Convection in Syrup-Packed Products [a, b]

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Problems encountered in heating syrup-packed products have a long history. The difficulty of heating these products is well established. When solids such as fruits and vegetables are placed in a liquid, the solids heat by conduction, and the assumption is usually made that the liquid heats by convection, commonly acknowledged to be a more rapid method of heat transfer than conduction. However, there are notable instances in which heating does not proceed as rapidly as expected. Braun *(7)* and Braun, Hays, and Benjamin *(8)* report the results of adding dry sugar to cans of sweet potatoes. Excessive spoilage in these packs was attributed to the failure of the sugar to dissolve completely with a resulting retardation of normal convection currents.

The higher viscosity of syrup, compared with water, has been suggested and investigated as the source of the difficulty of heating syrup-packed products *(5, 9, 10, 12, 14)*. That increased viscosity retards convection to some extent is not questioned. Nevertheless, the results of these studies, which include determinations of the heating of pure syrups of various concentrations and comparisons of the heating of foods packed in water with the same foods packed in syrup, show that viscosity alone cannot account for the slower heating observed.

It is suggested that the explanation of this problem lies in an analysis of the liquid and soluble solids exchanges taking place between product and covering liquor. These exchanges, during which the soluble solids contents of product and liquor approach equilibrium, are known to take place over a period of time that is long compared with the heat processing time *(1, 4, 6, 11, 15)*. However, after adding syrup to the product, the water leaving the product rises to the top of the container with the result that within minutes appreciable differences in syrup concentration are established between the top and bottom of the container. This phenomenon, called product-induced stratification, will be reported in detail in a subsequent paper *(13)*.

Most analytical treatments of convection heating are restricted to the case of a homogeneous fluid in which the density differences that cause convection are the result of temperature differences only. However, if the fluid is not homogeneous, as is the case when the syrup concentration is not uniform throughout the container, then density differences will be a function of both syrup concentration and temperature. Because the density is a function of these two variables, there can be combinations of syrup concentration and temperature that will prevent convection currents. It is the purpose of this paper to show what combinations of syrup (sucrose) concentration and temperature will prevent convection.

ANALYSIS

The forces of importance for convection acting on parcels of liquid are buoyant forces, gravity, and viscosity. In the case of no relative motion, viscosity may be neglected because the velocity is zero. Viscosity will affect the rate of convection currents, but not the onset of convection.

Consider two neighboring points in a jar, P_1 and P_2 (P_1 above P_2) at which the densities are given by $\rho_1(p_1 T_1)$ and $\rho_2(p_2, T_2)$ where ρ is density, p is the sucrose concentration, and T is the temperature. If $\rho_1 < \rho_2$, then there will be no convective exchange of liquid between these two points; that is, the criterion of no convection is $\Delta\rho_{1,2} \equiv \rho_1 - \rho_2 < 0$ and since $\rho = \rho(p,T)$ then $\Delta\rho = \left(\frac{\delta\rho}{\delta p}\right)_T \Delta\rho + \left(\frac{\delta\rho}{\delta T}\right)_p \Delta T$.

$$\Delta\rho_{1,2} = \left(\frac{\delta\rho}{\delta p}\right)_T \Delta p_{1,2} + \left(\frac{\delta\rho}{\delta T}\right)_p \Delta T_{1,2} < 0 \qquad (1)$$

is a restatement of the criterion for no convection.

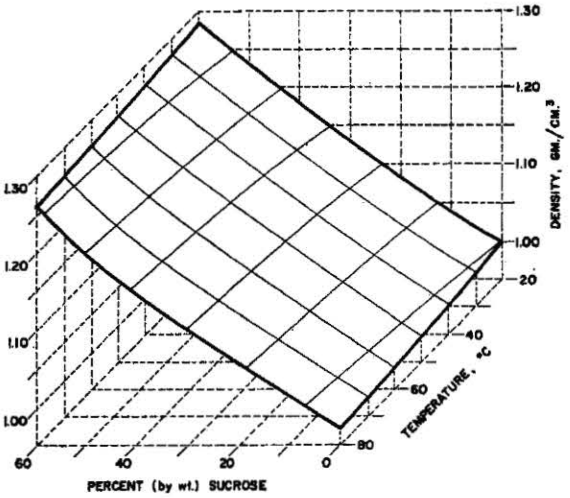

Figure 1. Density of sucrose syrups as a function of temperature and per cent sucrose.

Figure 1 shows the function ρ in the sucrose concentration range of 0–60%, by weight, and the temperature range of 20–80° C (densities taken from reference *3*). This surface was fitted by the method of averages to the equation

$$\rho = a + bp + cp^2 + dT \qquad (2)$$

in which ρ is in g/cm^3, p is in %, T is in ° C, a = 1.016 g/cm^3, b = 3.96×10^{-3} g/cm^3%, c = 1.24×10^{-5} g/cm^3%^{2}, and d = -6.16×10^{-4} g/cm^3 °C. These constants give errors of about ±0.5% in the concentration and temperature range studied.

