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Prediction of Chilling Times of Foods in Situations Where Evaporative Cooling is Significant—Part 3. Applications

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ABSTRACT

Heuristics (rules of thumb) are proposed for extending the chilling time prediction method proposed in Part 1 and tested for model substances in Part 2 to real foods with non-unity water activity. Guidance is given for selecting three water activity values—one representing the maximally wetted starting condition, one representing the mean value during the active chilling phase, and the third describing the surface condition in the quasi-equilibrium state reached at the end of chilling. Chilling times of a product retaining a well-wetted surface during chilling (peeled carrots) were predicted to within approx. −10 to +15% of measured values. At least part of this difference can be attributed to experimental error. For a product not retaining a well-wetted surface due to skin resistance (unpeeled carrots) predictions of only slightly lower accuracy were achieved. Accurate prediction of chilling time across a wide range of conditions by a simple algebraic prediction method is possible in spite of the complexity introduced by evaporative cooling at the product surface with water activity less than 1.

NOMENCLATURE

a_w	Water activity at product surface
Bi	Biot number ($h\,R\,k^{-1}$)
c	Specific heat capacity (J kg^{-1} K^{-1})
D	Carrot diameter (m)

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f	Slope of a plot of ln Y vs Fo
Fo	Fourier number ($k\,t\,\rho^{-1}\,c_p^{-1}\,R^{-2}$)
h	Surface heat transfer coefficient (W m^{-2} K^{-1})
j	Lag factor or intercept of a plot of ln Y vs Fo
k	Thermal conductivity (W m^{-1} K^{-1})
Nu	Nusselt number ($h\,D\,k_a^{-1}$)
P	Total air pressure (Pa)
R	Characteristic length (radius) of product (m)
Re	Reynolds number ($D\,v_a\,\rho_a\,\mu_a^{-1}$)
t	Time (s)
T	Temperature (K or °C)
v	Air velocity (m s^{-1})
Y	Dimensionless temperature $(T-T_{eq})\,(T_{in}-T_{eq})^{-1}$
ρ	Density of product (kg m^{-3})
μ	Viscosity (kg m^{-1} s^{-1})

Subscripts

a	Air
c	Centre
Conv	Convection only
eq	Equilibrium
exp	Experimental
Evap	Evaporation and convection
in	Initial
p	Product
r	Relative (humidity)
w	Saturation

INTRODUCTION

When unwrapped food products are chilled, surface heat transfer may occur by both convection and evaporation, and the evaporative effect can significantly increase the rate of product cooling above that which would otherwise arise. In Parts 1 and 2, Chuntranuluck *et al.* (1998a,b) proposed a new, simple prediction method requiring only algebraic calculation for the determination of chilling times in such circumstances. The method predicted both thermal centre and mass-average temperature as a function of time. They successfully tested the method against experimental time–temperature data collected during chilling of a food analogue material under a wide variety of environmental conditions and for various a_w likely to be encountered in industrial practice. The measured product centre temperatures matched the predicted chilling profiles within a range of differences which could almost totally be explained by data uncertainties. Mass average temperature predictions were not tested experimentally, but on the basis that it was unlikely that the thermal centre temperature would be well-predicted and the mass-average temperature predicted poorly, good overall method performance was claimed.

In making predictions by the proposed methodology, as well as the data that would normally be required for a convection only chilling process, two new data are required — the product surface water activity, a_w and the air relative humidity, H_r. Limitations of the method are that it was derived for only three basic shapes (the infinite slab, infinite cylinder and sphere), and for products in which a_w can be assumed to be constant, although $a_w \leq 1$ is allowed. The latter factor distinguishes the method from much earlier research on evaporative enhancement of cooling. The method uses algebraic equations, and because these are stated in both Parts 1 and 2 (Chuntranuluck *et al.*, 1998a,b) they are not repeated here. Users of the method determine three parameters which define a semi-log plot of the fractional unaccomplished temperature change (Y) vs time. Predictions of the time–temperature history of the product are made from the semi-log relationship. The first of the parameters is the intercept parameter j_{Evap}, the second a slope parameter f_{Evap}, and the third is the product equilibrium temperature T_{eq} which is used in the definition of Y.

The difficulties in seeking to apply the method to real food products are two-fold. Firstly, many foods have skins and these have widely differing water transport resistance. Secondly, during a chilling process there can be temporary water depletion of the product surface leading to a changing surface water activity. In discussing these effects the terminology illustrated in Fig. 1 was adopted. There is an 'active chilling phase' during which the product temperature change with time is significant, and during which water activity may change with time. As time progresses a 'quasi-equilibrium phase' is reached in which a_w again becomes constant, although not necessarily at its starting value at time zero. The initial value of a_w reflects the handling of the product prior to entering the chiller.

