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ABSTRACT

DESIGN PARAMETERS FOR
HYDROCOOLING CHERRIES

by Rayburn E. Parker

A critical shortage of labor supply for havesting fruit crops has brought about a great demand for improvements in the mechanization of the harvesting operation. The currently accepted method of mechanically harvesting tart cherries is by shaking the tree branches. This method of harvest often causes additional bruising of the fruit compared with hand-harvested fruit. In order to reduce the excessive rate of deterioration brought on by this added bruising, growers are now hauling mechanically harvested cherries in water tanks. Many growers also go to the added expense of putting ice in their tanks in the orchard to further minimize the effects of bruising. This practice is expensive and inefficient.

The efficient and economical cooling of cherries should greatly enhance the practice of mechanical harvesting by promoting a higher quality end product. The objective of this study was to evaluate the physical and thermal properties of Montmorency (Prunus Crasus) cherries essential in the design of an efficient hydrocooling system.

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Rayburn E. Parker

From basic equations of heat transfer, it was shown that thermal diffusivity, specific heat, density, and diameter of cherries as well as the film coefficient for convection heat transfer for cherries in water must be known in order to calculate the hydrocooler capacity and cooling time required for a given cherry flow rate. All of these properties except the film coefficient were measured for many cherries varying in size and soluble solids content. The film coefficient was calculated for a wide range of cherry diameters, water velocities, and water temperatures using an empirical equation recommended by several heat transfer specialists.

Densities of cherry flesh and pits were measured by the water displacement method. Specific heats of cherry flesh and pits were measured by the method of mixtures using a specially designed calorimeter. Cherry diameters across the cheek and stem axis were measured by a micrometer gage. Thermal diffusivities of cherry flesh were measured by use of an infinite cylinder with constant surface temperature.

Actual measurements of reported properties were made during the harvesting seasons of 1964 and 1965 on hand-harvested cherries. In 1964, sixteen samples of six cherries each were compared by their weights and diameters. A least squares analysis indicated a highly significant correlation between cherry weight and average cherry diameter. Furthermore, the average cherry diameter was very close to the diameter of a sphere having the same weight as the cherry.

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Rayburn E. Parker

For this reason, all heat transfer equations related to cooling-time calculations were based on the assumption that the cherry is a sphere having a diameter equal to the average cherry diameter.

From measurements taken on 58 samples of 50 cherries each in 1964, it was shown that the cherry pit contributes very little to the weight of the whole cherry. It was also found that pit density is almost the same as flesh density. These findings support the assumption that the cherry is homogeneous as far as cooling-time calculations are concerned.

The average specific gravity of cherry flesh in 1964 and 1965 was 1.05 and 1.07, respectively. A significant correlation between specific gravity and soluble solids content existed for both years.

The specific heat of cherry flesh averaged 0.890 BTU/lb.°F over the two year period and was independent of the flesh density or soluble solids in 1965. However, specific heat was affected only slightly by the combined effects of soluble solids and flesh weight per cherry in 1964.

The average thermal diffusivity of 20 samples of cherry flesh tested in 1965 was 5.104×10^{-3} sq. ft./hr. Multiple correlation analysis revealed that diffusivity was independent of flesh density and specific heat but was related to soluble solids.

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DESIGN PARAMETERS FOR

HYDROCOOLING CHERRIES

By

Rayburn E. Parker

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INTRODUCTION

Quality of agricultural products in the United States is strongly emphasized because of two primary factors: (a) competition and (b) economics. Because of an abundance of most farm products, processors as well as consumers seek those products of higher quality. At the same time, the grower of high quality products is rewarded by receiving higher prices. On the other hand, a consistent decrease in farm labor supply coupled with a continuous increase in farm wages have brought about a dynamic need for mechanizing farm operations in order to maintain a reasonable production cost as well as to insure the harvest. Mechanizing harvesting and handling operations, however, generally results in an end product of somewhat lower quality.

Growers of some farm crops may mechanize at the expense of quality, but food growers in particular cannot do this without diminishing their markets. In the field of tart cherry production, new and improved techniques of harvesting, handling, and processing are being developed each year. The acceptability of each new technique is invariably based upon its effect on quality.

The currently accepted method of mechanically harvesting cherries is by shaking the tree branches. This method

was accepted even though it was recognized that it would cause (a) additonal bruising of the cherries, (b) an increase in the number of cherries harvested with stems (which have to be sorted out at the processing plant), and (c) an increase in overripe, damaged, immature or otherwise undesirable cherries which would not normally be harvested by hand. Mechanical destemmers and electronic sorters have been developed recently to speed up the processing of mechanically harvested cherries. Also, growers are now hauling these cherries in water tanks instead of wooden lug boxes in order to reduce the excessive rate of deterioration brought on by the additional bruising. Many growers also go to the added expense of putting ice in their cherry tanks in the orchard to further reduce the effects from bruising.

It is generally recognized that handling cherries in water and also holding cherries at low temperatures reduce their rate of quality deterioration. Levin and Gaston (1954) were able to maintain quality of hand-harvested cherries by cooling the cherries in water and hauling them to the processor in water. The cherries were cooled in hauling tanks to less than 60°F by circulating 55°F water through them. The cooling water was not recirculated but was allowed to flow over the top of the tanks for as long a period of time as was necessary to reach the desired cherry temperature. They concluded that cherries hauled in water lose less weight in transit, show less scald, and require less sorting than cherries which are hauled in lugs.

In a more elaborate study with cherries deliberately bruised to simulate mechanical harvesting and handling methods, Whittenberger et al. (1963) confirmed that scald was negligible after 24 hours for cherries bruised during harvest if they were cooled to and maintained at 50°F. In addition, they found that cherries subjected to recurrent bruising after harvest decreased in fresh weight and in yield of pitted product. Again, these decreases were less for cherries which were cooled to the lower temperatures. As an example, cherries which had been bruised at the time of harvest and again three hours afterwards had a yield of pitted cherries of 83.1 percent when held in 50°F water and 78.6 percent when held in 78°F water. Both of these percentages were less when the cherries were held in air at the respective temperatures.

La Belle (1965) reported that scald and oxidation of cherries (the most noticeable indicators of cherries in a deteriorated quality condition) are triggered by bruising and proceed at a rate governed by temperature until freezing or canning halts the physiological process. He considered hydrocooling as the ideal method of cooling the fruit and consequently minimizing scald.

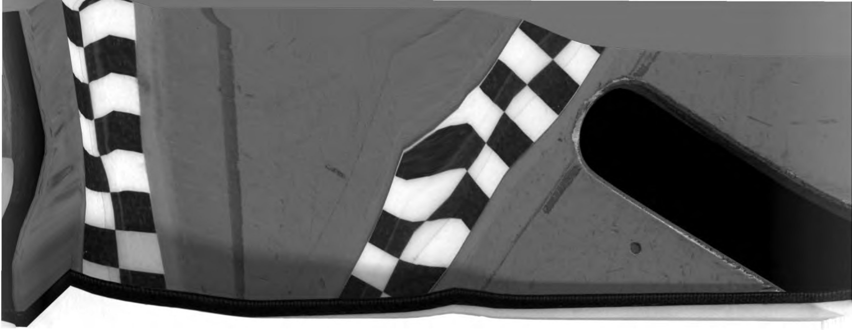
It is also recognized that fresh fruits are alive and therefore carry on within themselves a process of respiration whereby decomposition products are formed and heat is given off. The rate of decay and heat given off vary directly with temperature. Wright, et al. (1954) report that the

rate of heat released by tart cherries (estimated from carbon dioxide production) is 1320 to 1760 BTU/ton/24 hrs. at 32°F and 11,000 to 13,200 BTU/ton/24 hrs. at 60°F.

In essence, the cooling of cherries as soon after harvesting as possible should (a) decrease decomposition and rate of heat liberation due to respiration and (b) minimize the effects from bruising which show up as scald at the processing plant. The economical accomplishment of these two goals should greatly enhance mechanical harvesting of cherries by promoting a higher quality end product.

Since most fruit growers who mechanically harvest cherries already employ water as a means of handling their crops, cooling the cherries by water is apparently the most practical and readily available means of removing their field heat. The efficiency of current cooling systems, however, could be greatly improved by properly designing a cooler specifically for cherries. Since the design of the improved system would depend upon many of the basic properties of the cherries, a thorough knowledge of these properties is required. Although estimates can be made, an inaccurate assumption could mean (a) an unnecessary increase in the cost of the system or (b) the construction of an inadequate system.

The objective of this study was to evaluate physical and thermal properties of Montmorency (Prunus Crasus) cherries essential in designing an efficient hydro-cooling system.



REVIEW OF LITERATURE

Cherry Properties Required to Design a Hydrocooler

The cooling of cherries involves transferring heat from the cherry to the cooling medium. The rate of heat transfer is of utmost importance in the design of the cooler since it aids in establishing the time required to cool the cherry to a specified temperature. This required time in turn establishes the length of the hydrocooler for a given cherry velocity.

Assuming the cherry to be a sphere of homogeneous material and to have a finite internal and surface resistance to heat flow, the temperature history T(r,t) at time t and radius r from the center may be found by solving the basic differential equation given by Kreith (1958)

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

The solution to equation (1) for a sphere initially at uniform temperature T_i throughout and suddenly exposed to a cooling medium at temperature T_∞ is given by Schneider (1955) as:

$$\frac{T(r,t) - T_\infty}{T_i - T_\infty} = 4\frac{r_1}{r}\sum_{n=1}^{\infty}\frac{\sin M_n - M_n \cos M_n}{M_n\, 2M_n - \sin 2M_n}\sin(M_n \frac{r}{r_1})\exp(-M_n{}^2\theta) \qquad (2)$$

where: r_1 = radius of the sphere (ft.)

