	35.6
f and j Factors Method	39.7	33.2	1.22	156
EHTD Method	31.7	25.9	1.17	113
Analytical Method	32.0	25.4	3.17	105

Half-Cooling Time Method

For a given hydrocooling process, knowledge of both the hydrocooling time and the half-cooling time are required to test the performance of the half-cooling time method. From the hydrocooling time database, only twelve data points were identified which provided both hydrocooling time and half-cooling time. For these twelve data points, the half-cooling time method produced an average absolute prediction error of 16.9% with a standard deviation of 5.84%. The absolute prediction error ranged from a minimum of 6.95% to a maximum of 26.1%. The half-cooling time method performed consistently for all three commodities in the data set.

Cooling Coefficient Method

A total of 51 data points provided cooling coefficient data and were used to test the performance of the cooling coefficient method. The average absolute prediction error for the cooling coefficient method was 17.1% with a standard deviation of 8.82%. For the 51 data points, the absolute prediction error ranged from a minimum of 2.30% to a maximum of 35.6%.

The cooling coefficient method produced a large average absolute error, 20.5%, with the data set from Dincer [10], which consists of 16 data points for the hydrocooling times of tomatoes, cucumber, eggplant and squash. The method performed well against the 2 data points given by Dincer [30], producing an average absolute prediction error of 6.96%. This data set consists of hydrocooling times for pears and eggplant. On other data sets consisting of apricots, cucumbers, plums, peaches and tomatoes [9, 31, 32, 33], the cooling coefficient method produced average absolute prediction errors of approximately 15%.

Factors *f* and *j* Method

A total of 61 data points provided *f* and *j* factor data and were used to test the performance of the *f* and *j* factor hydrocooling time estimation method. The average absolute prediction error for the *f* and *j* factor method was 39.7% with a standard deviation of 33.2%. For the 61 data points, the absolute prediction error ranged from a minimum of 1.22% to a maximum of 156%.

The *f* and *j* factor method produced average absolute prediction errors in excess of 50% for the data sets from Nicholas et al. [12], Dincer and Genceli [9] and Dincer and Genceli [34]. These data sets, which include 26 of the 61 data points, consist of hydrocooling time data for apples, cucumbers, peaches, pears, and tomatoes. Approximately 1/3 of the data points used to test the *f* and *j* method were from Smith et al. [35], and the *f* and *j* factor method produced an average absolute prediction error of 27.3% for this data.

Analytical Method

The hydrocooling time database contained only 59 data points which provided sufficient information to permit performance testing of the analytical hydrocooling time estimation method. The average absolute prediction error for the analytical method was 32.0% with a standard deviation of 25.4%. For the 59 data points, the absolute prediction error ranged from a minimum of 3.17% to a maximum of 105%.

The analytical method produced a rather large average absolute prediction error of 52.1% for the 11 data points from Dincer and Genceli [34]. The analytical method produced average absolute prediction errors of less than 13% for the six data points obtained from Dincer [21], Dincer and Genceli [9] and Dincer [31]. The analytical method produced an average absolute prediction error of 30.3 % for the forty-one data points from Nicholas et al. [12] and Smith et al. [35].

Equivalent Heat Transfer Dimensionality Method

The hydrocooling time database contained only 64 data points which provided sufficient information to permit performance testing of the equivalent heat transfer dimensionality (EHTD) hydrocooling time estimation method. The average absolute prediction error for the EHTD method was 31.7% with a standard deviation of 25.9%. For the 64 data points, the absolute prediction error ranged from a minimum of 1.17% to a maximum of 113%.

The EHTD method produced rather large average absolute prediction errors (>50%) for the data sets of Bennett et al. [36] and Dincer and Genceli [34]. These two data sets consist of 14 of the 64 data points used to test the EHTD method and include hydrocooling times for peaches, pears and tomatoes. The EHTD method produced average absolute prediction errors of less than 15% for the nine data points obtained from Dincer [20], Dincer [21], Dincer [30], Dincer and Genceli [9] and Dincer [31]. The EHTD method produced an average absolute prediction error of 28.5 % for the forty-one data points from Nicholas et al. [12] and Smith et al. [35].

CONCLUSIONS

A quantitative evaluation of selected hydrocooling time estimations methods was presented in this paper. The performance of each of the estimation methods was determined by comparing its calculated results with a comprehensive empirical hydrocooling time data set compiled from the literature.

The performance testing indicates that the half-cooling time estimation method and the cooling coefficient method give the best results. In addition, these two methods performed very similarly. However, it should be cautioned that the evaluation of these two methods is based upon a very small data set. Therefore, the performance of these two hydrocooling time estimation methods, based upon this small data set, may not represent the true behavior of these methods. In addition, the half-cooling time method and the cooling coefficient method require that either the half-cooling time or cooling coefficient be known for the particular hydrocooling process. This information may not be available, and thus, there may be limited applicability for these two methods.

The remaining three prediction methods, namely, the *f* and *j* factor method, the EHTD method and the analytical method, all produced similar results. Of these three methods, the EHTD method produced slightly better results than either the analytical method or the *f* and *j* factor method.

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NOMENCLATURE

Bi	Biot number
c	specific heat capacity
C	cooling coefficient
E	equivalent heat transfer dimensionality
f	cooling time parameter
Fo	Fourier number
j	cooling time parameter
k	thermal conductivity
L	characteristic dimension
M_1^2	characteristic value of Smith et al. (1968)
t	temperature
t_i	initial temperature
t_m	cooling medium temperature
Y	fractional unaccomplished temperature difference
Z	half-cooling time
θ	time
ρ	density
ω	first root of transcendental Equation (6)