Method to evaluate the average temperature at the surface of a horticultural crop

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Goyette, B., Vigneault, C., Panneton, B. and Raghavan, G.S.V. 1996. Method to evaluate the average temperature at the surface of a horticultural crop. Can. Agric. Engr. 38:291-295. Precooling systems must decrease the temperature of freshly harvested horticultural crops as fast as feasible. A good system provides a uniform final temperature throughout the mass of produce immediately following treatment. Therefore, the evaluation of precooling systems should include measurements of both the cooling rate and the uniformity of the temperature within the cooled produce. Cooling rate measures, such as the half-cooling time, have been used to evaluate precooling systems but apply only with a known homogeneous cooling medium temperature. This paper describes an extension of these methods by which the mean temperature of the medium surrounding the produce is calculated using the same set of data required to evaluate cooling rates. The theoretical basis for the method is presented and a laboratory experiment demonstrates the technique and its accuracy. Keywords: vegetable, postharvest, precooling, icing, cooling rate coefficient, half-cooling time.

INTRODUCTION

Good cooling and temperature management practices are critical to prevent the physiological deterioration of fruits and vegetables (Ryall and Lipton 1972). High respiration rates must be slowed down by prompt, rapid, and uniform cooling immediately after harvest. Such cooling processes are called rapid cooling (Fraser 1991) or precooling (ASHRAE 1986).

Cooling rate coefficient, CC, and half-cooling time, HCT, methods have been used for comparing precooling techniques (Hackert et al. 1987; Gariépy et al. 1987; Baird et al. 1988; Fraser and Otten 1992) and were presented in detail by Guillou (1958). These two methods apply where the temperature of the cooling medium is uniform around the produce. Furthermore, the CC and HCT depend on the size of the produce being tested. In the particular case of evaluating the uniformity of ice distribution for broccoli precooled using an ice-water mixture, these two factors become very important. Broccoli stalks are asymmetric and their diameter is difficult to measure. Because ice distribution is rarely uniform inside a box of produce, there is a non-uniform temperature distribution around the produce (Prussia and Shewfelt 1984).

Although the amount of ice retained in boxes ensured sufficient cooling capacity, Prussia and Shewfelt (1984) did not obtain uniform temperature throughout the mass of produce over a 36 h period.

A method is required to evaluate ice distribution inside boxes of produce. Based on preliminary experiments, measuring ice distribution using only visual observation was not precise enough. Ice fell into empty spaces as broccoli was removed from the package.

The objective of this study was to improve and extend the methods currently used to measure the efficiency of a cooling system by estimating temperature uniformity throughout the produce during the precooling process. This extended method has been developed especially to evaluate the effect of ice to water ratio and ice particle size on the performance of a liquid ice system developed by Vigneault et al. (1995).

THEORY

The heat-transfer process can be divided into three classes depending on the Biot number (Mohsenin 1980). The Biot number is defined as the ratio of the external resistance to the internal resistance to heat transfer:

\[
Bi = \frac{h S_0}{k}
\]

where:

- \(Bi\) = Biot number,
- \(h\) = convective heat-transfer coefficient (\(\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}\)),
- \(S_0\) = characteristic length of the body (m), and
- \(k\) = thermal conductivity of the product (\(\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}\)).

When \(Bi > 10\), \(h\) is high compared to \(k\) and the thermal conductivity of the product becomes the limiting factor to heat transfer. On the other hand, when \(Bi < 0.2\), \(k\) is high compared to \(h S_0\). In such a case, the temperature is consid-
ered uniform throughout the whole volume of the product and \( h \) is considered as the limiting factor to heat transfer. By definition, such a condition does not occur with solid food when performing the precooling process because \( k \) of solid food is relatively small compared to \( h \). Between a \( Bi \) of 0.2 and 10, there is a finite internal and external resistance to heat transfer (Mohsenin 1980). Precooling processes for horticultural crops are considered to be within this range.