It is postulated that to extend the methodology to real foods the values of a_w used in determining f_{Evap}, j_{Evap}, and T_{eq} should be adjusted according to the nature of the food product. The adjusted values would then be used in the existing equations. It

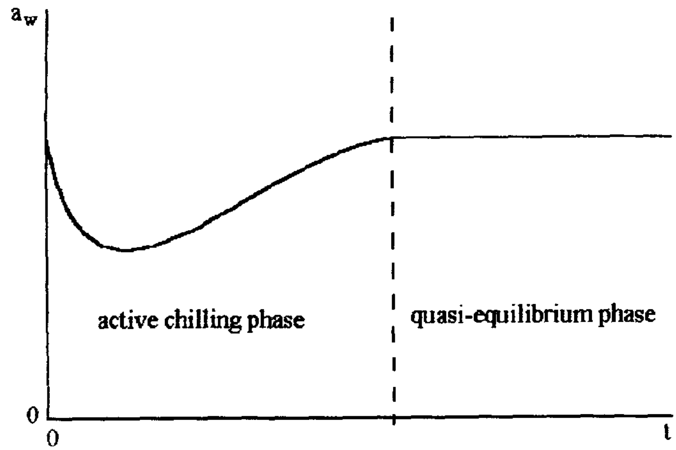

Fig. 1. Concept diagram showing the change in a_w during a typical chilling experiment in which the internal water movement rate within the product cannot maintain a fully wetted product surface.

is further postulated that different values of a_w might be appropriate for finding each of the parameters. For example, the value used to find the intercept parameter at time zero (j_{Evap}) might reflect the initial state of the product, while that for the slope parameter (f_{Evap}), which controls the active chilling mode might be lower, and that used to find the equilibrium temperature (T_{eq}) might reflect the quasi-equilibrium state. The research objectives were to establish theoretical bounds on a_w, to test these experimentally, and finally to develop a set of heuristics (rules of thumb) for practical application of the method to real foods.

For convenience, nomenclature used for the different a_w values was as follows:

(1) the initial (time zero) value used to determine j_{Evap} (a_{wj}),
(2) the mean value during active chilling used to determine f_{Evap} (a_{wf}),
(3) the quasi-equilibrium value used to determine T_{eq} ($a_{w,eq}$).

For a_{wj} there appeared to be no need to establish upper and lower bounds. It was proposed that a_{wj} would always represent the product condition at the commencement of chilling (and this would normally be the 'maximally wetted' state before any water loss from the surface had occurred).

For a_{wf} a plausible lower bound is that of a very dry surface ($a_{wf} \rightarrow 0$), whereas the upper bound would be a maximally wetted surface for the product, which in all probability would be represented by a_{wj} in many cases. If there is significant skin resistance to water transport the appropriate value of a_{wf} will lie towards the lower bound. Of course, care must be taken if the skin resistance is very large. In that case evaporation might be minimal, and predictions should be carried out assuming convection-only cooling. If there is no skin resistance (e.g. a cut food surface) and water movement within the product occurs easily then the correct value will be towards the upper bound. A food with no skin, but in which internal mass transfer is slow could approach the lower bound.

For $a_{w,eq}$ the lower bound would be expected to be $a_{w,eq} = H_r$. This is because if a_w became lower than H_r, rapid condensation, to restore the equality, would occur. The upper bound which would arise for materials with no skin resistance would be the quasi-equilibrium value for a maximally wetted surface, which is likely to be represented by $a_{w,eq} = a_{wj}$.

Ultimately, the aim was to develop heuristics to narrow these bounds, but this was not considered feasible until at least one food system had been studied experimentally. It was anticipated that analysis of the experimental results would help in developing ideas for converting the statements of principle above into more useful working rules. For convenience, and to match the experimental work with the model food system, it was decided to work with a cylindrical food. It was desirable to use a product for which skin resistance could be included or excluded by choice, but which was also homogeneous and readily available. The product selected was carrots—for practical applications carrots can be acceptably considered as cylinders if chosen carefully, and they have an appropriate length to diameter ratio to minimise end effects. They have a low respiration rate and their skin can be easily peeled. Their disadvantages were that they are not perfectly homogeneous, nor perfectly cylindrical, and that due to their small size and rigid structure accurate thermocouple placement was difficult.

It was decided to conduct two sets of experiments, one with skins peeled and the other with skins present, each covering a wide range of chilling conditions. The results of these experiments would be used to assess and improve the proposed heuristics (bounds), thus increasing the likelihood that the simple model could be successfully applied to less idealised conditions than those for which it was developed.

