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HEATING RATES IN GLASS CONTAINERS AS AFFECTED BY HEATING MEDIUM AND PRODUCT

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GIVEN THE AMOUNT of heat necessary to preserve a product, the processing system may be designed to achieve this heat level. Since sterilization or pasteurization of food products is accomplished during non-steady flow of heat into the container and product, generally the problem is one of obtaining maximum temperature in a minimum time at minimum cost. Therefore, detailed knowledge of the heat transfer characteristics of the system is a necessary ingredient of efficient design.

This study treats factors affecting the heat transfer coefficient between heating medium and container. The purpose is to compare several heating media—water spray, steam-air mixtures, water bath, and saturated steam—at temperatures in a range of 165°F. to 225°F. in two sizes of glass containers (pints and quarts) for two primary methods of heating; namely, conduction and convection.

Townsend *et al.* (6) investigated the properties of 1 percent bentonite (convection heating) and 5 percent bentonite (conduction heating) heated in saturated steam and in water at temperatures of 240°F. and 250°F. in various sizes of both tin and glass containers. Their principal objective in this thorough study was the comparison of glass with tin. They found no significant differences between steam and water. They observed appreciably slower heating by convection in glass compared with tin, but a less pronounced difference in conduction heating for all sizes of containers compared.

Powers *et al.* (5) extended the available information on glass to comparisons between convection and conduction heating (also 1 percent and 5 percent bentonite) in both pints and quarts at 212°F. for steam and water. They found no significant differences between the heating media.

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Esselen *et al.* (2) compared water spray and water bath heating (temperatures in the range 170°F. to 185°F.) of whole fresh packed pickles and found that heating rates were essentially the same for these two media.

This study, therefore, covers the uncharted region of steam-air mixtures below 212°F. and compares this heating medium with some already investigated.

EXPERIMENTAL

The simple systems of water and of 5 percent bentonite, representative of convection and conduction heating, were selected as exemplifying the product extremes encountered in food processing. The water was taken from the laboratory tap; the bentonite (1) was made up as 5 percent clay, by weight, of the suspension (Volclay Micron Bentonite, USP Bentonite, American Colloid Company). Temperatures were measured with 24-gauge copper-constantan thermocouples introduced into the top of the jars, through suitable pressure fittings, inside rigid ¼″ plastic rods; temperatures were measured and recorded with a Minneapolis-Honeywell 12-point 1-min. cycle (smallest chart division 1°F.) temperature recording potentiometer. Table 1 gives the technical description of the jars used. When temperatures were measured in bentonite, the thermocouple junction was located at the geometrical center of the jars; when measurements were made in water, the junction was located 1.0 cm. from the bottom of the pint jars and 1.5 cm. from the bottom of the quart jars. These locations are in the vicinity of the slowest heating points in these two jars, as determined from heating rate profiles made at points along the jar axes from top to bottom.

All the jars were started at an initially uniform inside temperature of 95°F.—obtained by allowing the jars to equilibrate in a constant temperature bath prior to testing.

TABLE 1—Data on containers used in study

	Jars	
	Pint	Quart
Capacity (oz.)	16	32
Outside diameter (in.)	3⅛	3¾
Height to finish (in.)	4¼	6½
Overflow capacity (oz)	16½	33
Weight of glass (lb.)	0.45	0.84

Water Bath

The water bath used in these studies was a rectangular, uninsulated steel tank, 24 x 48 x 15 inches; a 12 in. water depth was maintained. It was steam heated by a ¾ in. pipe coil in the bottom of the tank. The temperature in the water bath was controlled by a Taylor Model 87RU417 temperature controller modulating a valve in the steam line. A pressure reducing valve permitted adjustment of the up-stream steam pressure to give optimum control. The water was agitated by a Lightening Model L electric mixer with shaft in a vertical plane; the jars were in general located from 10 to 18 inches from the 2-in. diameter, 3-blade propeller, which was 9 in. below the water surface.

Point-to-point temperature variation in this bath was less than 1.25°F. and the standard deviation of the variation at any one point was about 0.25°F.

Water Spray

The water spray tests were conducted in a loosely closed, vertical, laboratory retort, which was modified for these tests by the addition of an external pump and seven spray nozzles located a few inches below the cover. The bottom 6 in. of the retort served as a reservoir for the temperature controlled recirculated water. The tops of the jars were about 9 in. below the nozzles. It was found that by maintaining the water in the reservoir at about 1.5 to 2.0°F. above the desired spray temperature, the spray temperature could be kept at the desired mean with a variation of about 1.0°F. Point-to-point variation in the spray was no more than 2.0°F.