θ = Fourier modulus = $\frac{\alpha t}{r_1{}^2}$

α = thermal diffusivity of the sphere material

= $k/\rho c$ (sq. ft./hr.)

k = thermal conductivity of the sphere (BTU/hr.ft.°F)

ρ = density of the sphere (lb./cu. ft.)

c = sphere specific heat (BTU/lb.°F)

M_n = roots of the transcendental equation

$$1 - M_n \cot M_n = \bar{h}r_1/k = \text{Biot Modulas (Bi)}$$

$\bar{h}$ = average convective heat transfer film coefficient for the surface of the sphere (BTU/hr. sq. ft.°F)

The mean temperature $\bar{T}$ within the sphere at time t after exposure to the cooling medium can be calculated from the equation

$$\frac{\bar{T} - T_\infty}{T_i - T_\infty} = 6\sum_{n=1}^{\infty}\frac{1}{M_n^2}\left[\frac{(\sin M_n - M_n \cos M_n)^2}{M_n - \sin M_n \cos M_n}\right]\exp(-M_n^2\theta). \qquad (3)$$

Also, the central temperature history T(0,t) can be found by the equation

$$\frac{T(0,t) - T_\infty}{T_i - T_\infty} = 4\sum_{n=1}^{\infty}\frac{\sin M_n - M_n \cos M_n}{2\,M_n - \sin 2M_n}\exp(-M_n^2\theta). \qquad (4)$$

From equations (3) and (4), it is apparent that k, ρ, c, r_1 and $\bar{h}$ must be known in order to calculate the time required to cool a cherry to an average temperature $\bar{T}$ or to a central temperature T_o for a given fluid and initial cherry temperature. Of the four properties α, k, ρ, and c, it is necessary to know only three since $\alpha = k/\rho c$. All of the required properties except $\bar{h}$ are independent of the method of cooling. To find appropriate values for $\bar{h}$, it will be assumed that cooling takes place in water by a process of forced convection over single cherries.

It is important to note here that the solutions to equation (1) as given by equations (2), (3) and (4) were based on the assumption that the cherry properties along with $\bar{h}$ do not vary with time. This also infers that these properties do not vary with temperature since the temperature of the cherry is being continuously lowered during the cooling period. In actuality, however, the cherry properties may be expected to vary with temperature similar to the variation of water properties with temperature since the principal constituent of cherries is water. As given in Table A1, ρ and c increase while k and α decrease for decreasing water temperatures below 80°F.

Expectations Based on Reported Property Values

Specific Heat.--A widely used empirical equation for estimating specific heat of fruits is given by Wright et al. (1954) as

$$c = 0.008\,A + 0.20 \qquad (5)$$

where A is the percent water in the fruit and the constant 0.20 is an assumed value which represents the specific heat of the solid constituents. Using equation (5), the maximum specific heat of cherries would be 1.0 if the moisture content were 100 percent.

Morris (1946) states that 78 to 88 percent of any succulent fruit is water. Volatile constituents such as essential oils and esters are usually negligible in quantity. Non-volatile constituents include sugars, fruit, acids, pectin and gums, woody fibre and cellulose, nitrogenous substances, mineral salts, and in a few cases starch. Of the non-volatile constituents, sugars are the most abundant. Morris found as much as 10.6 percent sugars in the cherry flesh. Also, he found no more than 2.7 percent insoluble solids (fibre, etc.) in cherry flesh. (See Table A3 for comparison with apples.)

Morris also reported that total solids for cherry flesh alone ranged from approximately 12 to 17 percent. Using these values, c could vary from 0.86 to 0.90 BTU/hr. °F by use of equation (5). If the weight of the pit were also considered, c for whole cherries would be considerably below these values. In order to avoid the necessity of measuring the moisture content, c should be measured and related to such factors as soluble solids, weight and density which are measured more easily.

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Ordinanz (1946) reported that the specific heat of fresh berries containing 84 to 90 percent water ranged from 0.89 to 0.98 BTU/lb.°F, while that for fresh plums containing 75 to 78 percent water was 0.84 BTU/lb.°F. Charm (1963) reported values of c for applesauce and banana puree to be 0.96 at 91°F and 0.875 at 76°F, respectively. La Belle (1965) used an estimated value of c of 0.82 BTU/lb.°F to calculate the cooling capacity required to cool a given weight of cherries. Reported values of specific heats for other fruits are given in Table A2. An extensive search of the literature revealed no case in which specific heat of tart cherries was measured.

Density.--Schmidt and Levin (1963) reported a density of tart (Montmorency) cherries of 83 lb./cu. ft. Density was calculated by dividing the weight of the cherry by the volume of a sphere whose diameter was equal to the average cherry diameter. The result appears to be higher than the actual density since it is generally assumed that cherries are only slightly heavier than water. By comparison, Bennett (1963) found that density of peaches varied from 58.2 to 60.7 lb./cu. ft. depending on variety.

Thermal Conductivity.--Thermal conductivity of fresh fruit is generally estimated to be near that of water since a large percent of the fruit consists of water. Conductivity of water varies with temperature, however; and for the

expected range of cherry temperatures, k varies from 0.319 to 0.353 BTU/hr. ft.°F at 32°F and 80°F, respectively.

For peaches, Bennett (1963) found that k varied from 0.276 to 0.313 depending upon variety. Conductivity was calculated by measuring density and "effective" thermal diffusivity of whole peaches and assuming a specific heat of 0.9 BTU/lb.°F. Bennett, et al. (1964) also reported values of k for Valencia oranges and Marsh grapefruit juice vesicles of 0.25 and 0.27 BTU/hr. ft.°F, respectively. Charm (1963) gives k for applesauce and banana puree as 0.40 and 0.32 BTU/hr. ft.°F, respectively. Therefore, thermal conductivity of tart cherries is expected to be around 0.3 BTU/hr. ft.°F.

Thermal Diffusivity.--Bennett (1963) measured the "effective" thermal diffusivity of different varieties of whole peaches and reported values ranging from 0.0051 sq. ft./hr. to 0.0058 sq. ft./hr. depending upon variety. He also found that thermal diffusivity for peaches varied linearly with temperature. On the average, thermal diffusivity increased from 0.0056 sq. ft./hr. to 0.0062 sq. ft./hr. when peach temperature was increased from 40°F to 73°F. Thermal diffusivity of water also increased from 0.0052 sq. ft./hr. to 0.0056 sq. ft./hr. for the same increase in temperature (see Table A1). Thermal diffusivity of tart cherries is expected to be near that of water.

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Cherry Diameter.--Tart cherries are by no means perfectly spherical in shape. Their diameter may be given as either "stem diameter," "suture diameter," or "cheek diameter" as defined by Mohsenin (1965). However, since their cheek and suture diameters differ only slightly, only their maximum (cheek) diameters and minimum (stem) diameters are given generally.

Schmidt and Levin (1963) reported the maximum and minimum diameters of a 3.7 gram tart cherry as 0.750 in. and 0.5625 in., respectively. Cherry diameters can be expected to vary according to cherry weight. They also may vary between cherries having the same weight.

Heat Transfer Film Coefficient For Forced Convection Over Spheres

Fluid flow and heat transfer investigators have developed the conception that when a fluid flows over a surface, a stagnant film adheres to that surface. In heat transfer studies, the stagnant fluid film acts as a barrier to the flow of heat. The thickness and corresponding effectiveness of this barrier are reduced by increasing the velocity of the fluid over the surface. The rate at which heat is conducted through this film is presumed to be dependent upon the size and shape of the surface, the specific heat and conductivity of the fluid, the difference in temperatures between the two sides of the film, and the film thickness. Although the film thickness is not generally measured, it h

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has been found by numerous investigators to be dependent upon its density and viscosity and also upon the fluid stream velocity.

By dimensional analysis, Brown and Marco (1958) show how the following expression, commonly known as Nusselt's expression, was derived:

$$\frac{\bar{h}D}{k} = C \left[\frac{VD\rho}{\mu}\right]^b \left[\frac{c_p \mu}{k}\right]^d \tag{6}$$

where: C, b and d are constants,

D = diameter

V = velocity

μ = absolute viscosity

ρ = density

c_p = specific heat at constant pressure

k = thermal conductivity

$\frac{\bar{h}D}{k}$ = Nusselt number or boundary modulus

$DV\rho/\mu$ = Reynolds number

$\frac{c_p \mu}{k}$ = Prandtl number.

Brown and Marco recommend that the physical properties be evaluated at the bulk temperature of the fluid (for water) provided the temperature drop across the film is not more than 10°F. For larger temperature drops, the properties should be evaluated at the arithmetic mean of the bulk and surface temperatures. Evaluation of the density of the fluid c

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may be based on the bulk temperature instead of the mean film temperature since the Reynolds number is primarily related to flow rate and subsequently depends upon the density of the main body of the stream. On the other hand the concept of convection as a process primarily of conduction through a stagnant film requires that all physical properties be evaluated at the film temperature. It has not been conclusively established which of the practices results in the better correlation with test results.

Kramers (1946) found the following correlation between Nusselt number, Prandtl number and Reynolds number for forced convection of water over single spheres for Reynolds numbers from 0.4 to 2,100:

$$Nu_f = 2.0 + 1.3\,(Pr)_f^{0.15} + 0.66\,(Pr)_f^{0.31}\,(Re)_f^{0.50} \qquad (7)$$

where the subscript f denotes properties to be evaluated at mean temperature of the water film surrounding the spheres.