MATERIALS AND METHODS

Material selection and sample preparation

Carrots were selected from local retail vegetable outlets with large stocks, thus allowing reasonably cylindrical carrots of about the same dimensions to be selected. Not all carrots could be selected at the same time, and they were not necessarily in the same physiological state, so some carrot to carrot variability was inevitable (Gan & Woods, 1989). When a carrot was peeled, it was rounded (using a razor) until the size and shape were uniform. The carrots used were 21–32 mm in diameter with a ratio of length to diameter of between 4 and 5.

By first creating penetrations through the ends of the carrot, and then pushing the wires into place, two copper–constantan thermocouples (28–30 SWG) were placed on the central axis of each carrot about 25 mm either side of the mid-point. Another thermocouple was inserted along the radius to the centre position at the mid-point of the carrot. The diameter of the carrot was measured at the three temperature measurement positions using Vernier calipers. Since the carrot was not perfectly round, the mean diameter of two measurements at right angles to each other was calculated, and then the largest of the three mean values thus derived was used in all further analysis. To minimise the influence of end effects, polystyrene foam insulation end caps were applied to both ends of the carrot prior to commencement of the chilling trials.

Chilling trials

A typical run consisted of holding the wrapped sample at its desired initial temperature for about 6 h, unwrapping it and then transferring it immediately to an air tunnel in which stable air velocity, temperature and relative humidity had been achieved. The air tunnel and measurement systems used were described in Part 2 (Chuntranuluck *et al.*, 1998b). Chilling runs lasted at least 3.5 h, at which time the carrot samples had reached their quasi-equilibrium condition.

The thermocouple readings showing the slowest temperature change were used as the best estimate of true centre temperature, irrespective of whether it was the thermocouple located at the thickest diameter position. This was justified on the basis that data from a very central thermocouple in a slightly thinner region would more accurately represent the true centre temperature at the thickest position than a badly placed thermocouple in the thickest region.

Physical properties of carrots

The mean measured water content of the peeled carrots was 86% and the range of measured values 84–88%. The mean measured density (using a water displacement technique) was 1050 kg m^{-3} and the range of measured values 1010–1090 kg m^{-3}. The mean value was used in all calculations.

Thermophysical properties of carrot were not experimentally measured. A thermal conductivity of 0.519 W m^{-1} K^{-1} is reported by Hayakawa (1978) and the mean specific heat capacity from Heldman and Singh (1981) and Hayes (1987) is 3.873 kJ kg^{-1} K^{-1}. The accuracy of these data is unknown, but they are consistent with expectations for a product of about 86% water content. Further, because these data were used for both heat transfer coefficient determination and cooling trial analysis any error in thermal properties would be expected to partly cancel itself.

A Water Activity System (Decagon Model CX-2) rated to ±0.3% of the measured value was used in measuring the surface water activity of thin slices of peeled (cut) carrot. The overall mean measured a_w for all samples was 0.977 with the range 0.954–1.0. It was found that the mean a_w measured prior to the commencement of chilling was 0.981 and that after chilling was completed it was 0.972. This indicates that there may have been slight moisture depletion, and hence increased concentration of dissolved solutes. The value of 0.977 was used to represent the fully wetted condition of a peeled carrot.

By definition, the water activity of unpeeled carrots can only be determined using uncut whole carrots. A suitable apparatus was not available for this, and so no measurements were made.

Surface heat transfer coefficients

Surface heat transfer coefficients were determined by cooling carrots wrapped with a thin plastic film, and applying heat penetration theory in the manner already described in Part 2 (Chuntranuluck *et al.*, 1998b). Because the plastic film was very thin and fitted tightly it was assumed that it did not change the overall heat transfer coefficient significantly. Variations in heat transfer coefficients could be caused by any pockets of air trapped between the carrot and the plastic film (due to the rough carrot surface), the difference between the diameter used in calculation and the true diameter, and to a lesser extent by deviation of thermocouples from the central axis of the cylinder.

Experimental plan

Experimental trials were conducted across as wide a range of practical conditions as possible:

air velocity	0.5–3.0 m s^{-1}
relative humidity	0.70–0.90
air temperature	0–10°C
initial temperature	20–30°C

In total, 18 runs (based on a four-variable factorial experiment plus two centre points) were conducted for each of peeled and unpeeled carrots. In addition, there were a further 18 runs for each in which heat transfer coefficients were measured. Details of the experimental plan and results are given in the thesis from which this paper has been drawn (Chuntranuluck, 1995).

