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Influence of Fruit Size and Coolant Velocity on the Cooling of Jonathan Apples in Water and Air

Results of fruit cooling studies have been reported by Guillou,[1] and Bennett,[2] among others. Studies of fruit cooling, in general, have been concerned with the average temperature of field run fruits cooled in bulk using a cooling medium of unknown heat transfer characteristics.

The resistance of heat transfer during the cooling of fruit has usually been assumed to be concentrated at the surface of the product. If this is so, a near-uniform internal temperature should result. Pflug and Blaisdell[3] have shown that, when there is internal resistance as well as surface resistance to heat flow, the center temperature lags and the average temperature is greater than that predicted by the simplified model.

The purpose of the research reported here is to show the effect of product size and coolant velocity on the cooling of apples in water and air. Nicholas, et al.[4] surveyed the general effects of these variables on the cooling of McIntosh and standard Red Delicious apples. In this report, the cooling of Jonathan apples will be examined in detail. The objectives of this study were: evaluation of the f and j values for water and air cooling; examination of the effect of coolant velocity and fruit size of f and j; evaluation of the exterior film coefficients (h) and the effect of cooling media and velocity, using uniform temperature metal cylinders of known thermal properties; examination of the development of values for thermal diffusivity (and therfore thermal conductivity) using Siebel's formula,[5] see Eq (9), and experimentally determined size, density and moisture content; and evaluation of film coefficients in air through an analysis of the experimental cooling data and a comparison of the results with the values obtained using the metal cylinders and theoretical values.

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EXPERIMENTAL

Mathematical Model

The differential equation for conduction heat transfer in a sphere initially uniformally at T_0 and suddenly exposed to an environment of constant temperature T_1 is:

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} \right) \tag{1}$$

with the boundary conditions

$$T = T_0 \text{ at } t = 0 \text{ for all } r$$

$$\frac{\partial T}{\partial r} = 0 \text{ at } r = 0$$

$$\frac{\partial T}{\partial r} = \frac{h}{k}(T - T_1) \text{ at } r = R \text{ for } t > 0.$$

The second boundary condition results from temperature symmetry at r = 0 (the origin was selected to be the center of the sphere). The last boundary condition is the surface heat flux, and it is obtained by comparing the rate of heat transfer through the surface hA (T_1 - T) to Newton's law of heat flux at the surface - Ak $\partial T/\partial r$).

The exact solution is given by Schneider [6]:

$$\frac{T-T_1}{T_0-T} = \qquad (2)$$

$$\frac{4}{\beta_i}\frac{R}{r}\sum_{i=1}^{\infty}\frac{\sin\beta_i-\beta_i\cos\beta_i}{2\beta_i-\sin 2\beta_i}\, e^{\frac{-\beta_i^2\alpha}{R^2}t}\sin\left(\beta_i\frac{r}{R}\right)$$

Where the β_i factors are the roots of the transcendental equation

$$N_{Bi} = 1-\beta_i\cot\beta_i \qquad (3)$$

After a long period of time, all the terms except the first can be neglected and Eq (2) becomes

$$\frac{T-T_1}{T_0-T_1} = \frac{4}{\beta_1}\frac{R}{r}\left(\frac{\sin\beta_1-\beta_1\cos\beta_1}{2\beta_1-\sin(2\beta_1)}\right)e^{\frac{-\beta_1^2\alpha}{R^2}t}\sin\left(\beta_1\frac{r}{R}\right) \qquad (4)$$

The temperature history T (r, t), in the center where r = 0, will be

$$\frac{T-T_1}{T_0-T_1} = 4\,\frac{\sin\beta_1-\beta_1\cos\beta_1}{2\beta_1-\sin(2\beta_1)}\,e^{\frac{-\beta_1^2 d}{R^2}t} \qquad (5)$$

as $$\frac{\sin\left(\beta_1\frac{r}{R}\right)}{\left(\beta_1\frac{r}{R}\right)} = 1 \text{ when } r=0$$

Converting Eq (5) from base e to base 10:

$$2.303\log\frac{T-T_1}{T_0-T_1} = \qquad (6)$$

$$2.303\log\left(4\,\frac{\sin\beta_1-\beta_1\cos\beta_1}{2\beta_1-\sin 2\beta_1}\right)\ \frac{-\beta_1^2\alpha}{R^2}t$$

which is a straight line when $(T-T_1)$ / (T_0-T_1) is plotted vs t on semilogarithmic paper.