Another useful non-dimensional parameter in the study of the transient heat transfer process is the Fourier number, \( Fo \), the square of the ratio of the temperature-wave penetration depth, \((\alpha t)^{1/2}\), at time \( t \) to the characteristic dimension of the body, \( S_0 \):

\[
Fo = \frac{\alpha_0 t}{S_0} \quad (2)
\]

Holman (1986) gives general solutions in terms of infinite series for transient heat transfer applicable for different shapes. These shapes are: infinite plate, infinite cylinder, and sphere. Broccoli stalk can be approximated as an infinite cylinder. Holman (1986) shows that for \( Fo > 0.2 \), the infinite series solution for the center temperature of a body, initially at a uniform temperature, can be approximated within 1% error using a single term:

\[
Q = \frac{\theta}{\theta_i} \frac{C_b}{C_o} \exp \left( -A_b \frac{\alpha_0 t}{S_0} \right) \quad (3)
\]

where:
- \( Q \) = temperature ratio,
- \( \theta \) = \( T_b \cdot T_{so} \) (°C),
- \( \theta_i \) = \( T_i \cdot T_{so} \) (°C),
- \( T_b \) = temperature of the body (°C),
- \( T \) = temperature of the surface of the body (°C),
- \( T_i \) = initial temperature inside the body (°C),
- \( C_b \) = constant, a function of \( Bi \) and the shape of the body,
- \( A_b \) = constant, a function of \( Bi \) and the shape of the body.

Equation 3 holds for a cylinder having a constant and uniform thermal conductivity and \( S_0 = r_0 \), the radius of the cylinder. Coefficient \( A_b \) can be determined from

\[
A_b J_1 (A_b) = J_0 (A_b) \quad (4)
\]

where \( J_0 \) and \( J_1 \) = Bessel functions of the first kind. Coefficient \( C_b \) can be determined from:

\[
C_b = \frac{2}{A_b J_0^2 (A_b) + J_1^2 (A_b)} \quad (5)
\]

From Eq. 3, the logarithm of the temperature ratio, \( \ln \left( \frac{\theta}{\theta_i} \right) \), plotted against time should give, after a certain lag time, a straight line where \( CC \) is the slope of the line (ASHRAE 1986) and denotes the change in produce temperature per unit time (Gariépy et al. 1987). Guillou (1958) presented \( CC \) as a function of the temperature ratios at two times, \( t_1 \) and \( t_2 \):

\[
CC = \frac{\ln \left( \frac{\theta}{\theta_i} \right)_{t_2} - \ln \left( \frac{\theta}{\theta_i} \right)_{t_1}}{t_2 - t_1} \quad (6)
\]

ASHRAE (1986) defined the \( HCT \) as the time required to reach a temperature ratio of 0.5, that is:

\[
HCT = \ln \left( \frac{0.5}{CC} \right) \quad (7)
\]

Based on Eqs. 3, 6, and 7, both \( CC \) and \( HCT \) depend very much on the radius of the body being cooled. Furthermore, the coefficient \( A_b \) is a function of \( Bi \) (Eq. 4) which varies with the radius of the produce. In practice, \( CC \) and \( HCT \) vary with produce subjected to the same cooling conditions, mainly because all conditions are not tightly controlled. For example, the diameter of a broccoli stalk is a physical parameter relatively difficult to measure (the stalk being particularly misshapen). Hackert et al. (1987) installed thermocouples in the center of broccoli stalks to read their internal temperatures and measure the \( HCT \). Their results were fairly constant under laboratory conditions but were imprecise under field conditions.

The temperature at any position inside a product attempts to reach equilibrium with the temperature of the cooling medium at the surface of the product, \( T_{so} \), through heat transfer (Holman 1986). It was hypothesized that, over a specific period of time during the precooling process, \( T_{so} \) can be determined by recording the temperature of a product at regular time intervals. The recording period must correspond to a period where \( CC \) is constant and it can be determined from the \( Q \) ratio (Eq. 3) in which values of 0.2 for \( \alpha_0 t / r_0^2 \), 2.4 for \( A_p \) and 1.6 for \( C_p \) (Holman 1986) have been substituted. These values of \( A_p \) and \( C_p \) imply a very large \( Bi \) number which should accommodate all possible conditions found in precooling horticultural crops. Under these conditions, \( Q \leq 0.5 \) and is linearly related to time.

\( T_{so} \) is the unknown to be determined. Since \( Q \) also needs to be determined, \( T_{so} \) is initially assumed to be the initial temperature of the cooling medium. For example, if broccoli is harvested at a temperature of 24°C (\( T_b \)) and it is processed with liquid ice at 0°C (assumed \( T_{so} \)), \( Q = 0.5 \) is reached when \( T_b = 12°C \) \( (0.5 = (T_b - 0) / (24 - 0)) \). The temperature of produce is recorded from \( T_b = 12°C \) and until \( T_b \) reaches a temperature equivalent to \( Q = 0.125 \). Then, \( T_{so} \) is iteratively adjusted to get the greatest linear correlation coefficient by plotting \( \ln (Q) \) against cooling time. The \( T_{so} \) finally obtained is considered as the mean temperature at the surface of the product during the precooling process.