Saturated Steam

The heating rate of quart jars of water was evaluated at 165, 180, 195, 210 and 225°F. in saturated steam. The laboratory retort previously described was used in these experiments and was equipped with an external condensing chamber, tail pipe and pump plus a gas pump for removing non-condensables. This system had sufficient capacity to maintain a vacuum of 22 in. of mercury in the retort when operating at a low flow rate at 150°F. In heating rate studies, the temperature equilibrated jars were placed in the retort, which was sealed and evacuated prior to turning on the steam. The by-pass around the control valve was opened during the come-up period to reduce come-up time which was less than 1 minute and was neglected in calculating

f_h and j. The point-to-point temperature variation was less than 1.0° F. and the variation at any given point was less than 0.5°F.

Steam-air Mixtures

These tests were of two kinds: first, heating rate studies under conditions comparable to commercial processing in which the pressure was held at 1 atm. for each temperature tested; second, for academic interest, the temperature was held constant while the steam-air ratio of the atmosphere was varied for each test.

In the heating rate studies at 165, 180 and 195°F. and one atmosphere of pressure, the laboratory retort was used with the lid closed but not fastened. The temperatures of the steam-air mixture were measured using a thermocouple sensing element located at the midpoint-of-the-jar level.

Steam, entering through the cross in the bottom of the retort, discharged at right angles to the retort diameter at a 45° angle with the bottom. A steam-air mixture can be described as an atmosphere condition of 100 percent relative humidity, probably with some fogging. The heat capacity of the system is, therefore, small and temperature control difficult.

In the atmospheric pressure studies, the retort was equilibrated at the test temperature before the jars were placed inside. The jars were added quickly to minimize cooling of the retort; only 2 quart or 4 pint jars could be added without upsetting the system. The temperature regulation was poorer than for the water bath, water spray or saturated steam tests. The standard deviation of the temperature at any point was, in the worst case, about 2.1°F., and the point to point variation was sometimes as much as 3.0°F.

The studies, at different steam ratios but the same temperature, were made by using the vapor and air removal system described above, a pressure control system to maintain total pressure and a temperature control system to maintain the temperature. Pressures were measured with a mercury manometer, corrected to barometric pressure. These latter tests bridged the gap between the saturated steam studies and steam-air studies at one atmosphere of pressure.

ANALYSIS

During the tests, the temperature in the jars under study was recorded automatically every minute. After a test was completed, the data from the chart was plotted on semi-logarithmic paper according to the method described by Ball and Olson (1), and the slope of the heating curve (f_h) and the lag factor (j) determined. The integrated lethality (Ball and Olson, (1)) of the heat process, calculated at the heating medium temperature (U_{RT}), was computed for some of the tests. For these calculations, a thermal death time curve slope (z) of 18°F. was assumed.

RESULTS

Comparison of Water Bath and Steam-Air at 165, 180, and 195° F

The data for heating pint and quart jars in a water bath and in a steam-air mixture at atmospheric pressure are presented in Tables 2 and 3. The mean values of the three parameters f_h, j, and U_{RT} are presented for both water and bentonite. These data are the means of four replications. The U_{RT}'s for water were calculated for a process time of 15 and 25 minutes for pints and quart jars, respectively, and for process times of 60 and 80 minutes for pints and quarts of bentonite, respectively.

TABLE 2—Heating characteristics of water (mean values)

Heating medium...		Water bath			Water spray			100% steam			Steam-air		
Parameters.......		j	f_h	U_{RT}	j	f_h	U_{RT}	j	f_h	U_{RT}	j	f_h	U_{RT}
Pints	165°F.	1.21	11.2	2.77	1.46	10.0	2.99	....	....	....	1.36	22.0	0.22
	180°F.	1.22	11.2	2.20	1.42	9.6	2.83	....	....	....	1.50	17.5	0.23
	195°F.	1.30	10.0	2.27	1.22	9.5	2.80	....	....	....	1.64	13.2	0.55
Quarts	165°F.	1.42	15.0	6.63	1.57	13.3	7.51	1.39	12.9	8.54	1.35	29.2	0.96
	180°F.	1.45	14.4	5.79	1.58	12.2	7.63	1.41	12.5	8.01	1.46	23.0	1.42
	195°F.	1.59	12.9	6.13	1.40	11.8	7.65	1.46	11.9	7.65	1.45	17.4	2.87