In noting that for pure conduction of a sphere at uniform temperature in a stagnant medium, the Nu number theoretically should be 2.0 instead of $2.0 + 1.3\,(Pr)_f^{0.15}$, Bird, et al. (1960) reported the following correlation between the Nu, Re, and Pr numbers:

$$\frac{\bar{h}D}{k_f} = 2.0 + 0.60\left(\frac{DV\rho_f}{\mu_f}\right)^{1/2}\left(\frac{c_p\mu}{k}\right)_f^{1/3}. \qquad (8)$$

Bird gave no D or Re number limitations for equation (8).

McAdams (1953), also noting for small ΔT between sphere surface and free stream fluid and zero Reynolds number that the value of $\bar{h}D/k_f$ theoretically should be 2.0, derived the following correlation from Kramer's data:

$$\frac{\bar{h}D}{k_f} (Pr)_f^{-0.3} = 0.97 + 0.68 \left(\frac{VD\rho}{\mu_f}\right)^{0.5} \tag{9}$$

Equation (9) applies to flow of water and spindle oil (Prandtl number from 7.3 to 380 and ΔT from 11° to 71°F) past single spheres having diameters from 0.279 to 0.496 inch and for a Reynolds number range between 1 and 2,000.

Kreith (1958) recommends use of equation (9) for calculating the average unit-surface convection coefficient for spherically shaped particles being heated or cooled by a liquid. He points out that equation (9) will still yield satisfactory results for irregularly shaped particles if the sphere diameter is replaced by an equivalent diameter D_o which represents the diameter of a spherical particle having the same surface area as the irregular particle.

The use of equation (9) is also recommended by such notable investigators as Holman (1963), Rohsenow and Choi (1961), and others.

EQUIPMENT AND METHODS

Scope, Time, and Location

As pointed out in the review of literature, the parameter values required for properly designing a hydro-cooler are: diameter, density, specific heat, and thermal conductivity of the cherry and the film coefficient of convection heat transfer for cherries in water. The test procedure of this study was designed in such a way as to yield a range of possible values for these parameters. In addition, because of the method of sample selection, it was possible to relate those properties which are not so easily determined (specific heat and thermal conductivity) to properties which are easily determined (cherry weight, density, and soluble solids content).

All measurements were made during the 1964 and 1965 cherry harvesting seasons. No attempt was made to evaluate the effect of seasonal variations on cherry properties. All cherries used in the tests were hand harvested and were free of scald and skin blemishes or scars.

In 1964, two separate tests were made at two different locations. The first test was carried out at East Lansing, Michigan and was designed to relate cherry diameter to cherry weight. The second test was conducted at Traverse

City, Michigan and was designed to find relationships between cherry weight, pit weight, cherry flesh density, flesh specific heat, and flesh soluble solids content.

In 1965, essentially a repeat of the second test of 1964 was conducted with additional data being taken on thermal diffusivity of cherry flesh. The entire 1965 study was conducted at Traverse City.

In addition to making actual measurements of cherry properites, theoretical values for the film coefficient were calculated for a wide range of cherry diameter, water velocity, and water temperature. All such calculations were made using the McAdams empirical equation for forced convection over spheres in water.

With the information derived from this work, the designer of a hydrocooler should be able to determine with better accuracy the required cooling capacity of the hydrocooler and the exposure time for lowering the temperature of cherries initially at T_i down to T_t at the rate of X pounds per hour using water at a given temperature T_∞ and flowing past the cherries at a given relative velocity V.

Measuring Techniques

Weight.--No fewer than 50 pits were weighed at one time to establish average pit weights. Six cherries were weighed together in collecting the 1964 data at East Lansing. Each sample at Traverse City in 1964 and 1965 consisted of 50 cherries. Weights were measured to the nearest 0.1 gram (Figure 1).

<u>Cherry Diameter</u>.--Cherry diameters were measured to the nearest 0.001 inch by a micrometer caliper. Maximum diameter was measured across the cheek of the cherry (perpendicular to the stem axis) and minimum diameter was measured parallel to the stem axis.

<u>Density</u>.--Whole cherries were weighed first. Then their volume was determined by the water displacement method (Figure 2). A 100 cubic centimeter cylinder with one cubic centimeter graduations was used to measure displacement. Because of the wide variation of cherry size, however, the number of cherries of each sample which could be deposited into the cylinder at one time varied from 10 to 25. Volume displacement was estimated to the nearest 0.1 cubic centimeter and density was calculated by dividing weight by displacement (gms./cc).

The density of the cherry pits was determined in the same manner except that a smaller cylinder was used (graduated in 0.1 cc) in measuring their volume. Then, density of the cherry flesh was calculated by

$$\rho_{fl} = \frac{W_c - W_p}{V_c - V_p} \tag{10}$$

where: ρ_{fl} = flesh density (average of 50 cherries)

W_c = weight of the whole cherry

W_p = weight of the pit

V_c = volume displacement of the whole cherry

V_p = volume displacement of the pit.

Figure 1. Uniform sized cherries being weighed in bulk to determine average weight per cherry.

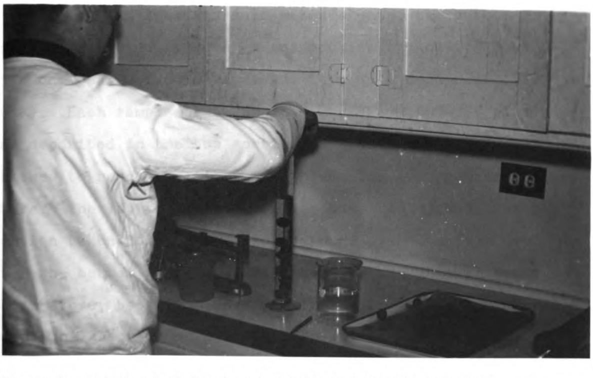

Figure 2. Volume of whole cherries being determined by water displacement method.

Specific Heat.--Specific heat measurements were made by the method of mixtures. A calorimeter as illustrated in Figure 3 was constructed of Styrofoam material and coated on the inside surface with 10.7 grams of paraffin wax (bottom portion) to prevent absorption of water by the insulation.

As a check on the heat loss from the bottom portion of the calorimeter for extreme conditions, one pound of distilled water at 81°F was poured into the calorimeter. The calorimeter was then taken inside a 41.5°F cold room. By measuring the rate of cooling of the water and assuming a specific heat of the water of 1.0 BTU/lb.°F., the heat loss from the calorimeter was calculated to be 0.3 BTU after five minutes exposure and 0.8 BTU after 10 minutes.

In making specific heat measurements, the bottom portion of the calorimeter was approximately half filled with one pound of cold water and left in a cold room (36-40°F). Each sample of 50 whole cherries or 400-500 pits was deposited in the top portion of the calorimeter and allowed to reach equilibrium with outside atmospheric temperature. The lid to the top portion was then closed, the top portion taken inside the cold room and placed upside down over the bottom portion. After reading the initial water temperature, both lids were withdrawn, thereby allowing the sample of cherries or pits to drop into the cold water. The lids were closed immediately to reduce heat loss.

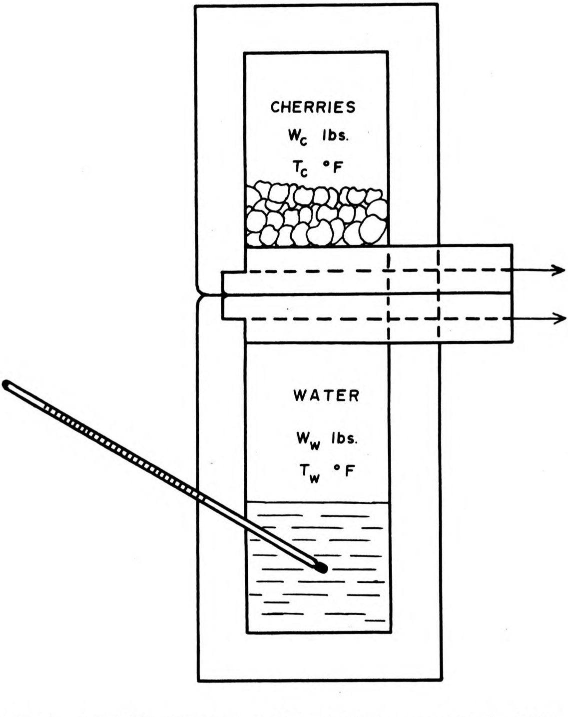

Figure 3. Top and bottom portions of specially constructed calorimeter in position for measuring specific heat of whole cherries.

Equilibrium temperature was then read to the nearest 0.1°F after approximately five minutes of mixing.

Error due to heat transfer through the walls of the calorimeter was considered to be negligible since the water used was initially four to five degrees below the cold room temperature and the equilibrium temperature was four to five degrees above cold room temperature. Thus, the calorimeter gained heat from the room during initial cooling of the sample and lost heat to the room during final cooling.

Specific heat of pit samples alone was calculated by the heat balance equation

$$(cW\Delta T)_p = (cW\Delta T)_w + (cW\Delta T)_{paraffin} \tag{11}$$

where the subscripts p and w denote pits and water respectively and c and W are the specific heat and weight of the respective materials. The following values were the same for all samples:

c_w = 1.0 BTU/lb.°F

$c_{paraffin}$ = 0.69 BTU/lb.°F (Baumeister, 1958)

W_w = 1.0 lb.

$W_{paraffin}$ = 0.0236 lb.

It was also assumed that $\Delta T_w = \Delta T_{paraffin}$ since the paraffin was in direct contact with the water.

After measuring the weight and specific heat of the whole cherries and pits, in that order, the specific heat of the flesh was calculated by the heat balance equation where

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$$(cW\Delta T)_{fl} + (cW\Delta T)_p = (cW\Delta T)_w + (cW\Delta T)_{paraffin} \qquad (12)$$

where the subscript fl denotes the cherry flesh (including skin). Also, $\Delta T_{fl} = \Delta T_p$ and $\Delta T_w = \Delta T_{paraffin}$ when equation (12) was used to calculate specific heat of flesh.