Differentiation of equation (2) gives $$\left(\frac{\delta\rho}{\delta T}\right)_p = d \qquad (3)$$

and $$\left(\frac{\delta\rho}{\delta p}\right)_T = b + 2cp \qquad (4)$$

Equations (3) and (4) substituted in equation (1), which is then solved for $\Delta p_{1,2}$, give $\Delta p_{1,2} < -\frac{d\Delta T_{1,2}}{b + 2cp}$. (5)

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[b] Presented before the Nineteenth Annual Meeting of the Institute of Food Technologists, Philadelphia, Pennsylvania, May 19. 1959.

Consider a representative acid-food processing condition at the beginning of heat processing, when the temperature difference between product and heating medium is a maximum. Suppose the initial sucrose concentration is 50% in the syrup and essentially zero in the product, and that syrup and product are initially at 20° C. Let the heating medium temperature to which the container is subjected be 80° C. Let P_1 be some point above the bottom of the jar which is still at the initial temperature of 20° C and let P_2 be a point at the bottom of the jar which has reached the bath temperature of 80° C and where the syrup concentration is still 50% sucrose. Substitution of these values of temperature and sucrose concentration in equation (5) gives $\Delta p_{1,2} < -7\%$ or $p_1 < p_2 - 7\%$ or $p_1 < 43\%$ for the criterion of no convection between points P_1 and P_2 as defined. If at the point P_1, still at 20° C, the sucrose concentration has dropped to less than 43%, then convection will not take place even though the temperature of the liquid at P_2 is 60° C higher than the temperature at P_1. Naturally, if ΔT is smaller than 60° C, the Δp required to prohibit convection will be proportionally smaller. Obviously there are unlimited combinations of temperature and percentage sucrose that will prohibit convection between specified points. Only one such combination has been exhibited in order to show the concentration difference required to prohibit convection under the most favorable temperature difference for convection.

DISCUSSION AND CONCLUSIONS

In the present study it has been shown that a difference of 7% in sucrose concentration between two points will prohibit convection between these points even if the heavier syrup is 60° C higher in temperature. Mulvaney, Nicholas, and Pflug *(13)* showed that 2 minutes after processing begins, differences of over 9% in sucrose concentration were found between the top and bottom of jars of sweet fresh cucumber spears. By the end of the heat processing period, this concentration difference had increased to about 15%.

If convection is prevented or inhibited, heating rates, f_h, as defined by Ball *(2)*, can be expected to increase. Table 1 gives representative heating rates of some fresh cucumber pickle products. These data are labeled as representative because many factors, such as pickle-to-liquor ratio, have minor effects on the heating rate. These data, published and unpublished, were taken from the authors' file of the heating rates of these various products. A comparison of the heating rates in these products indicates that the greatest effect is due to the presence of sucrose in the covering liquor. Except for the small, whole cucumber pickles, the addition of sucrose syrup has nearly doubled the heating rates. The exception helps to verify the criterion of no convection. The covering liquor instead of 50% sucrose, was 36%, which equation (5) shows requires a larger Δp to prevent convection. Moreover, at the end of the heat processing period, the difference in concentration between top and bottom of the jar was less than 6% (unpublished data). Because product-induced stratification was less extensive than in the other products, the heating rate was not affected by the presence of sucrose in the covering syrup.

TABLE 1

Heating rates, f_h, min, of some fresh cucumber pickle products

Product	Jar size (oz.)	Covering liquor	
		Syrup[1]	Brine
Liquor only	16	12	11
Small, whole	16	18	18
Spear	16	36	21
Spear	28	52	22
Slice	16	33	20
Slice	32	45	24

[1] 50% sucrose except for the small. whole pickles which was 36%.

The heating rates, f_h, of 1% and 5% bentonite suspensions in 16-oz jars are about 11 min and 48 min, respectively *(16)*. It can be assumed from these data that the heating in sweet cucumber products (spears and slices) has not reached a state of pure conduction. There is ample room for speculation as to what is really happening during the heating of syrup-packed products, such as these sweet fresh cucumber pickles. To exhibit a criterion for no convection between specified points is not to say that convection cannot take place between other points. But, as density differences increase due to product-induced stratification, convection will be inhibited as the net force producing convection currents decreases. One possibility is that convection currents, rather than traversing the whole jar as would be expected for a pure convection situation, are restricted to smaller portions of the jar, depending on relative densities.

SUMMARY

This paper presents a method of calculating a criterion of no convection in syrup-packed products and presents evidence to suggest how this criterion is related to the difficulty of heating syrup-packed products in which product-induced stratification has occurred.

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