The intercept is

$$j_c = 4\,\frac{\sin\beta_1-\beta_1\cos\beta_1}{2\beta_1-\sin 2\beta_1} \qquad (7)$$

and

$$\text{the slope} = -1/f = -\beta_1^2\,\alpha/2.303\,R^2 \qquad (8)$$

Eq (8) gives the relationship between the slope of the straight line portion of the cooling curve, the thermal diffusivity α, N_{Bi} and the dimension of the body.

Materials

Jonathan apples were chosen as the product for investigation because they are nearly spherical and are stable enough to permit several cooling and warming tests for each piece of fruit. The apples were obtained from the Michigan State University horticulture farm following controlled atmosphere storage. The individual apples for the tests were selected for symmetrical shape and weight. The radius R assumed to be radius of a sphere of equivalent volume.

Water and air were chosen as cooling media not only because of their wide usage but also because of the nearly 100-fold differences in readily obtained values for surface heat transfer coefficients, and for their 3000-fold difference in heat capacity.

Air Cooling Apparatus

The object to be cooled was hung in the center of either a 7.5 or a 11.5-in. dia horizontal du(
53 and 58 in., respectively, upstream of a variable speed blower or fan, respectively. For natural convection studies, the objects were suspended vertically in the center of a 9.75-in. dia, 12-in. high closed drum to reduce drafts. This study was carried out in a walk-in refrigerated space having a 0.75 F amplitude cycle with a time period of 9 min.

Water Cooling Apparatus

Water cooling studies were carried out by pumping cold water past the object, which was suspended along the central axis of a 16-in. long, 4-in. dia vertical pipe. By frequent addition of ice to the reservoir, the temperature of the water past the fruit was maintained at 37 ± 0.4 F. The apparatus used in this study was the same as that used and illustrated by Nicholas, et al. [4]

Metal Cylinders

Experimentally-determined heat transfer rates of a copper and an aluminum cylinder, 4 1/2 in. high x 3 in. in dia, were used to determine the exterior film coefficients in the cooling apparatus. Since the thermal conductivity of these metals is relatively high, the Biot number hL(
in the radial and axial direction is sufficiently small so that the 90% cooling time, f, is nearly

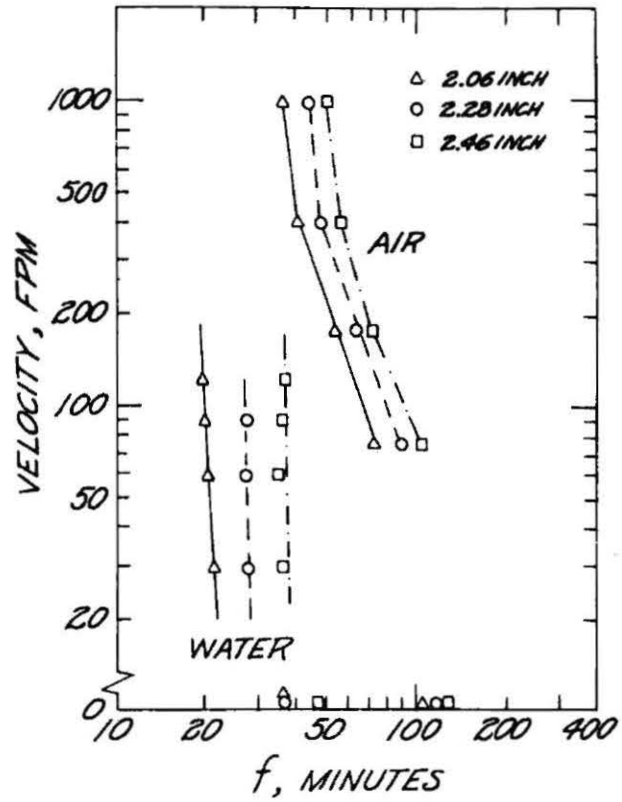

Fig. 1 The effect of media velocity on f value

inversely proportional to the exterior film coefficient. However, the heating rates at the geometric center were converted into the equivalent h values using the charts of Blaisdell and Pflug.[3]