<u>Thermal Diffusivity</u>.--By heat transfer terminology, the adjective "infinite" when used to describe a cylinder infers that no transfer of heat occurs along the "z" or longitudinal axis, that is, $\frac{\partial T}{\partial z} = 0$. The basic differential equation which describes the radial temperature distribution in an infinite cylinder is given by Kreith (1958) as

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right). \qquad (13)$$

If the initial temperature distribution throughout an infinite cylinder is uniform and equal to T_i and the surface of the cylinder is suddenly lowered to T_s at time $t = 0$ and maintained at T_s for all $t > 0$, then the temperature history at the center of the cylinder as derived from equation (13) is given by Schneider (1955) as

$$\frac{T(0,t) - T_s}{T_i - T_s} = 2\sum_{n=1}^{\infty} \frac{\exp(-M_n^2\,\theta)}{M_n\,J_1(M_n)} = C(\theta) \qquad (14)$$

where $C(\theta)$ is a function of the Fourier modulus θ and the values of M_n are the roots of the zero-order Bessel function $J_o(M_n) = 0$. Values of θ corresponding to a wide range of values of $C(\theta)$ are tabulated in Table A4.

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A 15 inch-long cylinder with an inside diameter of 3.0 inches and an outside diameter of 5.0 inches was fabricated from aluminum and its ends were insulated with 1.5 inch Styrofoam. Aluminum was chosen because of its high thermal conductivity in comparison to the estimated conductivity of cherry flesh. The cylinder was made thick to insure a uniform inside surface temperature T_s even though slight variations in outside surface temperatures may occur both radially and longitudinally because of non-uniform convection cooling.

To verify that the boundary conditions during the actual cooling period were the same as those which were assumed in arriving at equation (14), a constant record of the inside surface temperatures was maintained by use of radially and longitudinally located thermocouples and a multipoint recording potentiometer. The thermocouples were made of specially calibrated copper and constantan and were located within 1/16 of an inch of the inside surface at 90 degree intervals radially and at 1.5 inch intervals longitudinally as shown in Figure 4. Another thermocouple was located in the center of the cylinder and was used to measure $T(0,t)$. This thermocouple was held on the z-axis by exerting a slight tension on a monofilament line which was attached to the thermocouple itself. The lead wires of the central thermocouple passed through the center of the bottom cover plate and the monofilament passed through the center of the top plate (Figure 5).

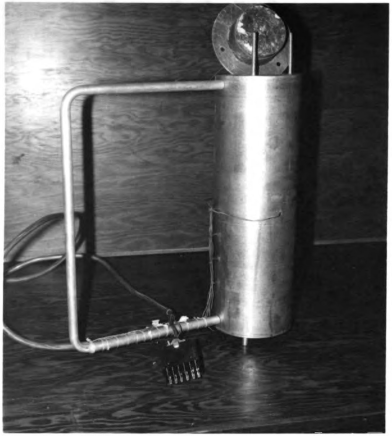


Figure 4. Aluminum cylinder used to measure thermal diffusivity of cherry flesh. Note insulated cap and distribution of thermocouples.

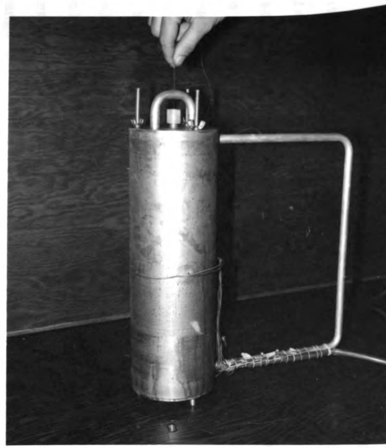


Figure 5. Exerting tension on monofilament line connected to axial thermocouple. Tension was maintained by tightening the knurled cap.

Thus, by maintaining T_s constant and uniform, the central temperature read from the chart after cooling time t is sufficient to calculate $C(\Theta)$. Knowing $C(\Theta)$, Θ can be read directly from Table A4. Since $\Theta = \alpha t/r^2$, where r is the inside radius of the cylinder, α is the only unknown remaining.

To minimize temperature reading error in measuring α, a cooling time was selected at which a maximum change in $C(\Theta)$ occurs for a unit change in α. Following the procedure outlined by Beck and Dhanak (1965), $C(\Theta)$ was differentiated first with respect to α to find the change in $C(\Theta)$ for unit change in α. The time at which this change is a maximum was then found by solving

$$\frac{\partial}{\partial \Theta}\left(\alpha \frac{\partial C(\Theta)}{\partial \alpha}\right) = 0. \qquad (15)$$

Equation (15) is satisfied at $\Theta = 0.197$. Since $t = \Theta r^2/\alpha_{fl}$, the optimum cooling time t was found to be 38 minutes (assuming an approximate value of $\alpha_{fl} = 0.0049$ sq.ft./hr. Thus, T(0,t) was read from the chart 38 minutes after the cylinder was submerged in a highly agitated water bath.

The following steps were taken to minimize the effects of possible error-causing phenomena:

1. If air pockets existed in the cherry flesh mixture, the flesh would cool slower and the measured diffusivity would be lower than the actual diffusivity. To eliminate

air pockets, the cylinder was filled in layers of approximately three inches. Each layer was compacted until juice rose to the top of the flesh. The cylinder was filled with a sufficient volume of flesh to insure that some juice would be forced out of the cylinder upon final sealing.

2. If convection cooling occurred by movement of the juice inside the cylinder, the flesh-juice mixture would be cooled faster and the measured diffusivity would be higher than the actual diffusivity. The cylinder was placed in a horizontal position during the cooling period to minimize convection cooling inside the cylinder.

3. If the center thermocouple were not in the exact center of the cylinder (on the z-axis), the measured diffusivity would be higher than the actual diffusivity. As stated previously, tension on the center thermocouple was maintained throughout both the filling and cooling periods to insure proper location.

4. If heat were lost through the cylinder ends, the flesh would cool faster. Hence, the measured diffusivity would be higher than the actual diffusivity. The cylinder ends were heavily insulated to prevent heat loss. Actual temperature measurements along the length of the cylinder confirmed that no temperature gradient existed during cooling. It was concluded, therefore, that heat loss through the ends was negligible.

5. If the inside cylinder surface temperature were not lowered to a constant immediately upon submersion, the

measured diffusivity using equation (14) would be lower than the actual diffusivity. In the actual cooling process, the cylinder was submerged directly over a propeller, which was driven by an electric motor, to minimize the delay in reducing the surface temperature to a constant. Temperature-time charts showed that the surface temperature was lowered to within one degree of final surface temperature during the first minute of cooling. Calculation of diffusivity for different cooling times for the same sample indicated that this source of error was insignificant for cooling times over 30 minutes.

6. Equation (14) is applicable only if T_s is maintained constant throughout the cooling period. To satisfy this boundary condition, the heat which was absorbed by the cooling water from both the cylinder and the mixer was offset by slowly adding chips of ice to the water.

7. The assumed boundary conditions would not be satisfied if the inside surface temperature fluctuated. Although the temperature on the outer surface of the cylinder may have varied radially during actual cooling, the fact that the cylinder was made of one inch aluminum (highly conductive) tended to mask out this variation sufficient enough to give a constant inside surface temperature.

Soluble Solids.--After density and specific heat had been determined for each 50-cherry sample, the soluble solids content of the flesh was measured by first pitting the entire sample (Figure 6) then depositing a representative

sample of the flesh juice on an Atago hand sugar refractometer (Figure 7). The percentage of sugar concentration as measured by this instrument is equal to the percentage measured by Brix's saccharimeter according to the manufacturer.

The instrument was washed with distilled water after each reading and was regularly adjusted to read zero percent for distilled water at room temperature.

Testing Procedure

Cherry Weight and Diameter.--Approximately five pounds of cherries were hand-harvested at East Lansing on July 27, 1964. From this large lot, 48 cherries of approximate equal color were selected and divided into eight groups of six cherries each according to size. Each group was then weighed and the maximum and minimum diameter of each cherry was measured. The procedure was repeated on July 28 for eight more groups of six cherries each.

A least squares analysis was made to relate average maximum diameter (D) and average minimum diameter (d) to average weight (W_c). The data from the 16 groups were fitted to the following regression equations:

$$W_c = K_o + K_1 D \tag{16}$$

$$W_c = L_o + L_1 d \tag{17}$$

$$W_c = M_o + M_1\left(\frac{D + d}{2}\right) \tag{18}$$

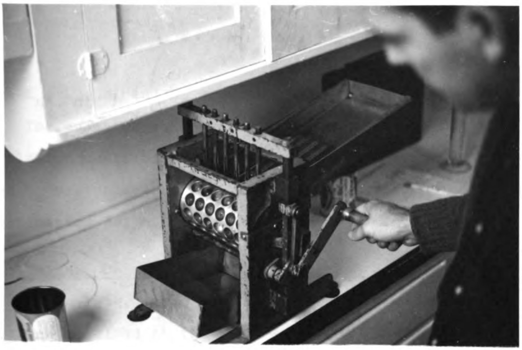


Figure 6. Pitting a sample of 50 cherries before measuring soluble solids content of the flesh.

Figure 7. Measuring soluble solids with an Atago hand sugar refractometer.

$$W_c = N_o + N_1 \left(\frac{D + d}{2}\right)^3 \qquad (19)$$

where K_n, L_n, M_n and N_n are constants.

The equation which resulted in the highest multiple correlation coefficient and lowest standard error of estimated W_c was chosen as the most appropriate equation to use in estimating weight from diameter measurements.