**MATERIALS AND METHODS**

Evaluation of the hypothesis concerning the feasibility of calculating \( T_{so} \) for a horticultural crop during precooling was performed on broccoli stalks. Tests were performed under laboratory conditions. Since a broccoli stalk has the smallest surface-to-volume ratio among other parts of a broccoli head, it is assumed to be the critical part during the precooling process (Jiang et al. 1987). Two sets of five broccoli stalks were used. The diameter of the stalks ranged from 0.022 to
0.037 m and the length was 0.125 m. A temperature probe was inserted into the center of the stalk. The initial temperature of the stalks was approximately 24°C. To insure uniform cooling conditions, the first set of broccoli stalks was placed in a 10 L reservoir filled with ice and water. Water was circulated around the broccoli stalk using a pump. Ice was added to maintain the temperature of the water at 0.1°C. The temperatures of the ice-water mixture and at the center of the broccoli stalk were recorded every minute until the temperature at the center of the broccoli reached about 3°C. The second set of broccoli stalks was used to test the method under non-uniform cooling conditions. The broccoli stalks were lying on an ice bed with about half of the surface exposed to ice. The ice bed and broccoli stalks were placed in a cold room at 6°C. The ice surface to air was insulated using a thin styrofoam board to reduce the temperature gradient between the ambient air and the ice bed. A fan was used to create air movement above the ice bed surface. With this set up, one side of the broccoli stalks was exposed to 0.1°C (water-ice mixture) and the other side to 6°C (air). The temperature at the center of the broccoli stalk was recorded every minute until the temperature at the center of the broccoli was stable. Temperature sensors were calibrated with a freezing water bank to obtain a 0.1°C accuracy. Both \( T_\infty \) and \( CC \) were calculated using a macro developed on Microsoft Excel\textsuperscript{TM}. This macro was documented to be user friendly and is available upon request.

**RESULTS AND DISCUSSION**

Figure 1 shows the effect of \( T_\infty \) on the relationship between \( \ln(Q) \) and cooling time, \( t \). The \( T_\infty \) obtained while cooling a broccoli stalk on the ice bed and 6°C forced air was 3.16°C with a \( CC = -0.053 \) and \( R^2 = 0.9998 \). If \( T_\infty \) is assumed at 0°C, as it is assumed while using the liquid ice system, we obtain \( CC = -0.035 \) and \( R^2 = 0.9919 \). By assuming this incorrect \( T_\infty \), the linearity of \( \ln(Q) \) vs time is lower, as shown by the curved line results (\( T_\infty = 0°C \)). Although the correlation coefficients are fairly close together, these results demonstrate the importance of choosing the right value of \( T_\infty \) (changing from -0.035 to -0.053 \( \text{min}^{-1} \)).

These results also demonstrate that the linearity of \( \ln(Q) \) vs time begins at a value of \( Q \) even greater than 0.5. This was predictable since the limiting value of \( Q = 0.5 \) was calculated by using conservative values for \( Bi \). This conservative value permits the extension of the results to the precooling process of any size and shape of horticultural produce. The relative effect of underestimating to overestimating the \( T_\infty \) on the \( R^2 \) was calculated (Fig. 2). For a particular \( T_\infty \), there is much less variation in \( R^2 \) when \( T_\infty \) is underestimated than when it is overestimated. For values of \( T_\infty \) ranging from 3°C to 3.25°C, the same \( R^2 \) of 0.9998 was obtained when using four decimal precision. A fifth decimal precision had to be used to determine \( T_\infty \) at ± 0.1°C.

\[
\text{Fig. 2. Effect of overestimating or underestimating } T_\infty .
\]

Figure 3 shows the results obtained by plotting \( \ln(Q) \) against time during the hydrocooling of broccoli stalks of five different diameters. The time zero of these data is taken at the instant when \( Q \) reached 0.5, as established by Eq. 3. The temperature of the ice-water mixture showed a variation of 0.1°C throughout the whole cooling process; this implies that the ice melting heat sink compensated very well for the heat lost from the broccoli. The \( T_\infty \) of the broccoli stalks varied between 0.13°C and 0.20°C for the five broccoli diameters tested (Table I). The \( R^2 \) of each best fit regression line was 0.9982 and higher. This result showed that the linear regression method allows the calculation of \( T_\infty \) independently from the size of the produce. Figure 4 shows the importance of the relation between \( CC \) (\( \text{min}^{-1} \)) and \( D \) (m) during the hydrocooling process (Eq.5).

\[
CC = 1.7 \times 10^4 D^2
\]\n
The \( T_\infty \) of the broccoli stalk was also calculated when the temperature was not homogeneous around the stalks. Table II
Table II: Temperature at the surface calculated using the surface temperature method and \( R^2 \) of the best fit straight line for broccoli of different diameters under liquid ice / forced air hybrid cooling process.