RESULTS AND DISCUSSION

Heat transfer coefficients

As was the case in the experimental work with model food systems, the heat transfer coefficient was best-fitted as a function of velocity. Whereas for the earlier work it had been possible to develop simple h vs v plots for each of the two standard cylinder sizes, the varying carrot diameters meant that a dimensionless number approach was required. Over the ranges covered the variation of Prandtl number was small, so Nu vs Re relationships proved adequate. These were separately fitted for peeled and unpeeled carrots because the unpeeled carrots were less cylindrical in shape, were of less uniform size, and had a rougher surface, which may have led to more air entrappment under the plastic film. Nonlinear regression analysis of the data for peeled carrots gave:

$$Nu = 0.267 Re^{0.597} \ (R^2 = 0.913) \tag{1}$$

whereas for unpeeled carrots:

$$Nu = 0.704 Re^{0.466} \ (R^2 = 0.870) \tag{2}$$

Heat transfer coefficents from these correlations were used in all further calculations. Individual measured values lay within about $\pm 15\%$ of these lines, but h values from the best fit lines should be more accurate. Details are given in the source thesis (Chuntranuluck, 1995).

Chilling trial results

In presenting the results, the apparent steady state condition at 3.5 h was used as an approximation to equilibrium as all runs had reached steady state within the sensitivity of the measurement system in less than this time. As expected, when the product was wrapped with the plastic film for heat transfer coefficient measurement (no evaporation), $T_{eq,exp}$ equalled T_a. Under the same environmental conditions, the cooling curves and $T_{eq,exp}$ values of a carrot when unpeeled and peeled were very different (e.g. Fig. 2). For the unpeeled carrot, there is the resistance to moisture movement in the skin which lowers the evaporation rate and thus the rate of cooling is slower than for the peeled carrot. The quasi-equilibrium state reached (no further temperature change, constant evaporation rate) suggests that $a_{w,eq}$ is very different in the two cases.

Figure 3 illustrates that successful linearisation occurred using $T_{eq,exp}$ to calculate Y values for preparation of semi-log plots ($R^2 > 0.98$), but the slope and intercept parameters were markedly different between the peeled and unpeeled carrots. Full tabulated results are presented by Chuntranuluck (1995), including the experimental values of f_{Evap}, j_{cEvap} and $T_{eq,exp}$.

Peeled carrots

Analysis of the peeled carrots data closely paralleled the processes used in Part 2 (Chuntranuluck *et al.*, 1998b) for analysing the experimental data in idealised systems. It was considered likely that the rate of internal water movement would be rapid, and thus the cut surface would remain fully wetted. Hence initial testing was carried out assuming $a_{wj} = a_{wf} = a_{w,eq} = 0.977$ (the mean measured value). Predictions were carried out with both the finite difference method from Part 1 (Chuntranuluck *et al.*, 1998a), and the proposed simple prediction method.

These results are shown in Table 1 and Table 2. The results are very similar to those achieved for the food analogue experiments except that the standard deviations are larger, probably indicating increased experimental error (which was expected). All three parameters T_{eq}, f_{Evap} and j_{cEvap} were well predicted on average, and both the simple method and finite differences tended to predict high or low on the same runs. The mean offset for the f values was close to 0%, whereas for the j values the mean difference was about +3.0%. The latter is more affected by deviation of thermocouples from the central position inside the products, and this factor alone might explain the offset. Overall, the quality of prediction was considered acceptable taking into consideration the extra data uncertainties compared with the food analogue experiments, especially those in the heat transfer coefficients, the possible non-cylindrical shape of the product, and differences in both composition and maturity between different carrots.

Tables 1 and 2 also show the comparisons between measured (t_{exp}) and predicted chilling (t_{pred}) times to reach certain centre temperatures ($T_{c,exp}$) which corresponded to $Y_{c,exp} = 0.10$, 0.35, and 0.70. The method of calculation is outlined by