Weight, Density, Specific Heat, and Soluble Solids (1964).--In 1964, large samples of cherries were taken as they were received at the Cherry Growers Incorporated processing plant at Traverse City, Michigan. From each large sample, a group of 50 cherries of approximately the same size and color was selected and weighed. The volume of each sample was then measured by the water displacement method.

After removal of excess surface moisture by paper towels, the cherries were placed in the top portion of the calorimeter and allowed to reach equilibrium with room temperature. The specific heat of the whole cherry was then determined (Figures 8 and 9).

The 50 cherries were then pitted and the pits were weighed (after removing excess flesh and surface moisture). The volume of the pits was next determined as shown in Figure 10. The pits were allowed to reach equilibrium with room temperature (Figure 11) before measuring their specific heat. Specific heat of the cherry flesh alone was calculated

Figure 8. Dropping warm cherries in cold water by sliding out the lids of both parts of the calorimeter simultaneously.

Figure 9. Recording final equilibrium temperature of cherries and water before calculating specific heat.

Figure 10. Measuring the volume of pits taken from a 50-cherry sample.

Figure 11. Recording initial temperature of warm pits before dropping them into cold-water portion of the calorimeter.

by use of equation (12). The soluble solids content of the flesh from the same 50-cherry sample was measured as the final step in the procedure. The entire procedure was repeated for 57 other samples for a wide range of cherry sizes and colors.

The method of least squares fit was used to test for possible relationships between (a) pit weight and cherry weight, (b) specific heat of the flesh and soluble solids, weight of the flesh, and flesh density and (c) flesh density and soluble solids, flesh weight and flesh specific heat.

The following types of equations were used to find a possible relationship between pit weight (expressed as a fraction of the total cherry weight) and cherry weight (W_c):

$$\mathrm{Log}_{10} \frac{W_p}{W_c} = A_o + A_1 \, \mathrm{Log}_{10} W_c \qquad (20)$$

$$\mathrm{Log}_{10} \frac{W_p}{W_c} = B_o + B_1 \, \mathrm{Log}_{10} W_c + B_2 W_c \qquad (21)$$

$$\frac{W_p}{W_c} = C_o + \frac{C_1}{W_c}, \qquad (22)$$

where A_n, B_n, and C_n are constants to be determined by analysis. The equation which gave the best fit with the data (based on the standard error of the estimate) was chosen the most appropriate equation to describe the entire cherry population.

from zero at the 0.05 level or less) was chosen as the most appropriate equation to describe the entire cherry population.

Density, Specific Heat, Soluble Solids, and Diffusivity (1965).--In 1965, much the same procedure was followed as in 1964 except that measurements of flesh diffusivity were included. Since the 1964 data revealed that cherry size had very little effect on flesh specific heat and no effect at all on flesh density, cherries were grouped according to color alone in 1965. A lot weighing approximately three thousand grams and having uniform color was thoroughly mixed and three representative samples of 50 cherries each were taken from it at random. Soluble solids and flesh specific heat were then determined for each of the three 50-cherry samples and averaged. The average flesh specific heat and soluble solids were assumed to be representative of the entire lot. The remainder of the cherries in the lot was pitted and used to fill the aluminum cylinder. The cylinder was weighed before and after being filled. The density of the cherry flesh in the cylinder was calculated since both weight and volume were known.

The cylinder was placed inside an insulated box (Figure 12) where it was allowed to remain until all thermocouples gave the same reading (T_i) at outside-air temperature. The box with the cylinder was next taken inside a cold room where the cylinder was immediately submerged in an agitating cold-water-bath (Figure 13). The entire procedure was repeated

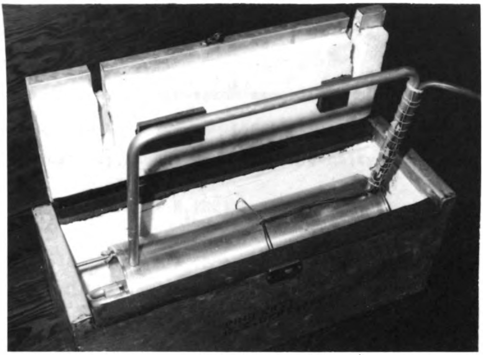


Figure 12. Insulated box used for holding cylinder of cherry flesh until uniform temperature existed throughout.

Figure 13. Dropping cylinder of warm cherry flesh into bath of cold water. Central and surface temperatures as well as water temperature were recorded continuously on the strip chart.

for 19 additional lots each having a wide range of cherry colors.

The following regression equations were used in an attempt to find the best equations from which to estimate flesh diffusivity, conductivity, and density:

$$\alpha_{fl} = K_o + K_1(SS) + K_2\rho_{fl} + K_3\, c_{fl} \tag{29}$$

$$\alpha_{fl} = K_4 + K_s(SS) + K_6\rho_{fl} \tag{30}$$

$$\alpha_{fl} = K_7 + K_8(SS) \tag{31}$$

$$\rho_{fl} = a_o + a_1(SS) + a_2\, c_{fl} \tag{32}$$

$$\rho_{fl} = a_3 + a_4(SS) \tag{33}$$

$$k_{fl} = L_o + L_1(SS) + L_2\rho_{fl} + L_3\, c_{fl} \tag{34}$$

$$k_{fl} = L_4 + L_5(SS) + L_6\rho_{fl} \tag{35}$$

$$k_{fl} = L_7 + L_8(SS), \tag{36}$$

where K_n, a_n, and L_n are constants to be determined by analysis.

Thermal conductivities used in solving for the coefficients in equations (34-36) were calculated for each of the 20 samples by multiplying the measured diffusivity by $(\rho_{fl})(c_{fl})$. As was done for the 1964 data the appropriate equation from each of the three groups of equations

describing α_{fl}, ρ_{fl}, and k_{fl} was selected as being representative of the entire cherry population of 1965.

Because of the relatively small contribution of the pit to both weight and volume of the whole cherry, the measurement of α_p was considered impractical in this study. Furthermore, since early measurements showed that pit density was almost the same as flesh density, it was concluded that little error in cooling calculations would result if the cherry were assumed to be made up of flesh only. Therefore, major emphasis was placed on determining the pertinent properties of the cherry flesh.

RESULTS

Cherry Weight and Diameter

The relationship between whole-cherry weight and cherry diameter, based on the 16 samples of 6 cherries each which were checked in 1964 at East Lansing, is shown in Figure 14. Equation (19) gave the best equation for estimating cherry weight from diameter measurements. The corresponding regression equation was found to be

$$\hat{Y} = 0.073 + 9.915\ X^3 \qquad (37)$$

where $\hat{Y}$ is the estimated cherry weight (grams) and X is the average of the maximum and minimum cherry diameters (inches). The standard error of the estimate was $\pm$ 0.04 grams and the multiple correlation coefficient was 0.999. Also, the Y-axis intercept (0.073), was not significantly different from zero. The mean cherry weight was 4.12 grams and average cherry diameters ranged from 0.658 inch to 0.808 inch.

The average density of the cherries over all 16 samples was 1.05 gms./cc. Therefore, assuming a density of 1.05 gms./cc. and $\overline{D}$ to be the diameter of a perfect sphere (inches), the equation for cherry weight (grams) would be

$$W_c = 9.01\ \overline{D}^3. \qquad (38)$$

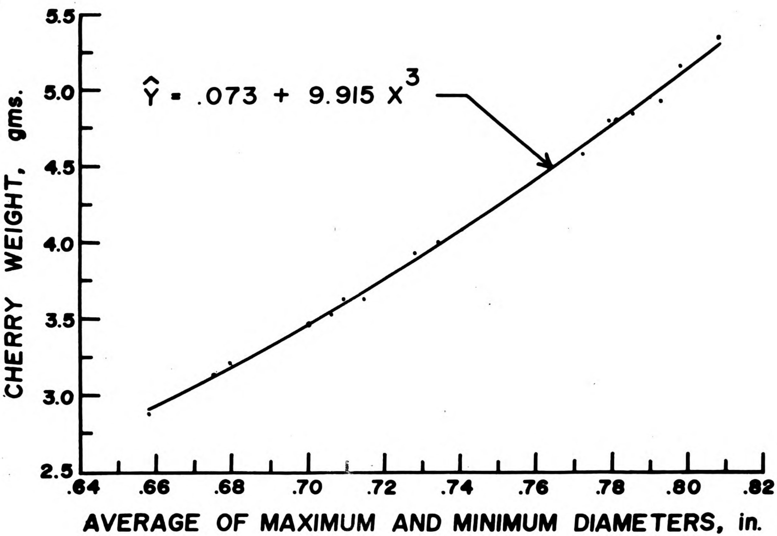


Figure 14. Relation between cherry weight and the average of the maximum and minimum cherry diameters.

Thus, equation (37) indicates that X is very nearly equal to the diameter of a perfect sphere having the same weight as the cherry.

Cherry Weight and Pit Weight

Cherry processors generally lose about 18 percent of the weight of a whole cherry during pitting (Whittenberger, et al., 1963). A large part of this loss is attributed to the weight of the pit itself. Based on the 58 50-cherry samples taken at Traverse City in 1964, a significant correlation was found to exist between cherry weight and pit weight. This relationship was best described by a regression equation in the form of equation (22).

Figure 15 shows the regression of pit weight (in percent of total weight, $\hat{Y}$) on cherry weight with the resulting regression equation

$$\hat{Y} = 2.1 + 15.1/X \qquad (39)$$

where X is the weight of the whole cherry (grams).

Although the information given in Figure 15 does not mean much to heat transfer specialists, it does serve to justify neglecting the pit in calculations of cooling time for whole cherries. It also illustrates that it is advantageous for processors to purchase the larger cherries. Since the average weight of cherries runs around 3.77 grams (Levin and Gaston, 1954), pit weight averages only about 6.2 percent of the total cherry weight.