TABLE 3—Heating characteristics of bentonite (mean values)

Heating medium...		Water bath			Water spray			100% steam			Steam-air		
Parameters.......		j	f_h	U_{RT}	j	f_h	U_{RT}	j	f_h	U_{RT}	j	f_h	U_{RT}
Pints	165°F.	1.98	49.0	4.31	2.01	47.5	....	2.05	46	....	1.85	54.9	3.27
	180°F.	1.94	48.5	3.34	2.12	46.5	....	1.83	47.5	....	1.82	51.2	3.07
	195°F.	1.97	49.0	2.25	1.98	48.2	....	1.82	50.2	....	1.92	50.4	2.09
Quarts	165°F.	1.80	77.2	3.96	1 78	74.0	4.26	1 74	77.5	3.92	1.92	74.1	3.12
	180°F.	1.80	73.8	2.60	1.72	75.8	4.12	1.75	77.2	2.15	1.80	79.4	1.71
	195°F.	1.75	75.9	1.72	1.74	74.8	2.85	1.76	75.5	1.64	1.73	77.5	1.59

The U_{RT}'s were not analyzed because these values are not comparable since the closer the initial temperature is to retort temperature, the higher will be the final temperature at the end of a fixed time (provided j and f_h are not temperature dependent) and, therefore, the higher the U_{RT}. The principal value of U_{RT} comparisons is the fact that this integrated value is the only way to take account of the fact that nearly two-thirds of the bentonite (and about one-fourth of the water) curves were broken (changes of slope of about 12 minutes at about 10°F. below bath temperature for the bentonite). Although U_{RT} comparisons among temperatures cannot be made, comparisons at the same temperature can be made between jars and media.

In both convection and conduction heating products, the container material, wall thickness, and container geometry are contributing factors to the overall heat transfer characteristics. However, the contribution of these factors to the overall heat transfer is quite different for a convection heating product inside the container, as compared with a conduction heating product. In conduction heating, the product itself provides the greatest resistance to heat transfer. Therefore, even quite large changes in wall thickness, for example, do not appreciably change the overall heat transfer coefficient; the heat transfer is product limited. In convection heating, the overall heat transfer is much more sensitive to wall material. (See Townsend, *et al.* (6)., glass vs. tin).

Comparison of 100 Percent Steam and Steam-Air Mixtures

The obvious differences between water and steam-air mixtures at the same temperatures resulted in a more extensive study of the effect of air on the heating rate. A series of tests were conducted in which saturated steam was compared with 75 percent steam-air mixtures (ratio of partial pressures calculated on a perfect gas basis) at several temperatures over the range from 165°F. to 225°F. Table 4 presents the average (two to eight individual readings) heating rates and lag factors. The individual and mean f_h values are illustrated as a function of temperature for saturated steam in Fig. 1.

In Fig. 2, the average f_h values are illustrated as a function of temperature for both the 100 percent and 75 percent steam-air mixtures. Two important conclusions can be made: (1) there is a marked difference between the f_h for saturated steam and for steam-air mix-

TABLE 4—Average lag factor and heating rate of quart jars of water heated in 100 percent steam and a 75 percent steam-air mixture at several temperatures

Temperature °F.	j		f_h	
	75% Steam	100% Steam	75%	100%
165	1.29	1.39	15.6	12.9
180	1.44	1.41	13.9	12.5
195	1.41	1.46	13.0	11.9
210	1.41	1.36	12.4	11.8
225	1.34	1.46	12.5	11.2

tures at all temperatures, and (2) the heat transfer characteristics of steam are a function of temperature in the range studied since an increased rate of heating (smaller f_h) accompanied increases in temperature. Whether this change in f_h with temperature is analogous