Instrumentation

Twenty-four gauge, polyvinyl-insulated copper constantan thermocouples were used to measure fruit and air temperatures, and 30 gauge thermocouples were used in the metal cylinders. The temperatures were measured and recorded with a 12-point temperature recording potentiometer, with a -40 to +140 F range, graduated into 1 F divisions. These measurements were taken every 45 sec for fruit cooling and every 5 sec for metal cylinder cooling. The environment temperature for the fruit was taken as the average of the temperature measured about 3 in. downstream and 3 in. upstream.

Velocities in the forced air tunnel were measured using a thermoanemometer calibrated against a standard Pitot tube and microanemometer in the Michigan State University Mechanical Engineering Dept wind tunnel. The instrument had a calibrated accuracy of about 10%. Traverses across the tunnel indicated that differences in the central 4 in. of the duct were also within 10%.

Water velocities in the test pipe were regulated manually using a globe valve to obtain the desired velocity, for the specific fruit diameter. Water flow rate was measured using a calibrated rotameter with a range of 10 to 120 gpm water.

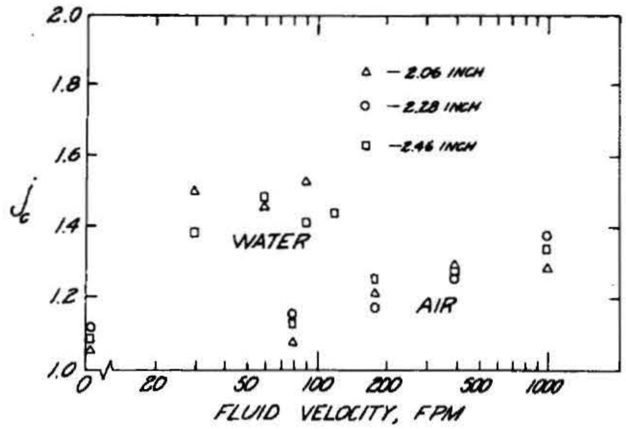

Fig. 2 Effect of media velocity on j_c

Procedure

Single thermocouples were inserted into the core of the apple. The lesion, caused by first inserting a hypodermic needle and subsequently by a thermocouple, was sealed with a hemisphere of commercial caulking compound to prevent entrance of water. The apples were warmed for a long time (at least 3-f times), to obtain an initial uniform temperature. The apples were warmed in air at 80 F for the air cooling study or in an automatic temperature controlled water bath maintained at 93 ± 0.5 F for the water cooling tests.

The cooling tests were continued until the apple had cooled to within 3 F of cooling medium temperature. The temperature-time data were plotted on semilogarithmic graph paper according to the method of Ball[7] as described by Pflug and Blaisdell.[3] Knowing the f value and the thermal conductivity and the specific heat, the β_1 can be calculated according to Eq (8). As N_{Bi} and j_c are functions of β_1 only (Eq (3) and (7), respectively), their corresponding values for a sphere can be evaluated from these equations. The h can be derived from the N_{Bi} as $N_{Bi} = \frac{hR}{k_p}$. (Pflug, et al.,[8] present curves and tables for finding the Biot number, N_{Bi}, directly from $\frac{f\alpha}{R^2}$.)

The moisture content of the apple was determined by drying in an air oven at 105 C[9] for about 3 hr until constant weight (within 0.1 mg) was obtained. The moisture content was found to be 80%. The specific gravity measured by displacement[9] was 0.821. The specific heat was calculated according to Siebel's formula,[5] see Eq (9). The radius used in all