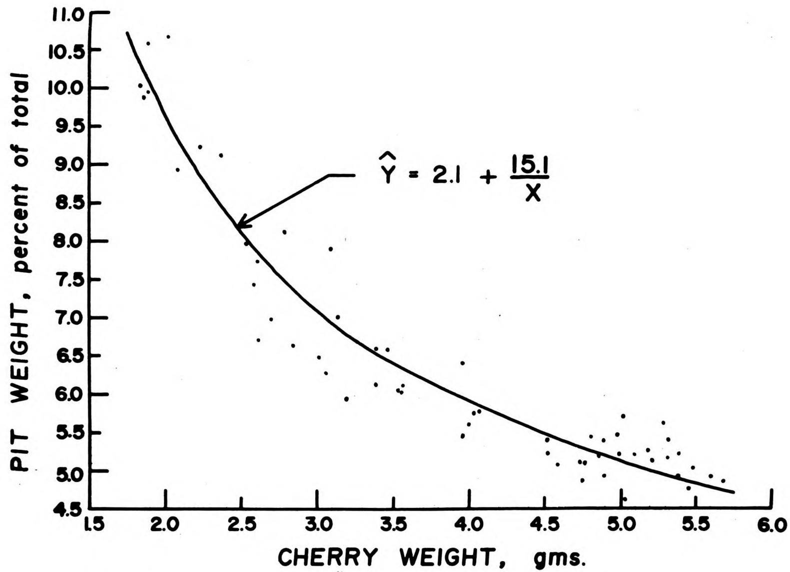


Figure 15. Relation between pit weight and total cherry weight (1964).

The standard error of the estimate of percent pit weight by equation (39) was $\pm$ 0.51 percent and the multiple correlation coefficient was 0.957. All constant coefficients were significantly different from zero.

Specific Gravity

In 1964, the average specific gravity (or density expressed as gms./cc) for pits and cherry flesh was 1.07 and 1.05, respectively. This further justifies neglecting the pit in cooler design calculations.

Neither specific heat nor cherry weight had any effect on the specific gravity of cherry flesh in 1964 or 1965 since the coefficients preceding these variables were not significantly different from zero (from regression analysis using equations 26, 27 and 32). However, specific gravity was related to soluble solids in both years as illustrated in Figures 16 and 17.

Standard errors of the estimates were $\pm$ 0.016 and $\pm$ 0.013 for the 1964 and 1965 regression equations, respectively. Correlation coefficients were 0.699 and 0.698 for the 1964 and 1965 data, respectively. Although the slopes of the curves in Figures 16 and 17 are very nearly the same, the 1965 cherries were slightly more dense than those of 1964. Slight variation in density from year to year can be expected. Soluble solids can also be expected to increase seasonally as cherries become more mature.

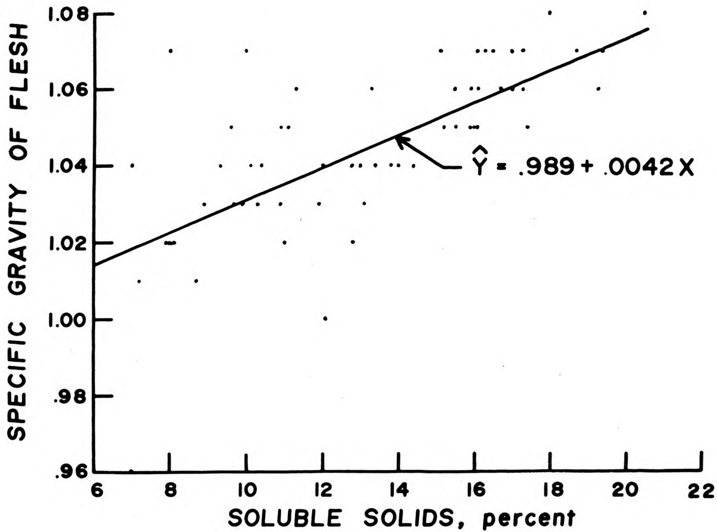


Figure 16. Relation between specific gravity and soluble solids of cherry flesh in 1964.

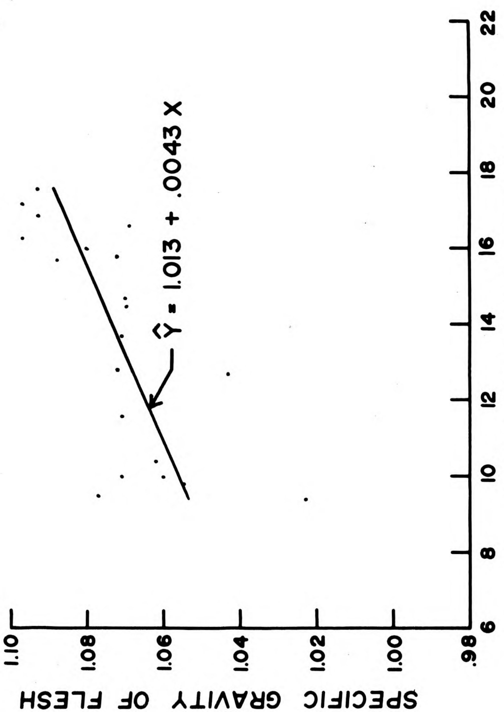


Figure 17. Relation between specific gravity and soluble solids of cherry flesh in 1965.

Specific Heat

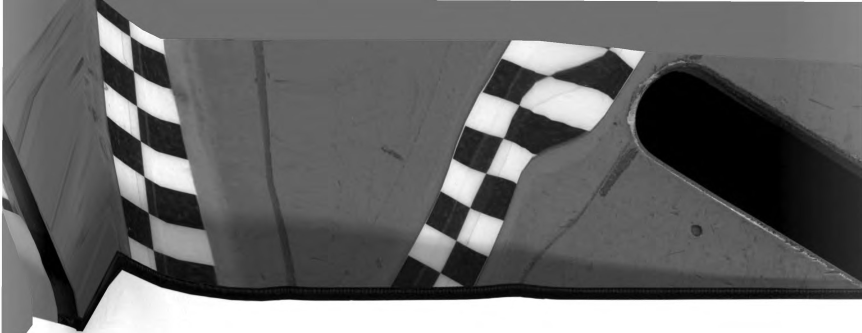
From multiple correlation analysis of the 1964 data, flesh specific heat was independent of flesh density (by equation 23) but was related to soluble solids and flesh weight per cherry in the following manner:

$$\hat{c}_{fl} = 0.900 - 0.005\,(SS) + 0.020\,W_{fl} \qquad (40)$$

where: $\hat{c}_{fl}$ = estimated flesh specific heat (BTU/lb.°F)
SS = soluble solids content of the flesh (percent)
and W_{fl} = flesh weight of each cherry (grams).

The standard error of $\hat{c}_{fl}$ was $\pm$ 0.060 BTU/lb.°F and the average specific heat was 0.906 BTU/lb.°F. The multiple correlation coefficient was only 0.401. Since the average specific heat was almost the same as the initial term of equation (40) and since the effects of W_{fl} and SS on c_{fl} almost cancel each other for average values of each, it was considered impractical to separate cherries according to weight. Instead, use of the average specific heat of 0.906 BTU/lb.°F would result in very little additional error over that which would result from use of equation (40) to estimate specific heat.

Since cherries were not separated according to weight in 1965, a complete analysis such as that of 1964 could not be made. However, a multiple correlation analysis on c_{fl}, SS, and ρ_{fl} again showed that c_{fl} was independent of SS or the combination of SS and ρ_{fl}. Average specific heat for



cherry flesh tested in 1965 was 0.874 BTU/lb.°F based on a total of 60 measurements (3 sub-samples from each of the 20 major samples). Therefore, the weighted average specific heat of cherry flesh for both 1964 and 1965 was 0.890 BTU/lb.°F.

Thermal Diffusivity

Average thermal diffusivity of the 20 samples of cherry flesh tested in 1965 was 5.104×10^{-3} sq. ft./hr. Multiple correlation analysis using equations (29-31) revealed that flesh diffusivity was independent of flesh density and specific heat but was related to soluble solids by the equation

$$\hat{\alpha}_{fl} = (5.320 - 0.0159SS)\ (10^{-3})\ \text{sq. ft./hr.} \qquad (41)$$

where SS is in percent. The standard error of $\hat{\alpha}_{fl}$ was $\pm\ 0.416 \times 10^{-3}$ sq. ft./hr. and the multiple correlation coefficient was 0.7564. This relationship is illustrated in Figure 18.

If thermal diffusivity were dependent upon temperature, the measured diffusivity should vary with time of cooling since the average temperature of the sample of flesh was continually being lowered during the cooling process. A continuous temperature check on one of the 16 samples over a two-hour cooling time instead of the optimum 38-minute cooling period revealed a trend toward lower diffusivity for lower temperature. Actual measurements for this particular sample are given in Table 1. The lower values of

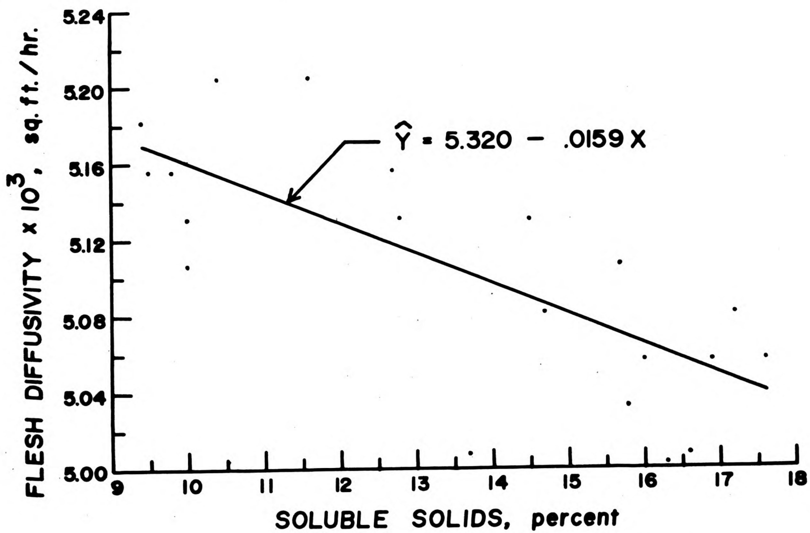


Figure 18. Relation between thermal diffusivity and soluble solids of cherry flesh in 1965.