<table>
<thead>
<tr>
<th>Diameter (m)</th>
<th>Temperature at the surface ( T_\infty ) (°C)</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.027</td>
<td>3.58</td>
<td>0.9999</td>
</tr>
<tr>
<td>0.028</td>
<td>3.50</td>
<td>0.9998</td>
</tr>
<tr>
<td>0.030</td>
<td>3.62</td>
<td>0.9999</td>
</tr>
<tr>
<td>0.036</td>
<td>3.45</td>
<td>0.9999</td>
</tr>
<tr>
<td>0.037</td>
<td>3.24</td>
<td>0.9999</td>
</tr>
</tbody>
</table>

Fig. 3. \( \ln(Q) \) as a function of time for broccoli stalks of different diameters during the hydrocooling process starting from \( Q = 0.5 \).

shows the results obtained for \( T_\infty \) varying between 3.24°C to 3.62°C for the five broccoli stalks tested. The \( R^2 \) of each linear regression is 0.9998 and higher. The broccoli stalks were supposed to be in an environment with an average temperature of 3°C. A small variation may have occurred because of the difficulty to expose exactly half of the surface of the stalks to each cooling medium. However, it demonstrates that the developed method can be used to calculate \( T_\infty \) under non-uniform precooling conditions.

CONCLUSION

A method to calculate the average temperature at the surface of produce being cooled has been developed and tested on a broccoli stalk. It can be used under both homogeneous and heterogeneous precooling conditions. The method is independent on the size of the produce. It was developed for the particular case of a liquid ice precooling, where the ice might not be uniformly distributed throughout the mass of produce. The uniformity of ice distribution depends on the size of ice particles and the ice to water ratio. Thus, the cooling uniformity has been evaluated by calculating the mean temperature at the surface of produce at different locations inside a box during the precooling processes.

REFERENCES


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**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_h$</td>
<td>constant, a function of $Bi$ and the shape of the body</td>
</tr>
<tr>
<td>$Bi$</td>
<td>Biot number</td>
</tr>
<tr>
<td>$C_p$</td>
<td>constant, a function of $Bi$ and the shape of the body</td>
</tr>
<tr>
<td>$CC$</td>
<td>constant, a function of $Bi$ and the shape of the body</td>
</tr>
<tr>
<td>$D$</td>
<td>diameter of the broccoli stalk (m)</td>
</tr>
<tr>
<td>$Fo$</td>
<td>Fourier number</td>
</tr>
<tr>
<td>$h$</td>
<td>convective heat transfer coefficient ($\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$)</td>
</tr>
<tr>
<td>$HCT$</td>
<td>half cooling time (min)</td>
</tr>
<tr>
<td>$J_{0,1}$</td>
<td>Bessel functions of the first kind</td>
</tr>
<tr>
<td>$k$</td>
<td>thermal conductivity of the solid ($\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$)</td>
</tr>
<tr>
<td>$Q$</td>
<td>temperature ratio</td>
</tr>
<tr>
<td>$r$</td>
<td>radial coordinate (m)</td>
</tr>
<tr>
<td>$r_0$</td>
<td>radius for the cylinder (m)</td>
</tr>
<tr>
<td>$R^2$</td>
<td>correlation coefficient</td>
</tr>
<tr>
<td>$S_0$</td>
<td>characteristic length of the body (m)</td>
</tr>
<tr>
<td>$T_b$</td>
<td>temperature of the body ($^\circ$C)</td>
</tr>
<tr>
<td>$T_i$</td>
<td>initial temperature inside the body ($^\circ$C)</td>
</tr>
<tr>
<td>$T_{oo}$</td>
<td>average temperature at the surface of a body ($^\circ$C)</td>
</tr>
<tr>
<td>$t$</td>
<td>time (s)</td>
</tr>
<tr>
<td>$t_1, t_2$</td>
<td>time at the instant 1 and 2 (min)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>statistical level of significance</td>
</tr>
<tr>
<td>$\alpha_0$</td>
<td>thermal diffusivity ($\text{m}^2$/s)</td>
</tr>
<tr>
<td>$\theta$</td>
<td>$T_b - T_{oo}$ ($^\circ$C)</td>
</tr>
<tr>
<td>$\theta_i$</td>
<td>$T_i - T_{oo}$ ($^\circ$C)</td>
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