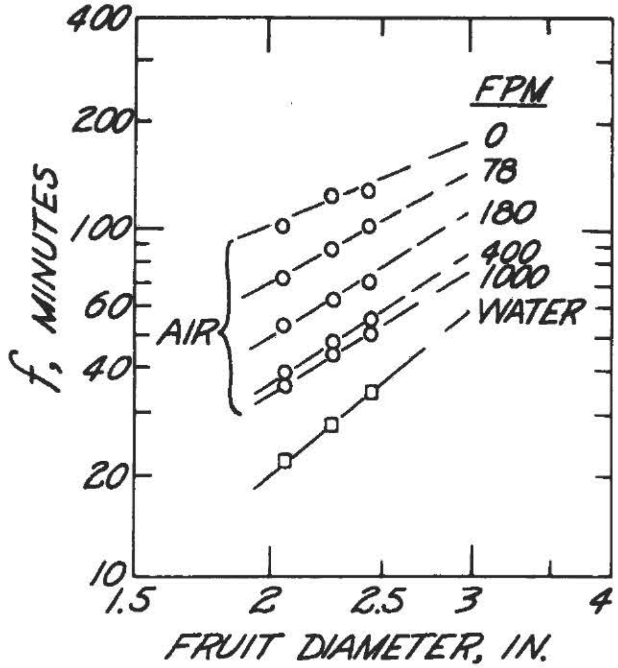

Fig. 3 Effect of fruit size and velocity on f

these calculations was that of a sphere of equivalent volume.

$$C_p = 0.008 \text{ (per cent moisture)} + 0.20 \quad (9)$$

RESULTS

The effects of velocity and cooling media on the f and j values are shown in Figs. 1 and 2 for the three sizes of apples. Fig. 3 shows the effects of apple size and the velocity on the 90% cooling time, f.

Fig. 4 shows the h value calculated using the assumed α; radius, R; and experimental f values for corresponding values of N_{Bi} in air. The values for h for forced convection cooling of apples in air were predicted using Eq 10-6 of McAdams [10]:

$$\frac{hD}{k_f} = 0.37 \left(\frac{DV\rho}{\mu_f}\right)^{0.6} \quad (10)$$

Eq 26-20 of Jacob [11] was used for determining the coefficient for forced convection cooling of the metal cylinders in water and air:

$$N_{Nu} = 0.020 \left(\frac{V\, De\, \rho_f}{\mu_f}\right)^{0.8} (N_{Pr})^{1/3} (D/D_1)^{0.53} \quad (11)$$

Eq 7-4D of McAdams [10] for natural convection for vertical cylinders (the natural convection tests in water and air were done in the vertical position), was used to calculate the coefficient under natural convection conditions:

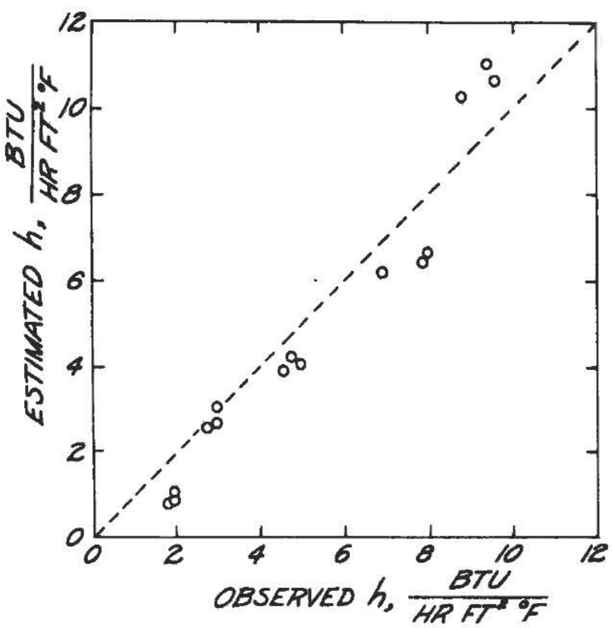

Fig. 4 Estimated h, Eq (10), vs the calculated h, Eq (8), in air (assuming lc alpha, radius and experimental f to be true

$$\frac{hL}{k_f} = 0.59 \left[\frac{(L^3 \rho_f^2 g \beta_f \Delta t)}{\mu_f^2} \frac{(C_p \mu)}{k_f}\right]^{0.25} \quad (12)$$

$$\frac{hL}{k_f} = 0.59 \left[(N_{Gr_{(L)}} N_{Pr})^{0.25}\right] \quad (12A)$$

The mean fruit temperature over time (which is independent of f) was taken from the heating curves and was 50 F, hence T_f was assumed to be 43 F. The values of h for natural convection in air where calculated using the curves recommended by McAdams's Figs. 7-7 and 7-8, [10] for air and a temperature difference of 15 F. The values for a ΔT of 15 F are about two-thirds of those for the initial and maximum ΔT of 55 F.