α_{fl} during the early cooling periods indicates that the initial time lag in reaching a constant T_s was significant in lowering the measured diffusivity. As cooling periods are increased, the effect of the initial lag time is decreased. Although a $\pm$ 0.2°F error in reading T_s becomes more significant as T(0,t) approaches T_s, there is still a definite trend toward lower diffusivity with lower flesh temperature.

TABLE 1.--Variation of flesh thermal diffusivity with cooling time.

Time in Cooling (min.)	T_i (°F)	T_s average (°F)	T_o (°F)	C(θ)	θ	$\alpha_{fl} \times 10^3$ sq.ft./hr.
20	80.3	33.6	71.4	0.8100	0.110	5.15
30		33.6	62.0	0.6080	0.166	5.18
40		33.6	54.6	0.4500	0.219	5.14
50		33.7	49.1	0.3305	0.273	5.12
60		33.8	45.1	0.2430	0.326	5.10
80		33.8	40.1	0.1356	0.427	5.00
100		33.8	37.4	0.0775	0.524	4.91
120		33.7	36.0	0.0483	0.606	4.74

Thermal Conductivity

Thermal conductivity for each of the 20 samples of 1965 was calculated by using the measured values of flesh density, specific heat, and diffusivity in the known relationship $k = \rho c \alpha$. Taking k_{fl} as the dependent variable

and solving for the coefficients in equation (29) by multiple correlation analysis, the following equation was obtained:

$$\hat{k}_{fl} = -0.275 - 0.009SS + 0.280\rho_{fl} + 0.327c_{fl}, \qquad (42)$$

where: $\hat{k}_{fl}$ = the estimate of flesh thermal conductivity (BTU/hr. ft.°F)

SS = flesh soluble solids content (percent)

ρ_{fl} = flesh density (grams/cc)

and c_{fl} = flesh specific heat (BTU/lb.°F).

Standard error of $\hat{k}_{fl}$ was $\pm$ 0.0025 BTU/lb.°F and the multiple regression coefficient was 0.9732. Average thermal conductivity for the 20 samples was 0.298 BTU/lb.ft.°F, which was slightly lower than that of water.

Film Coefficient ($\bar{h}$)

When the effect of temperature on water properties was considered in calculating $\bar{h}$ using equation (9), it was found that for relatively low water velocities water temperature had little effect on $\bar{h}$. A wide range of water velocities and adjusted cherry diameters were assumed in calculating $\bar{h}$ for Reynolds numbers within the range recommended by McAdams (1953). The relationship between VD_o and $\bar{h}D_o$ at different film-water temperatures is given in Figure 19.

It is suggested that the average of the maximum and minimum cherry diameters be used in determining D_o as well as r_1. Therefore, for average size cherries, r_1 would be

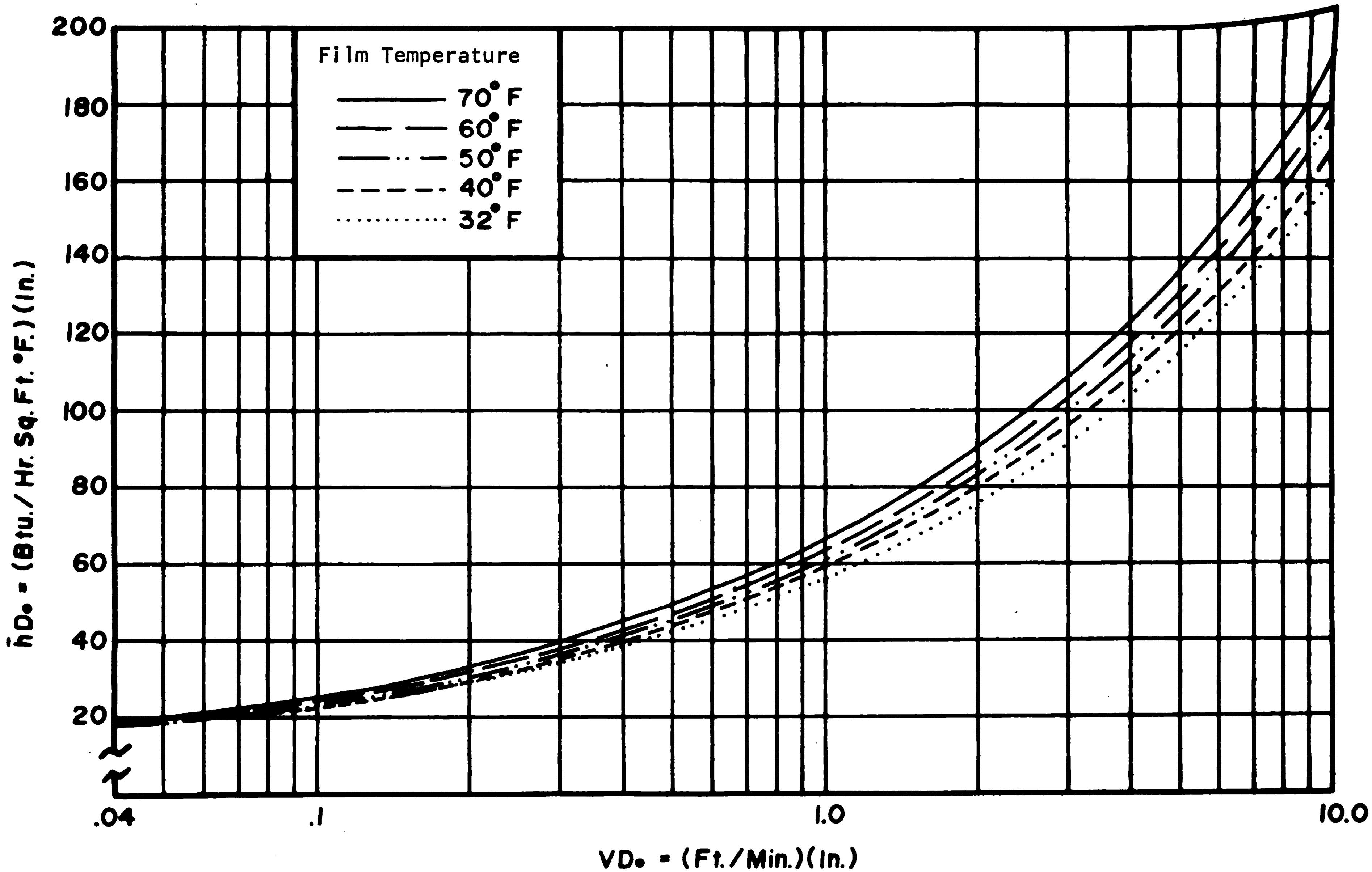


Figure 19. Convective film coefficient ($\bar{h}$) X sphere diameter (D_o) vs. water velocity (V) X (D_o) for wide range of water temperature.

about 0.38 inch and D_o would be about 0.76 inch according to the curve in Figure 14.

It is pointed out that the curves of Figure 19 are valid for film-water temperatures--the average of the cherry surface temperature and the free stream water temperature. Therefore, if 80°F cherries are to be cooled by 40°F water for example, the film temperature would be 60°F initially and would approach 40°F as the surface temperature of the cherry approaches 40°F. Therefore, the film coefficient may be expected to decrease slightly with cooling time for a constant water velocity.

As $\bar{h}$ increases, its effect (per unit increase in $\bar{h}$) on the calculation of cooling time for cherries decreases. For very large values of $\bar{h}$, the surface temperature of the cherry may be assumed to be the same as the cooling water temperature throughout the cooling process. Therefore, it is suggested that no appreciable loss in accuracy will result if $\bar{h}$ is evaluated at that temperature which is the average of the free stream temperature and the desired final central cherry temperature. For example, if 40°F water is to be used to cool cherries down to 45°F, $\bar{h}$ should be evaluated at a film temperature of 42.5°F and may be assumed to be constant throughout the cooling period.

DISCUSSION

To calculate the cooling capacity required to cool a desired tonnage of cherries per hour from say 75°F down to 40°F, it would help somewhat to know the average weight and soluble solids content of each cherry in estimating the specific heat of the cherries using equation (40). If these values are not known, however, one may assume the specific heat of cherries to be 0.89 BTU/lb°F which was the average specific heat of 1964 and 1965 cherries. Then, the cooling capacity (Q) required would be

$$Q = (W_c)\ (c)\ [T_1 - T(0,t)] \tag{43}$$

$$= (2{,}000\ \text{lb/ton/hr.})\ (0.89\ \text{BTU/lb°F})\ (35°\text{F})$$

$$= 62{,}300\ \text{BTU/hr./ton.}$$

To calculate the exposure time required to cool these cherries, equation (4) should be used to insure an adequate time for cooling the center of each cherry to 40°F. However, certain values for θ and Bi must first be established. As suggested previously, the average of the maximum and minimum diameters should be used in determining r_1 and D_0 for use in equations (4) and (9). Therefore, for average

size cherries (3.77 grams per cherry), r_1 would be about 0.38 inch and D_o would be 0.76 inch according to the curve in Figure 14. Then using $\alpha_{f1} = 5.54 \times 10^{-3}$ sq. ft./hr. according to Figure 18 for 14 percent soluble solids, $\theta = \alpha t/r_1^2 = 5.52$ t, where t is in hours.

