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THEORETICAL CONSIDERATIONS: SOME ENGINEERING ASPECTS OF COOLING FRUITS AND VEGETABLES

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ABSTRACT

The effect of post-harvest temperature on fresh fruits is a matter of plant physiology rather than of engineering, but a knowledge of the principles involved is desirable for the engineering of temperature control. The tissues of these products remain alive after harvest and normal life processes continue. With some exceptions the longest life and the best quality can be obtained by checking the life processes by low temperature as soon and as completely as possible. Moisture loss and the action of enzymes and microorganisms also cause deterioration that can be checked by low temperature. The rates of these various changes are commonly doubled or tripled with each 10° F rise in temperature. It may be estimated roughly that fresh fruits and vegetables deteriorate as much in an hour at 90°F as in a day at 50 or in a week at 32°E.

Keywords: *Post-Harvest Temperature, Plant Physiology, Moisture Loss, Enzymes & Microorganisms.*

Introduction

Heat-Transfer Principles

An object placed in surroundings at a constant lower temperature, if there is a negligible temperature gradient within the object and the thermal properties are constant, cools by condition according to Newton's Law (1):

$$dt/d\theta = -C(t - t_0)$$

Or

$$\theta = \frac{1}{C}\ \text{In}\ \frac{t_1 - t_0}{t - t_0} \quad .....(1)$$

Where

θ = time

t = temperature of the object

t1 = initial value of t

t0 = temperature of the surroundings

C = a constant depending on the best capacity of the object and the heat conductance to its surroundings.

The constant C is called the cooling coefficient and is a convenient measure of the characteristics of a cooling system. From equation (1) C is easily calculated from observations of time and temperature, or when C is known it may be used to calculate the temperature that will be reached in

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a given time. Graphically, C is the slope of a plot of ln(t1-t0)/(t-t0) against e which is easily constructed on semillon paper. More commonly In (t-t0)/ (t1-t0) is plotted against to give a cooling line sloping downward to the right, and the slope is C. Either plot is convenient for determining C from observations or for predicting times and temperatures when C is known.

A quantity mathematically related to the cooling coefficient and more intelligible to many persons is the time in which the temperature difference between an object and it s surroundings is reduced by one-half. G. F. Sainsbury (2) has introduced the symbol Z for this quantity, Suggested to him by R. Expressed in hours or minutes, this time is simply related to the actual time needed to cool the product commercially, which may for example be Z, 2A or 32 according to whether the final temperature difference between the product and its surroundings should be one-half, one-quarter, or one-eight s of the initial temperature difference. An approximate value of Z may be estimated by inspecting observations for the time at which the initial temperature difference is reduced by ore-half. More exactly, from equation (1) :

$$Z = \frac{1}{C} \text{ In } 2 = \theta \text{ (1n 2/1n } \frac{(t_1 - t_0)}{t - t_0}$$

Using a value of 0.7 for ln 2:

$$\frac{1}{\theta} = 0.7/\text{In } \frac{t_1 - t_0}{t - t_0}$$

This relation is very convenient for calculating the half-cooling time from observations of for predicting performance when the half-cooling time is known.

In the commercial cooling of fruits the conditions for Newton's law are seldom strictly satisfied. There is often a considerable temperature gradient within a container, or within individual fruits when these are exposed, and cooling is accomplished by convection and radiation as well as by conduction. Most important, the temperature of the immediate surroundings, such as the air among stacked containers or even the temperature of the main air stream, may fall considerably as cooling progresses. In most cases however, there is a final heat sink at reasonably constant temperature such as a thermostatically controlled space or the ice in a bunker, It has been our experience that Newton's law applies quite well if is taken as the average temperature of the product at time θ, and t0 as the temperature of the final heat sink. This application would be exact if the conductance from the thermal center of the product to a fixed temperature heat sink were constant. Apparent ly the departures from such a ideal condition are small.

For cooling in variable-temperature surroundings the cooling coefficient may be considered as the decrease in object temperature in degrees per hour divided by the average temperature difference between the object and its surroundings. This may be written as:

$$C = \frac{(t_1 - t)/\theta}{(t - t_0)\text{avg}} \qquad .....(3)$$

The resulting value of C is a measure of the exposure of the object in relation to its heat capacity, but it is obviously not possible to predict the cooling of an object from this coefficient without having also some means of predicting the surroundings temperature. Equation (3) may also be used when the surroundings temperature is constant. In this ca se determining (t-t0) avg from equally timed observations is the same as calculating it as the log mean of initial and final observations, and equations (1) and (3) are the same:

$$C = \frac{(t_1 - t)/\theta}{\dfrac{(t_1 - t_0) - (t - t_0)}{\text{In}\dfrac{t_1 - t_0}{t - t_0}}} = \frac{1}{\theta} \quad \text{In } \frac{t_1 - t_0}{t - t_0}$$

For a given object exposed in a given way, C is evidently the same whether it is determined in constant-or in variable- temperature surroundings, and a half-cooling time Z may be calculated from it, though Z will have a physical meaning only, when the surroundings temperature is constant.