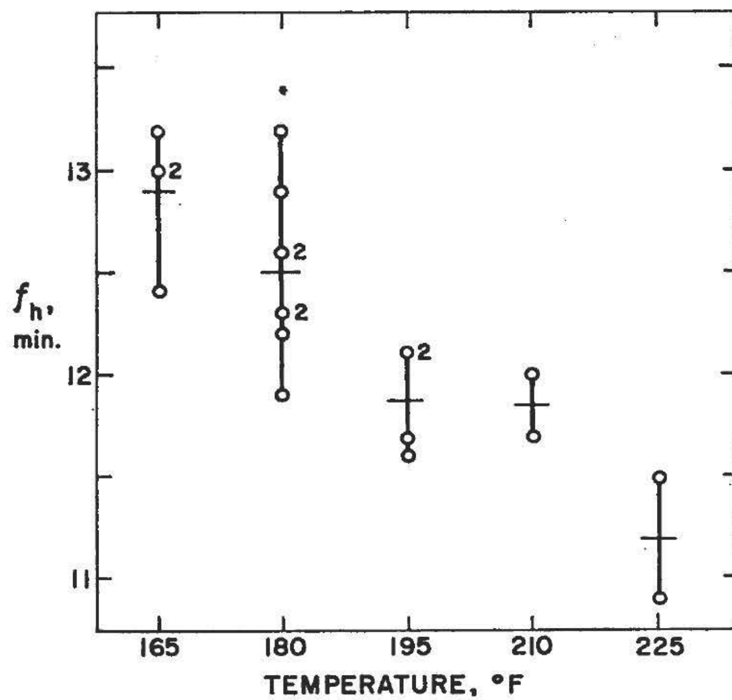

Fig. 1. Slope of the heating curve (f_h) of quart jars of water in saturated steam.

to the variation found by Evans (3) in his study and analysis of conduction heating, in which the decrease in f_h was shown to be a function of temperature according to changes in the thermal diffusivity, cannot be analytically demonstrated. The reason it can't is because there is at present no satisfactory derivation for the slope of the heating curve for convection heating products. One possible explanation may be that since these jars were at the same initial temperature, the larger temperature differentials accompanying the higher processing temperatures provided an opportunity for stronger convection currents.

Figure 3 illustrates the variation in the f_h value of water in steam-

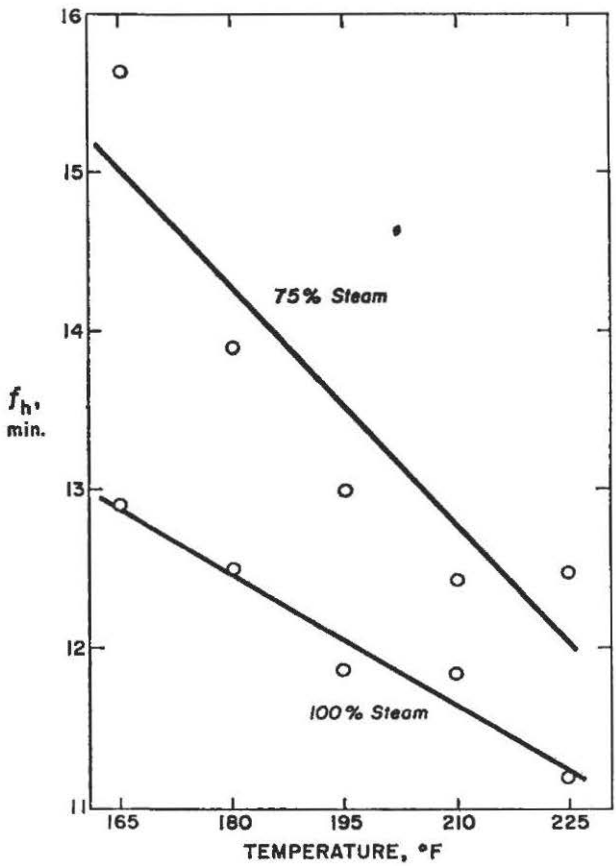

Fig. 2. Average heating rates of quart jars of water.