For a given water velocity and temperature, $\bar{h}$ for cherries having an average D_o of 0.76 inch can be determined from Figure (19). Also, k_{f1}, for cherries containing about 14 percent soluble solids and having a density of approximately 1.06 grams/cc can be calculated by equation (42) or by the relationship $k = \alpha\rho c$. The resulting values of $\bar{h}$ and k_{f1} should then be used to determine Bi and the corresponding M_n roots for equation (4). Solving for θ for given water and cherry temperatures by equation (4), the time required to cool the center of the cherry to $T_{(0,t)}$ can be found from the relationship $t = \theta/5.52$ (hrs.).

CONCLUSIONS

Cherry Diameter

Based upon measurements of average cherry diameter and weight from 16 samples of six cherries each, cherry weight was related to average diameter by the expression

$$W_c = 0.073 + 9.915\,D_o^3, \tag{44}$$

where W_c is in grams and D_o is in inches. Since cherry weights vary considerably from year to year, cherry weight measurements should be made yearly before assuming a value of D_o and subsequent r_1 to use in calculating cooling times by equation (4).

Cherry Homogeneity

Cherry flesh and pits were found to have very nearly the same density. It was also found that the portion of the total cherry weight which is attributed to the weight of the pit decreases with increasing cherry weight. This relationship closely follows the expression

$$\frac{W_p}{W_c} \times 100\% = 2.1 + \frac{15.1}{W_c} \tag{45}$$

where all weights are expressed in grams. It is concluded therefore, that the pit can be disregarded in cooling time

calculations and the cherry can be assumed to be a sphere of homogeneous cherry flesh having a diameter D_o.

Density

Based upon the results of density measurements over a two year period, reasonable values for the density of cherry flesh can be calculated by considering only their soluble solids content. The resultant equations for the regression of flesh density on percent soluble solids (SS) were:

$$\rho_{fl} = 0.989 + 0.0042 \text{ SS (gms/cc)} \qquad (46)$$

and $$\rho_{fl} = 1.013 + 0.0043 \text{ SS (gms/cc)} \qquad (47)$$

for 1964 and 1965 cherries respectively. It is recognized that density of cherries varies from year to year. This variation is reflected in the slight differences between the first terms of the two equations.

Specific Heat

The specific heat of cherry flesh was found to be relatively independent of other cherry properties, although it may vary slightly due to the combined effects of cherry weight and soluble solids. Flesh specific heat averaged 0.906 and 0.874 BTU/lb°F in 1964 and 1965 respectively. The specific heat of cherry pits was somewhat lower than that of the flesh. However, specific heat of whole cherries is very close to that of the cherry flesh alone, since the

weight of the pit constitutes such a small fraction of the weight of the whole cherry.

Thermal Diffusivity

The resultant equation for the regression of flesh diffusivity on percent soluble solids for 1965 cherries was found to be

$$\alpha_{fl} \times 10^3 = 5.320 - 0.0159\ SS\ \text{(sq.ft./hr.)} \qquad (48)$$

Thermal diffusivity was not affected by specific heat or density but decreased slightly with decreases in temperature. However, for practical applications to hydrocooler design the variation of α_{fl} with temperature can be disregarded.

Thermal Conductivity

Thermal conductivity of cherry flesh can be calculated by the use of the relation $k = \alpha\rho c$ or by the resulting regression equation for 1965 cherries

$$k_{fl} = -0.275 - 0.0009\ SS + 0.280\rho_{fl} + 0.327\ c_{fl}, \qquad (49)$$

where: k_{fl} = thermal conductivity of cherry flesh (BTU/lb.ft.°F)

SS = soluble solids (percent)

ρ_{fl} = flesh density (grams/cc)

and c_{fl} = flesh specific heat (BTU/lb.°F).

Again, the above equation (49) should give reasonable values for the conductivity of whole cherries because of the relatively small weight and size of the cherry pit. For simplicity, it should be just as accurate to estimate k_{fl} from estimated values of α_{fl}, ρ_{fl} and c_{fl} using the expression $k = \alpha\rho c$ as to estimate k_{fl} from equation (49).

Film Coefficient ($\bar{h}$)

Equation (9) should be used to evaluate the film coefficient for cherries in water. For best estimation of $\bar{h}$, film water temperature should be considered especially in the higher range of relative velocities. Film temperature as well as $\bar{h}$ decreases slightly as cherries are being cooled. Average film coefficient may be determined quickly for given cherry size and relative velocity by use of Figure 19. Cherry diameter may be taken as the average of the maximum and minimum diameters for use of this figure.

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APPENDIX

TABLE A1.--Physical properties of water at atmospheric pressure and specific temperatures.

T (°F)	ρ[a] (lb_m/cu.ft.)	c[b] (BTU/lb_m°F)	$\mu \times 10^3$[c] (lb_m/ft.sec)	k[c] (BTU/hr.ft.°F)	$\alpha \times 10^3$[c] (sq. ft./hr.)	Pr.[c]
32	62.42	1.009	1.20	0.319	5.07	13.7
40	62.42	1.005	1.04	0.325	5.21	11.6
50	62.38	1.002	0.88	0.332	5.33	9.55
60	62.34	1.000	0.76	0.340	5.47	8.03
70	62.27	0.998	0.658	0.347	5.57	6.82
80	62.17	0.998	0.578	0.353	5.68	5.89

[a]From Keenan and Keyes (1936).

[b]From Brown and Marco (1958).

[c]From Kreith (1958).

TABLE A2.--Reported physical properties of fruits.

Fruit	T (°F)	ρ (lb_m/cu.ft.)	c (BTU/lb_m°F)	k (BTU/hr.ft.°F)
Apples	75-85	51.4[f]	0.89-0.96[b]	
Applesauce	91	--	0.96[c]	--
	72.5	--		0.400[c]
Banana Puree	76	--	0.875[c]	--
	60	--		0.320[c]
Berries, Fresh	84-90	--	0.89-0.98[b]	--
Grapefruit, Marsh				
Juice Vesicle	86.5	--	--	0.267[a]
Whole	--	54.6[a], 51.7[d]	--	--
Grapes, Concord (Ripe)	--	67.0[d]	--	--
Oranges, Valencia				
Juice Vesicle	86.5	--	--	0.251[a]
Whole	--	61.2[a], 60.8[d]	--	--
Peaches				
Hale Haven	40-80	59.5[e]	--	0.311[e]
Red Haven	40-80	59.8[e]	--	0.276[e]
Plums, Fresh	75-78	--	0.84[b]	--

[a]From Bennett, Chace, and Cubbedge (1964).

[b]From Ordinanz (1946).

[c]From Charm (1963).

[d]From Jacobs (1951).

[e]From Bennett (1963).

[f]From Mohsenin, et al. (1965) for McIntosh variety in 1961.

TABLE A3.--Main constituents of cherries compared with those of apples.*

Fruit	Insoluble Solids (Fibre etc.) %	Soluble Solids %	Total Solids %	Total Sugars (Invert sugar) %
Cherries (stone-free):				
Highest	2.70	14.75	17.45	10.60
Lowest	0.95	10.70	12.35	6.90
Average (12 samples)	1.88	12.41	14.29	8.33
Apples:				
Highest	5.95	12.55	18.35	9.75
Lowest	1.60	9.50	12.15	4.20
Average (28 samples)	2.57	11.70	14.27	7.60

*From Morris (1946).

TABLE A4.--Values of the cylinder series C(θ).*

θ	C(θ)	θ	C(θ)	θ	C(θ)	θ	C(θ)
0.100	0.84836	0.180	0.56126	0.260	0.35577	0.340	0.22420
0.104	0.83349	0.184	0.54883	0.264	0.34767	0.344	0.21908
0.108	0.81846	0.188	0.53664	0.268	0.33975	0.348	0.21407
0.112	0.80333	0.192	0.52468	0.272	0.33201	0.352	0.20918
0.116	0.78813	0.196	0.51297	0.276	0.32444	0.356	0.20440
0.120	0.77293	0.200	0.50149	0.280	0.31704	0.360	0.19973
0.124	0.75776	0.204	0.49024	0.284	0.30981	0.364	0.19516
0.128	0.74265	0.208	0.47922	0.288	0.30275	0.368	0.19070
0.132	0.72763	0.212	0.46844	0.292	0.29584	0.372	0.18634
0.136	0.71273	0.216	0.45788	0.296	0.28909	0.376	0.18208
0.140	0.69798	0.220	0.44755	0.300	0.28249	0.380	0.17792
0.144	0.68339	0.224	0.43743	0.304	0.27604	0.384	0.17385
0.148	0.66897	0.228	0.42753	0.308	0.26973	0.388	0.16988
0.152	0.65475	0.232	0.41785	0.312	0.26358	0.392	0.16599
0.156	0.64073	0.236	0.40838	0.316	0.25756	0.396	0.16220
0.160	0.62692	0.240	0.39912	0.320	0.25167	0.400	0.1585
0.164	0.61332	0.244	0.39005	0.324	0.24592	0.410	0.1496
0.168	0.59996	0.248	0.38119	0.328	0.24030	0.420	0.1412
0.172	0.58683	0.252	0.37253	0.332	0.23481	0.430	0.1332
0.176	0.57392	0.256	0.36405	0.336	0.22945	0.440	0.1258

*Tabulated from Schneider (1955).