Obviously, will not be the same, however, for different portions of the heat circuit-for example, from product to adjacent air, from product to main air stream, of from product to ice bunker. Cooling coefficients or half- cooling times as given in references may have been determined in any one of the se ways and it is important to note which. A figure based on a constant-temperature heat sink is the only one that can be used to predict cooling behaviour. For this reason as well as for purposes of comparison, it is useful to at least estimate a conversion from one base to another.

Using primed symbols to indicate the shorter portion of the heat circuit, we may write for any time 0 :

$$C = \frac{(t_1 - t)\theta}{(t - t_0)avg} \quad \text{and} \quad C = \frac{(t_1 - t)/\theta}{(t - t_0)avg}$$

Hence

$$\frac{C}{C} = \frac{Z'}{Z} = \frac{t - t}{t - t_0}$$

For air-cooling systems, the heat capacity of the coolant is usually small. At any time the heat flowing t-to are inversely through the circuit is that being lost by the product. Under the se circumstances t-to and proportional to the heat conductance's over which they are measured. If the heat conductance's do not change with time, (t-t0)/ (t-t0) is a constant. The ratio of temperature difference between product and immediate surroundings to temperature difference between product and heat sink usually does not change as cooling progresses. If the temperature of the product is initially 50 F above the ice and 30 F above the air, it will later be 25 F above the ice and 15 F above the air and eventually 5 F above the ice and 3 F above the air.

Consequently

These ratios remaining constant as cooling progresses. This ratio of temperature differences is easily measured. For prediction it may be estimated from past experience and used to calculate the relation between a half-cooling time based on a heat sink and a half-cooling time based on immediate surroundings. Values of C and Z have been determined in many different cooling systems.

Refrigeration

Refrigeration is usually the large st single item in cooling costs. Tests show that only about one-half of the refrigeration is ordinarily used to cool the product. In addition to losses from condition and infiltration, considerable heat may be introduced by powerful funs. A 1 hp fan me lts about 570 ln of ice in 24 hr if the motor is in the cooled space, or 430 ln if the motor is installed outside. The cost of this refrigeration may be from five to ten times the cost of electricity to run the fan. Fans operating at high pressures may also drastically increase infiltration or else require expensive construction to prevent this.

Ice and mechanical refrigeration are competitive in commercial cooling operations. Ice quires a minimum investment in plant and where reasonable in price, is preferred for short seasons and pealed loads. Mechanical refrigeration is more economical if the season is long and the load steady enough for the saving in operating cost to offset the large investment. High humidity is usually desired to avoid drying the product and is assured by the use of ice. Mechanical units can be designed with large cooling surfaces operating at or above 32 F. but unfortunately this is not always done and the humidity is often lower than when ice is used. Cooling before packing may allow faster and more convenient methods to be used. On the other hand, the heat gained during subsequent exposure of the product must be offset by additional cooling, either before or after packing. A heat gain of 10 F, for example, would add around 25 percent to cooling costs. Regulation of final temperature may not greatly affect the total heat taken from the product, but it is important to the quality of some temperature-sensitive items and if effected by stopping the fans it can reduce refrigeration losses.

The thermal resistance within fruits is such that a relatively large temperature gradient initially occurs during most precooling. This initial temperature distribution is non-linear. As cooling progresses, changes occur in the temperature distribution and the gradient diminishes. As the gradient disappears the product temperature approaches a uniform distribution and may be obtained at any point. Such a temperature is indicative of product heat and thus would be the mass-average temperature. The mass-average temperature during the period of transient cooling may be predicted from knowledge of the temperature distribution as affected by the internal and external thermal characteristics of an object being cooled. A mass average temperature denotes a single value from the temperature distribution that would become the uniform product temperature under adiabatic conditions. The requirement of adiabatic conditions is artificially imposed primarily for the purpose of definition. The concept of a mass-average temperature is not new; use of the. concept however, has not been exploited.

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