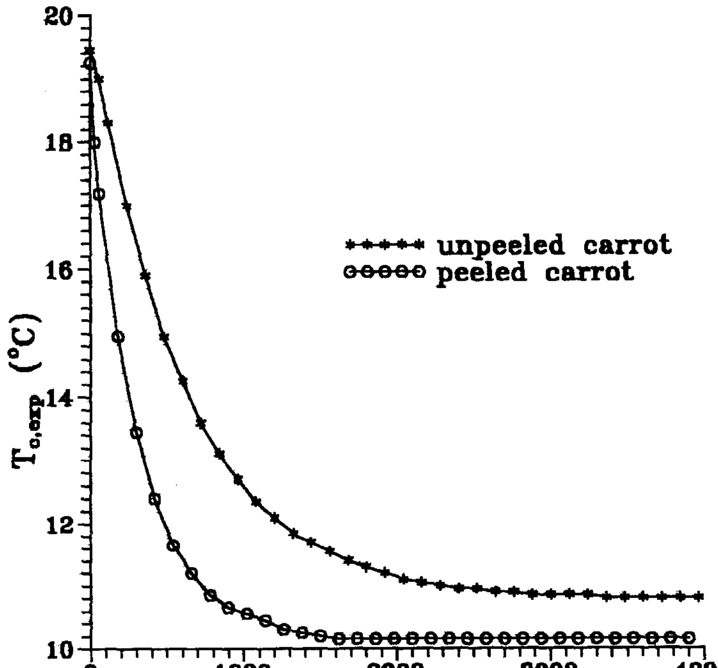

Fig. 2. Comparison of centre temperature vs time profiles for cooling of a carrot when peeled and unpeeled under the same environmental conditions.

Chuntranuluck *et al.* (1998b). Again, the finite difference and simple model failed to predict experimental data in similar ways (the correlation coefficients between % differences of the two models were close to 1). The mean offset for chilling time of both models at $Y_{c,exp} = 0.10$ and $Y_{c,exp} = 0.35$ was close to zero, whereas at $Y_{c,exp} = 0.70$ the mean offset was about 6%. The reason for the poorer agreement at the higher Y value is that the semi-log cooling regime is not always well established

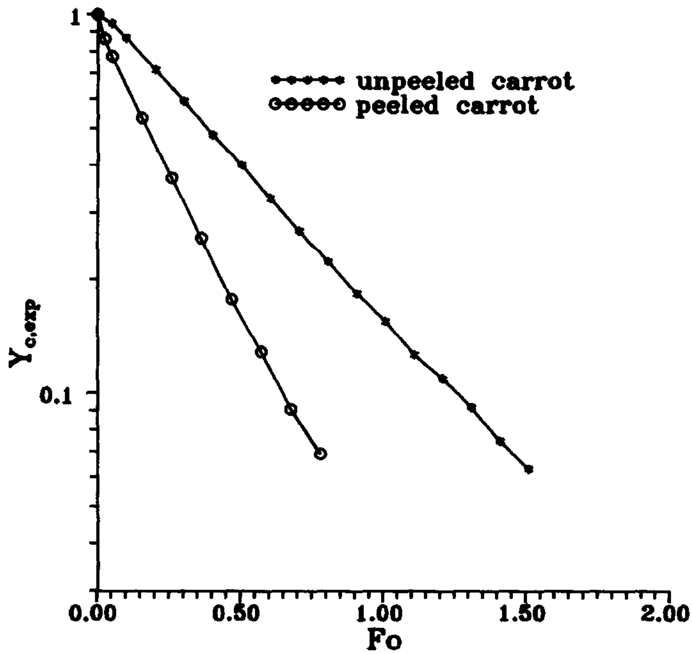

Fig. 3. Plot of ln $Y_{c,exp}$ (calculated using $T_{eq,\,exp}$ in the definition of Y) vs *Fo* for the cooling data shown in Fig. 2.

TABLE 1

Differences Between Results Calculated by the Finite Difference Method (Assuming $a_{w,eq} = a_{wj} = a_{wf} = 0.977$) and Results from the Experiments for Peeled Carrots

	% difference in f_{cEvap}/f_{cConv}	*% difference in* j_{cEvap}/j_{cConv}	*% difference in time to* $Y_{c,exp}$ = *0.10*	*0.35*	*0.70*	*Abs. difference in* T_{eq} (°C)
Mean	+0.7	+3.0	−1.3	+1.5	+5.8	0.1
SD	5.4	4.6	9.2	6.2	5.9	0.2
95% conf. interval	−10.6 to +12.0	−6.6 to +12.6	−20.6 to +18.1	−11.5 to +14.6	−6.6 to +18.2	−0.3 to +0.6

TABLE 2
Differences Between Results Calculated by the Proposed Curve-fit Equations (Simple Model) (Assuming $a_{w,eq} = a_{wj} = a_{wf} = 0.977$) and Results from the Experiments for Peeled Carrots

	% difference in f_{cEvap}/f_{cConv}	*% difference in* j_{cEvap}/j_{cConv}	*% difference in time to* $Y_{c,exp}$ =			*Abs. difference in* T_{eq} (°C)
			0.10	*0.35*	*0.70*	
Mean	+0.3	+2.9	−0.9	+2.0	+6.2	0.1
SD	5.3	4.4	9.1	6.1	5.7	0.2
95% conf. interval	−10.9 to +11.5	−6.4 to +12.2	−20.1 to +18.2	−10.8 to +14.7	−5.7 to +18.2	−0.3 to +0.6
R^{2a}	0.959	0.995	0.986	0.969	0.967	—