The predicted natural convection coefficient for apples was calculated according to the equations of Tsubouchi and Sato [12]:

$$\frac{hD}{k_f} = 2 + 0.59 \left[N_{Gr_{(D)}} N_{Pr}\right]^{0.25} \quad (13)$$

An attempt to predict the film coefficient (h), for the water studies assuming the accuracy of experimental f, and of the radius R, C_p and k (according to Eq 9 and 14) yielded an unreasonably low film coefficient.

The film coefficient obtained by the transducers and those obtained by theoretical correlations were both sufficiently large so that the N_{Bi} obtained for the apples was well over 100. In this region, the root value β_1 becomes almost independent of the N_{Bi} (see Table III). Using an arbitrary β value of 3.13 (the maximum value of β for sphere is π) produces a relatively small error, as indicated by Pflug, et al. [8] Assuming this value of 3.13, the thermal diffusivity of the three sizes of apples was calculated and was found to be an average of 0.00465 sq ft/hr. The thermal conductivity was calculated to be 0.206 Btu/hr, sq ft, F/ft. The thermal diffusivity was calculated to be 0.0068 sq ft/hr when the Anderson [13] formula, Eq (14), for thermal conductivity was used.

$$k_p = (\text{per cent moisture}/100)\ k_w + (0.15) \quad (14)$$

$$(100 - \%\ \text{moisture}) / 100$$

k_w = water thermal conductivity

DISCUSSION

Experimental f and j Values

The effect of cooling medium velocity on the 90% cooling time f is quite different for air than for water. The f values for water decrease less than 10% for an increase in water velocity from 30 to 120 fpm. In the water system, the f is almost independent of the water velocity. The f-value in air decreased 50% with a change in air velocity from 75 to 1000 fpm.

These differences in the effect of velocity arise from the fact that the effect of h is limited by the low diffusivity of the apple. A change in the water velocity with a corresponding change in the exterior film conductance will not change the system's total conductance as much as a change in the air surface film conductance resulting from a change in air velocity in the air cooling system.

Fig. 3 shows that an increase in fruit size has a more pronounced effect on the f value for

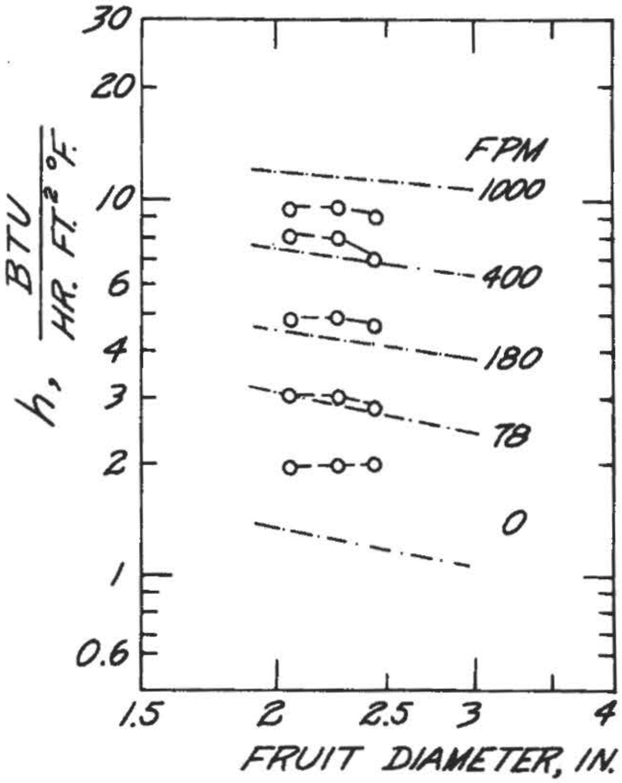

Fig. 5 Effect of fruit diameter on h in various velocities; the straight lines are the theoretical lines, Eq (10)

conditions of moderate to high film coefficients, such as high velocity air or water, than for low film coefficients (see Table I and II for film coefficients). For a spherical body, the f-value for large N_{Bi} or high film coefficient is proportional to $D^{2.5}$ (D-fruit diameter), and to $D^{1.25}$ in very low N_{Bi}. However, the theoretical