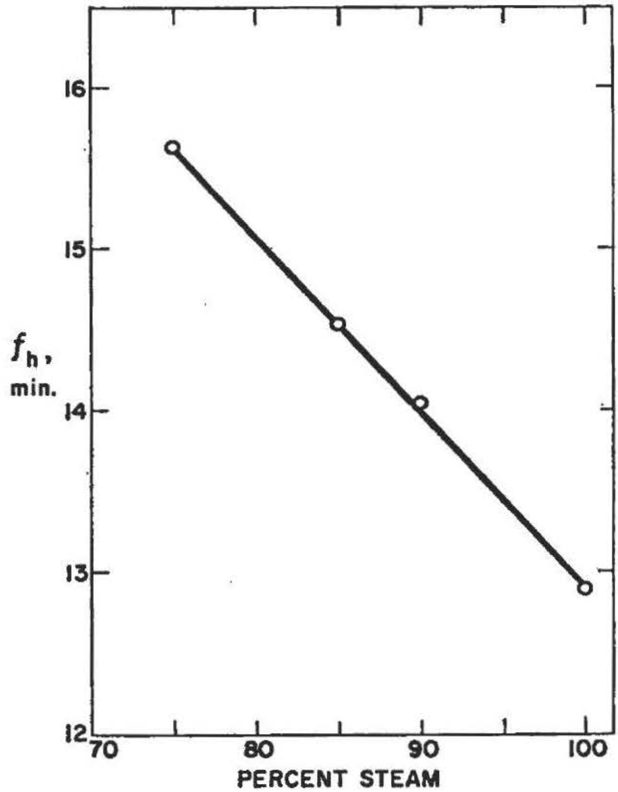

Fig. 3. Heating rate of water in quart jars in 165° F. steam-air mixtures.

air mixtures at 165°F. as a function of the percent of steam present. Each point (only 2 at 75 percent steam) is the average of four determinations.

From this evidence, it can be concluded that the increase in the rate of heating (decrease in f_h) of water, shown in Table 2, is composed of at least two parts—the decrease in f_h with increasing temperature, and the decrease in f_h as the percent of steam increases and approaches 100 percent.

The increase in f_h of jars of water in a steam-air mixture compared to jars of water in steam and the increase in f_h of jars of water with decreased percentages of steam appears to be due to a decrease in the heating medium heat transfer film coefficient that occurs when a vapor condenses in the presence of a non-condensable gas. Kern (4) discusses heat transfer involving condensation of a vapor from a non-condensable gas, as it applies to process heat transfer, and notes that for the condensation of steam from steam-air mixtures in heat exchanges, it is often possible to have a variation in the overall heat transfer coefficient from 1500 B.t.u./(hr)(ft^2)(°F) at the inlet to a value of 15 at the outlet. The decrease in heat transfer rate parallels a decrease in the percentage of steam present which appears to be the same phenomenon that was observed in these experiments.

In general, variations in the lag factor follow the opposite trend of the slope of the heating curve; however, the systematic variation in lag factor, if it exists, is not as large as the variation in f_h, and the data do not in every case verify the conclusion that lag factor is an increasing function of temperature (See Tables 2 and 4). However, it is concluded that both j and f_h for convection heating are either dependent or functions of a common parameter, such that increasing f_{h}'s can be associated with decreasing j's and vice versa.

Comparison of Water Spray With Saturated Steam

Pint and quart jars of both a 5 percent bentonite suspension and water were heated in a water spray at the three temperatures 165, 180, and 195°F. These data are also included in Tables 2 and 3.

Quart jars of bentonite at the three temperatures were compared by an analysis of variance to determine the heating efficiency of water spray vs. saturated steam. The analysis showed a significant difference in the f_h at the 1 percent level, water spray giving a smaller f_h than saturated steam (all temperatures considered together). The difference, although significant, is not appreciable, being 2 minutes for an f_h of about 75 minutes. Since a 5 percent bentonite solution heats primarily by conduction, the difference in the f_h between the heating media is perhaps attributable to the more favorable surface transfer coefficient of a water spray.

Comparisons of the individual and mean heating characteristics of water in pint and quart jars heated in a water spray are illustrated in Fig. 4. Analysis of variance of j and f_h for both pints and quarts reveals a significant difference in the heating rate at the different temperatures for quarts only. The trend for both heating curve parameters (f_h and j), in this particular instance, is a decrease with increasing temperature. The decrease in f_h is in line with the results of all the other experiments, but the decrease in lag factor (j) is not.