[a]Correlation coefficient between (a) % difference between simple method prediction and experiment; and (b) % difference between finite difference predictions and experiments.

before this $Y_{c,exp}$ is reached. This is a well-known weakness of any model based on assumed exponential behaviour. Once $Y_{c,exp}$ is close to zero, any error in $T_{eq,pred}$ is much more significant in its effect on chilling time prediction than at higher Y values. This is why the standard deviation is greater at $Y_{c,exp} = 0.10$ than at 0.35.

The results suggest that for any food product without a skin, and in which surface water replenishment is rapid the use of $a_{wj} = a_{wf} = a_{w,eq}$ will give satisfactory results.

Unpeeled carrots

Observation of the experimental plots (e.g. Fig. 2 and Fig. 3) suggested that the appropriate values of a_{wj}, a_{wf} and $a_{w,eq}$ would be quite different for a product with a skin. To carry out any analysis it was first necessary to find values of T_{eq} that linearised the semi-log cooling plots. Using $T_{eq,exp}$ data in the equation for T_{eq} derived in Part 1(Chuntranuluck *et al.*, 1998a):

$$T_{eq} \approx T_a - \frac{18\left(2.5\times10^6 - 2.5\times10^3 T_{eq}\right)}{29 c_a P}\{a_{w}e^{[23.4759-(3990.56/T_{eq}+233.833)]} - H_r e^{[23.4759-(3990.56/T_a+233.833)]}\} \quad (3)$$

it was possible to back-calculate values of $a_{w,eq}$. These are plotted in Fig. 4 in conjunction with the two bounds proposed earlier. All results lie within the bounds, but $a_{w,eq}$ is best-fit by:

$$a_{w,eq} = 0.792 H_r + 0.215 \ (R^2 = 0.853) \quad (4)$$

The relatively modest skin resistance of the carrots is sufficient to make the carrots behave more like a non-evaporating surface than a fully wetted carrot surface.

Within ranges defined by the lower and upper bounds for the three different a_w values the following possibilities were tested:

a_{wj} = 0.977 (the maximally wetted value of cut carrot tissue)
a_{wf} = 0.30
= 0.16
$a_{w,eq}$ = 0.977 (upper bound)
H_r (lower bound)
eqn (4) (best-fit line)

The selections for $a_{w,eq}$ and a_{wj} were straightforward, but that for a_{wf} was not. Observation of Figs 2 and 3 had suggested that a_{wf} would be low, but the theoretically determined bounds were $a_{wf} = a_{wj}$ (0.977) and $a_{wf} \rightarrow 0$. Not knowing what was an appropriate value the first calculations were performed with a value of 0.30. The value of 0.16 was subsequently selected as a value that led to better fitting of the data set and also enabled the sensitivity of predictions of inaccuracy in the selection of a_{wf} to be determined.

The three choices of $a_{w,eq}$ led to significantly different estimates of T_{eq}. The upper bound led to a mean offset of −0.9°C (predictions lower than observed data) and a standard deviation of 0.5°C, the lower bound to a mean of +0.4°C and a standard deviation of 0.2°C, and the best-fit line to a mean deviation of 0.0°C and a standard deviation of 0.2°C.

The effect of a_{wf} was examined by considering lack of fit between observed and predicted values of f_{cEvap}/f_{cConv}. At $a_{wf} = 0.30$ the mean difference was 8.1% and the standard deviation 9.4%, but at $a_{wf} = 0.16$ the mean difference became 2.6% and