Table I. A Comparison of Film Coefficients for Air

Velocity fpm	Fruit h, Btu/hr, sq ft, F — 2.06-in./dia Experimental	2.06-in./dia Theoretical	2.28-in./dia Experimental	2.28-in./dia Theoretical	2.46-in./dia Experimental	2.46-in./dia Theoretical	Cylinder h, Btu/hr, sq ft, F — Experimental Copper	Experimental Aluminum	Experimental Average	Theoretical
0*	1.95	0.91 1.03 1.45	1.97	0.87 1.00 1.47	2.00	0.86 0.97 1.35	1.4	1.7	1.55	0.63 0.81 1.02
77.5	3.0	2.7	3.0	2.6	2.8	2.5	-	-	-	1.41
180.0	4.8	4.1	4.9	4.0	4.6	3.8	4.6	4.7	4.65	2.78
400.0	8.0	6.6	7.9	6.4	6.9	6.1	6.3	6.2	6.25	5.25
1000.0	9.4	11.0	9.6	10.6	8.9	10.2	10.0	11.0	10.5	10.8

*The predicted natural convection coefficients are for 5, 15, and 45 F Δ T, respectively.

values are $D^{2.0}$ when $N_{Bi} \rightarrow \infty$ and $D^{1.0}$ when $N_{Bi} \rightarrow 0$, so the trends of experiments and predictions are similar. The empirical values are presently our best estimate for new but comparable cooling systems.

The predicted j_c values are different from the observed ones. Explanation for this phenomenon is: the observed j_c values were evaluated from the cooling curves. Evaluation of j_c in this manner is quite inaccurate unless the cooling curve yields a fairly straight line. When the shape of the object, such as an apple, is not exactly defined, the way of drawing the straight line becomes more subjective and any variation in the way the straight line is drawn will cause relatively small change in the f value but much larger changes in the j_c. Any errors in thermocouple location or in conduction along thermocouple wires will have a critical influence on the j_c value, but a rather small effect on the f-value. Theoretically, j_c can be used instead of f for calculating the N_{Bi} of the system (Eq 7); however, the N_{Bi} calculated using the f-value is much more dependable.

Film Coefficients

Tables I and II show that there is agreement between the film coefficient of the two metal cylinders. The data in Table I and in Fig. 4 show that, regarding air cooling, there is good agreement among the predicted film coefficients, the film coefficient calculated from metal cylinder experimental data and the film coefficient for the three different sizes of apples, assuming the apple thermal conductivity to be 0.206 Btu/hr, sq ft, F/ft.

Film coefficients evaluated from apple data where N_{Bi} is high are meaningless. Therefore, B_1 was assumed to be 3.13 corresponding to h>300, and the experimental water data for f were used to determine experimental thermal diffusivity values. As far as the metal cylinders are concerned, there is a difference between the observed film coefficients and those predicted. The difference may be due to the fact that the equation used for predicting these values (Eq 11) is for an infinitely long annulus in which the boundary layer has been established. In our experiment the 3-in. dia cylinder in the 4-in. pipe forms a very short annulus (4.5 in. long).

The film coefficient should be evaluated in a system where the N_{Bi} is as small as possible. When the N_{Bi} is high (>10), the N_{Bi} and, therefore, the evaluated h become very sensitive to any change either in the physical or geometric properties of the overall system. On the other hand, evaluation of the thermal diffusivity should be done in a system with a very high N_{Bi} so that the root value β_1 is insensitive to N_{Bi} (or h).