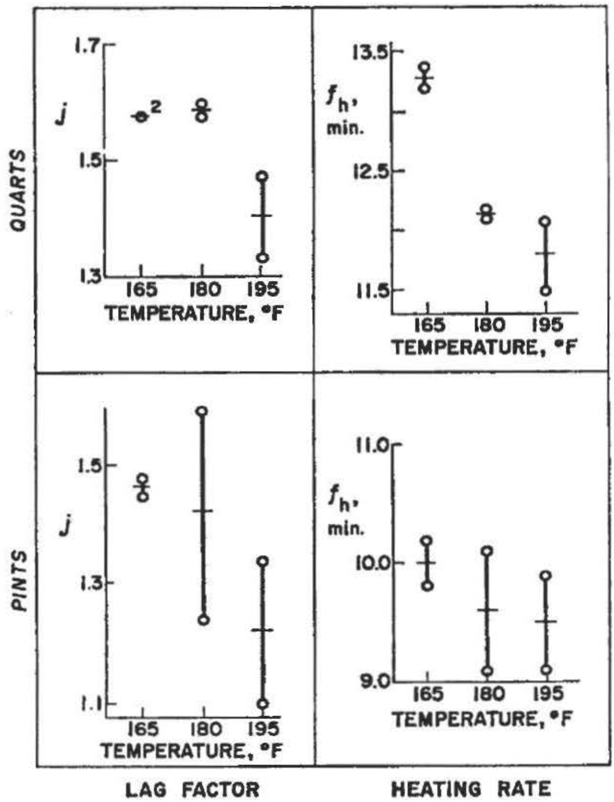

Fig. 4. Heating characteristics of water spray at various temperatures.

Discussion of All Heating Media

A comparison of the f_h of water in quart jars, as a function of temperature, for the four media, is given in Fig. 5. These data are taken from Tables 2 and 4 and Fig. 4. The dramatic change of f_h with temperature in the case of steam can be largely attributed to the change in steam-fraction with temperature. At 150°F., the steam fraction is less than 0.4, and at 180°F., it is about 0.5. These values should be compared with the heating rates in 75 percent steam at the corresponding temperatures (See Fig. 2).

In general, only minor differences among media and at different temperatures are found for bentonite; however, there are striking differences to be found both among media and at different tempera-

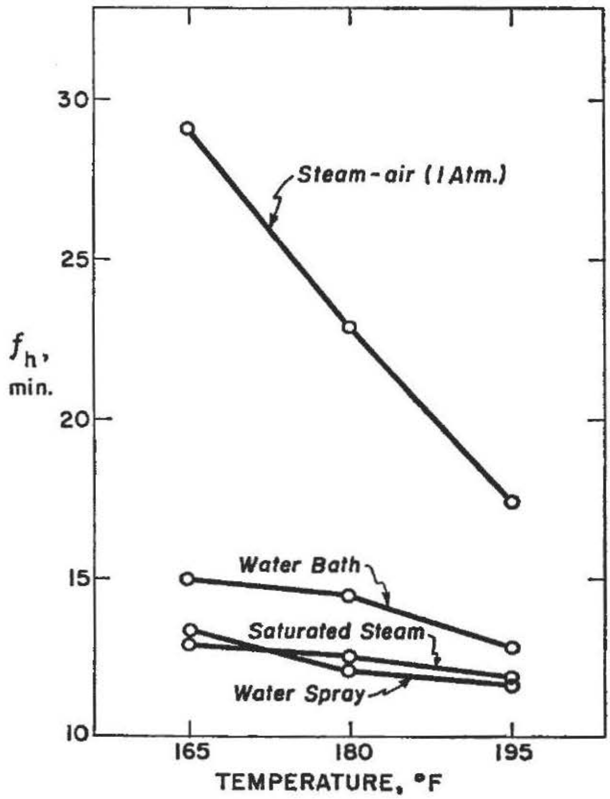

Fig. 5. Average heating rate of water in quart jars as a function of temperature.

tures in the case of convection heating. Presumably these differences in heating characteristics will also apply to liquids more viscous than water and to mixtures of solids and liquids. Some media differences at temperatures above the normal boiling point have already been exhibited.

Further research is indicated, particularly for water bath and water sprays, on the possible influence of spray intensity and agitation index on the heating rate, inasmuch as the rate of heating has been shown to be dependent on the heating medium.

These data should be helpful in explaining any difficulties that have been experienced by processors who converted from water baths to steam-air pasteurizers. If equal process times and temperatures were maintained using the two types of heating medium, then the lower heating rate of convection heating food products in steam-air, at the same temperature, will have delivered correspondingly reduced sterilizing or pasteurizing values, particularly if the temperature is very far removed from 212°F.

SUMMARY

The heating rate (f_h), lag factor (j), and in some cases the integrated sterilizing value U_{RT}, have been evaluated for convection and conduction type of product (water and 5 percent bentonite) for pint and quart glass jars for four heating media. The heating media used were: agitated water bath, water spray, saturated steam, and steam-air mixtures. The results indicate:

1. Steam-air mixtures are less efficient than water bath, water spray, or saturated steam.
2. That steam-air mixtures vary in their efficiency according to the percent of steam present, increasing with increased percentages of steam.
3. The slope of the heating curve (f_h) decreases with increases in temperature over the range studied.
4. That a processor in converting from one heating medium to another, especially if going to a steam-air mixture, must either increase the process time or temperature to obtain the same lethality.

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