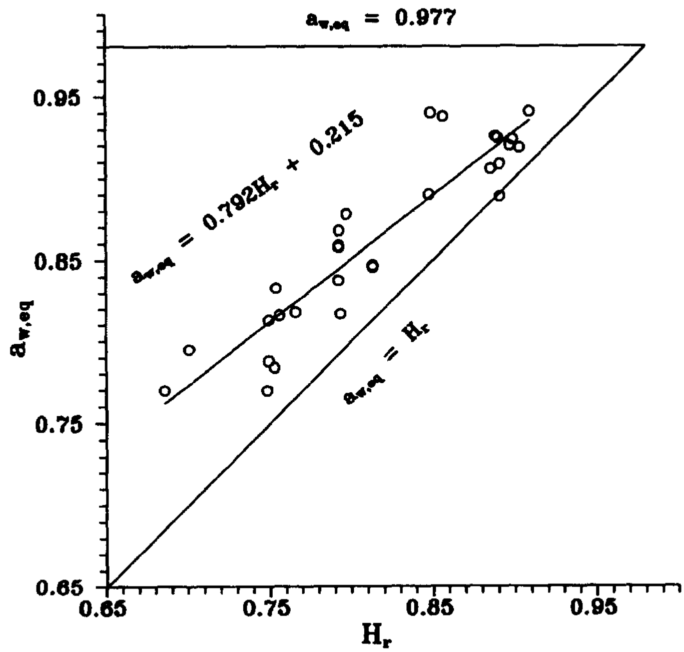

Fig. 4. Plot of values of $a_{w,eq}$ (back-calculated from eqn (3)) vs H_r for unpeeled carrots showing the postulated upper and lower bound lines and the best-fit equation.

the standard deviation 9.1%. The standard deviation is larger than for peeled carrots (for which it was 5.3%). Whilst there was more experimental error for the unpeeled carrots due to their rough surfaces and less cylindrical shape, it is unlikely that this alone explains the wider standard deviation. A contributor to the lack of fit will be that a_{wf} varies with time (as illustrated in Fig. 1), and the use of a mean value introduces some error.

To test the selection of a_{wj}, values of j_{cEvap}/j_{cConv} were calculated from both the experimental results and the proposed prediction method. The mean was 6.1% and the standard deviation 6.6%, both larger than the values of +2.9% and 4.6% for peeled carrots. Again, it is unlikely that the extra experimental error in the peeled carrot experiments can totally explain the increased lack of fit. It appears either the experimental starting value of a_w was less than 0.977, the mean value for peeled carrots, or that an improved heuristic is required.

Ultimately, the performance of the heuristics is best assessed by the ability to predict chilling time. In line with the method described in Part 2 (Chuntranuluck *et al.*, 1998b), the predicted chilling time, t_{pred}, was determined using:

$$t_{pred} = \left(\frac{ln\, Y_{c,pred} - \ln j_{cEvap,\ pred\ at\ a_{wj}}}{k f_{cEvap,\ pred\ at\ a_{wf}}} \right) \rho c_p R^2 \tag{5}$$

Table 3 summarises the comparisons between predicted and measured chilling times for $Y_{c,exp} = 0.10$, 0.35, and 0.70. The broad trends in the table are similar to those in Table 1 and Table 2. Reasons for poorer predictions at $Y_{c,exp} = 0.70$ and 0.1 than at 0.35 have already been given. As may have been expected, $a_{wj} = 0.977$, $a_{wf} = 0.16$, and use of the best-fit equation to evaluate $a_{w,eq}$ gave the best predictions overall. There were interactions between the various selections, but in broad terms, the effect of using other selections of a_w can be summarised as follows:

TABLE 3

Comparisons of Time to the Temperature that Corresponds to $Y_{c,exp} = 0.10$, 0.35, and 0.70 Between the Experimental Results and Simple Model (for unpeeled Carrots) using $a_{wf} = 0.16$ and $a_{wj} = 0.977$, and $a_{wf} = 0.30$ and $a_{wj} = 0.977$, and $T_{eq,pred}$ Under Different Conditions

Simple model		*% difference in time*								
		$T_{eq,pred}$ at $a_w = 0.977$			$T_{eq,pred}$ at $a_w = H_r$			$T_{eq,pred}$ at $a_w = 0.792H_r+0.215$		
		$Y_{c,exp}$ *[0.10]*	$Y_{c,exp}$ *[0.35]*	$Y_{c,exp}$ *[0.70]*	$Y_{c,exp}$ *[0.10]*	$Y_{c,exp}$ *[0.35]*	$Y_{c,exp}$ *[0.70]*	$Y_{c,exp}$ *[0.10]*	$Y_{c,exp}$ *[0.35]*	$Y_{c,exp}$ *[0.70]*
$a_{wf} = 0.30$ and	mean	−19.0	−10	−0.2	5.7	1.3	6.5	−5.3	−2.8	4.1
$a_{wj} = 0.977$	SD	11.4	8.7	10.0	10.6	7.9	10.6	9.3	7.7	10.2
$a_{wf} = 0.16$ and	mean	−14.7	−5.2	5.1	11.3	6.7	12.1	−0.2	2.4	9.6
$a_{wf} = 0.977$	SD	12.3	9.4	10.6	11.3	6.7	12.1	10.1	8.3	10.7

(1) $a_{w,eq} = H_r$; the mean difference was increased by about 10%, standard deviation increased slightly,
(2) $a_{w,eq} = 0.977$; results adequately predicted except at low $Y_{c,exp}$,
(3) $a_{wf} = 0.30$; mean difference is lowered by about 5%, standard deviation increases slightly,
(4) both $a_{w,eq} = H_r$ and $a_{wf} = 0.30$; the errors introduced roughly cancelled,
(5) both $a_{w,eq} = 0.977$ and $a_{wf} = 0.30$; the worst predictions.