The Thermal Property Assumption

Pflug, et al.,[8] observed that thermal diffusivity calculated using thermal conductivity by the Andersen equation[13] was unreasonably high for apples. The difference is probably due to intercellular air which may occupy approximately 20 to 25% of the volume of the fruit.[14, 15] The Andersen thermal conductivity prediction equation agrees with the sucrose solution data of Riedel[15] and presumably agrees with data on other foodstuff solutions, but does not agree well with the data of Smith, et al.[17] If an apple were a homogeneous solution of components without air, the Andersen equation would probably give satisfactory results. However, since as

Table II. Film Coefficient for Water Evaluated from the Metal Cylinders

Velocity fpm	h, Btu/hr ft^2 F		
	Experimental		Theoretical correlation (Eqs 11 and 12)
	Copper	Aluminum	
0*	45 59 97	46 64 107	42.7 61.5 76.7
30	455	440	139
60	635	625	240
90	875	880	328
120	1065	1035	415
240	1700	—	722

*The experimental and the theoretical values for natural convection are for 11, 25 and 45F ΔT, respectively.

much as 25% of the apple volume may be intercellular air spaces (calculations used for density measurement indicated that the average percentage in this study was 22%), a new approach is needed. It is suggested that an approach to predicting the thermal conductivity of such heterogeneous systems be made using parallel and series arrangements of the two phases, assuming a kind of random distribution.

CONCLUSIONS

The effects of fruit size and water and air velocity on the cooling of Jonathan apples were investigated. Good agreement was found between the measured and predicted values of cooling rate and, to a lesser extent, values of cooling lag and film coefficients. The influence of the structure of the product and the shape of the product on the validity of thermal conductivity predictions of the Andersen formula and of the predictions and analysis of cooling data by a linear asymptote after the method of Ball for canned foods are discussed. These limitations may not have immediate practical significance, but they suggest that efforts to predict and correlate the properties and the cooling of fruit require an appreciation of the peculiarities of physiology, composition and shape of each product.

NOTATION

C_p = Specific heat (at constant pressure) of product, Btu/lb F

D = Diameter: D, diameter of spherical or cylindrical product: D_1, diameter of the cooling tunnel: De, equivalent diameter that is D_1-D, ft

f = Time required for the asymptote of the cooling curve to cross one log-cycle, the time required for a 90% reduction of temperature on the linear portion of the cooling curve,7 hr

g = Gravitational constant, ft/hr^2

h = Surface heat transfer coefficient, Btu/hr, sq ft, F

j_c = Lag factor $j = (T_a-T_1) / (T_o-T_1)$. dimensionless

k = Thermal conductivity, k means product thermal conductivity, k_f means thermal conductivity of the fluid in t_f, Btu/hr, sq ft, F/ft

L = Characteristic length of product in the direction of fluid flow, ft

N_{Bi} = Biot number hr/k_p, dimensionless

N_{Gr} = Grashof number $L^3 \rho^2 g\beta (T_1-T_f)/\mu^2$ dimensionless

N_{Nu} = Nusselt number h(L or D)/k_f, dimensionless

N_{Pr} = Prandtl number $C_p \mu /k_f$, dimensionless

Table III. The β_1 vs N_{Bi} for High N_{Bi}	
$N_{Bi} = 1 - \beta_1 \cot \beta_1$	
1	N_{Bi}
3.100	75.49
3.105	85.82
3.110	99.41
3.115	118.11
3.120	145.48
3.125	189.32
3.130	270.99
3.132	327.49
3.134	413.76
3.136	561.73
3.138	874.45
3.140	1972.55
3.141 π	5300.89 ∞

R = Radius of sphere or cylinder, ft

r = Radial position in a sphere or cylinder, ft

T = Temperature: T means temperature of the product; T_a initial temperature as defined by the linear portion of the cooling curve, that is, the ordinate value of origin of asymptote of cooling curve; T_f means temperature of fluid that $(T_s + T_1)f/2$ where $T/_s$ is the surface temperature, T_1 means media temperature, F

t = Time, hr

V = Velocity, ft/hr

α = Thermal diffusivity that is $k_\rho/C_p\rho_p$ sq ft/hr

β = Volumetric coefficient of expansion, ℓ/F

β_n = Nth root of the boundary equation, dimensionless

μ = Viscosity of fluid, ℓb/ft, hr

π = Pi = 3.1416

ρ = Density: ρ_p means density of product; ρ_f means density of the fluid in t_f, lb/cu ft

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