If the situation-specific best-fit equation for a_{wf} had not been available and instead $a_{w,eq} = H_r$ had been used in finding $T_{eq,pred}$, and if $a_{wf} = 0.30$ had been arbitrarily chosen, predictions of almost equal accuracy to the best fit would have resulted.

Development of heuristics

The analysis here has considered only one material and so it is not possible to develop comprehensive working rules. However, an approach for seeking more precise rules can be suggested.

(1) Applicability of the method. If the product to be chilled has a highly resistant skin and the expected weight loss is low it would be advisable to carry out predictions for convection-only cooling instead.
(2) $a_{w,eq}$. If there is good evidence to suggest that there will be rapid internal water movement to replenish surface water, and there is no skin resistance then $a_{w,eq}$ should be selected as the 'maximally wetted value'. If water movement is slow, or there is a skin of even low resistance then $a_{w,eq}$ should be set equal to H_r. As experience is developed users of the method may wish to postulate the placing of a product-specific line between these bounds, as illustrated in Fig. 4.
(3) a_{wj}. There appears to be no sensible alternative to use of the a_w value for a 'maximally wetted' material. For many food materials this value will be close to unity. If this selection leads to error, the effect will tend to be over-prediction of chilling time. Chilling time is relatively insensitive to selection of this parameter, but the error will increase as skin resistance increases.
(4) a_{wf}. Observation of the surface condition in chilling experiments may be helpful. If there is even a small skin resistance then a_{wf} should be selected as approaching zero. For surfaces expected to remain hydrated a_{wf} should be selected as the maximally wetted value. Safe estimates of chilling times will be made if a_{wf} is under- rather than over-estimated.

It should be noted that the ability to carry out further research in this area is limited by the need to rapidly and non-intrusively measure a_w on small parts of product surfaces during chilling. It should also be noted that in Part 1, Chuntranuluck *et al.* (1998a) stated that there is an alternative approach to prediction method development. The skin resistance could be added into the finite difference simulations of Chuntranuluck *et al.* (1998a), and curve-fitting of new empirical equations including this extra variable as an input carried out. Only once this has been attempted and the resulting methodology tested can the better approach of the two be decided.

Ranges of method applicability

Based on the initial finite difference simulations and the demonstrated quality of curve-fit across these ranges demonstrated in Part 1 (Chuntranuluck *et al.*, 1998a), but also on the experimental testing reported in both this paper and Part 2 (Chuntranuluck *et al.*, 1998b), the ranges of environmental conditions for which the method is recommended for industrial application are:

Bi: 0.1 to 10.0
H_r: 0.60 to 0.95
T_a: 0 to 20°C

These ranges most likely cover industrial conditions. Product conditions and characteristics should lie within the following ranges:

T_{in}:	20 to 50°C
shape:	infinite slab, infinite cylinder, sphere
product thermal properties:	$\rho c_p = 2 \times 10^6$ to 4×10^6 J m^{-3} K^{-1}. $k = 0.3$ to 0.6 W m^{-1} K^{-1}.
position of interest:	centre and mass-average temperature
Y:	$Y_c < 0.7$, $Y_{av} < 0.55$

To these ranges is attached the caveat that the user of the methodology must be confident in the application of the heuristics described above. Further, it must be remembered that the method has not been experimentally tested for prediction of mass-average temperatures, but inaccurate mass-average temperature prediction is not likely if centre temperatures are well predicted.

CONCLUSIONS

Application of the proposed method to chilling time prediction for products with non-constant surface water activity may be possible if three different a_w values are used, one to represent the starting condition, one to represent the a_w value during the active chilling phase, and the third to represent the quasi-equilibrium phase. The heuristics developed are not precise, but will provide useful guidance to users of the methodology. Using them, chilling times of peeled carrots were predicted to within about -10 to $+15\%$ of measured values, and a major part of this difference can be attributed to experimental error. Using best-fit selections of a_w values, predictions of about the same level of accuracy were achieved for unpeeled carrots. When different selections of a_w values were made according to the proposed heuristics, chilling time predictions within about $\pm 20\%$ were achieved. Overall, the work represents a significant step towards development of an accurate yet simple algebraic chilling time prediction method for situations where evaporative cooling of the product surface is important and $a_w < 1$.

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