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A STUDY OF THE VARIABLES THAT AFFECT HEAT PENETRATION RATES IN GLASS CONTAINERS[1]

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ABSTRACT

Heating rate studies were made using 16-, 26-, 32-, 48-, and 64-oz. glass jars. Jars were filled with water, water plus ⅜-inch, ½-inch, and ¾-inch diameter marbles. These were heated in water and in steam-air mixtures at 165, 180, and 195° F. (initial temperature 95° F.) to determine the effect of: jar size, liquid vs. liquid plus solid particles, particle size, heating medium temperature, and heating medium on the rate of heating of the slowest heating zone in the container. Temperatures were measured using rod-type theromcouples located in the jars' cold zone and recorded using the temperature recording potentiometer. Time vs. temperature data were plotted on semi-log paper and the f- and j-values determined.

Results: A. The f-values correlated very well with the surface area to jar volume ratio. B. The f-value was smaller as the heating medium temperature increased. C. There was no detectable difference in the f-value due to difference in marble size. D. The jars containing water plus marbles had smaller f-values than jars filled with water.

INTRODUCTION

THE HEATING CHARACTERISTICS of convection heating liquid food products and conduction heating solid food products have been studied rather extensively. However, less is known about the heating characteristics of liquid-packed solids such as cherries, pickles, peas, and olives in brine or syrup and how the size and shape of the solids affects the heating characteristic of the liquid in the container. The objectives of this study were to compare, in terms of heating character-

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istics, three sizes of solids represented by glass marbles in a water model system. The effect of the marble size was evaluated in five different sizes of glass containers when heated in a water bath and in a steam-air mixture at three different temperatures, 165°, 180°, and 195°F.

EXPERIMENTAL PROCEDURE

Container Preparation

The five sizes of containers, range from 16- to 64-oz. capacity. The specifications of the glass containers are shown in Table 1.

TABLE 1—Jar specifications

Nominal size, oz.	16	26	32	48	64
Manufacturer	Brockway	Brockway	Hazel Atlas	Brockway	Brockway
Manufacturers Code	1844	2614	6770-4-X	2613-A	2388
Weight of empty jar, oz	7.16	11.66	13.98	19.85	22.96
Overflow capacity, oz	15.99	27.87	32.37	49.81	66.24
Height, in	4.75	5.00	7.12	7.25	8.38
Maximum diameter, in	3.12	4.00	3.69	4.62	4.75

Glass marbles ⅜-inch, ½-inch, and ¾-inch, in diameter were used as the food particle models. Marble fill data are shown in Table 2.

TABLE 2—Marble fill data

Jar capacity oz.	Contents per jar	Water only	Water plus small marbles	Water plus medium marbles	Water plus large marbles
16	Weight of water, gms	443.9	171	194	212
	Weight of marbles, gms	...	629	593	570
	Number of marbles	...	535	217	74
26	Weight of water, gms	779.4	312	333	376
	Weight of marbles, gms	...	1,096.4	1,064.4	981.4
	Number of marbles	...	932	389	128
32	Weight of water, gms	863.5	327.0	...	395
	Weight of marbles, gms	...	1,256.5	...	1,158.5
	Number of marbles	...	1,068	...	151
48	Weight of water, gms	1,343.0	539	542	599
	Weight of marbles, gms	...	1,931	1,909	1,801
	Number of marbles	...	1,642	698	235
64	Weight of water, gms	1,826.1	696	749	787
	Weight of marbles, gms	...	2,696.1	2,575.1	2,492.6
	Number of marbles	...	2,293	942	351

Preparing the Temperature Sensing Elements

Temperatures were measured using rod-type thermocouples similar to those described by Pflug and Nicholas (4). The thermocouples were inserted into the jars through Ecklund packing glands. Multipoint thermocouple rods similar to those described in (7) were used to determine the cold point in the containers. In this study the thermocouple junction was located 1/10 of the liquid height above the bottom of the jar, a location near the cold point for liquids in glass jars as found by Pflug and Nicholas (6). The temperatures were measured using a 12-point temperature-recording potentiometer. Temperatures read using the thermocouple system were checked at regular intervals against thermocouples located adjacent to mercury in glass thermometers.

Heating Media

Water Bath: A rectangular, uninsulated steel tank 24 x 48 x 18-inches equipped with an automatic controller was used as a water bath (4).

Steam-Air Mixture: The desired steam-air mixture was developed inside a laboratory retort in which the pressure was maintained at one atmosphere by a vent pipe and leaving the lid of the retort open approximately ¼-inch.

The temperature in the retort was automatically controlled. The retort was equipped with a baffle arranged so that the steam did not impinge directly on the containers being evaluated and so that the steam flow would eliminate as much as possible any air pockets within the retort. The steam-air mixture was maintained by positive air flow, which moved into the retort through a rotameter. A hand valve was used to modulate the air flow to the retort. The air and steam lines joined outside the retort so that the gas was mixed prior to flowing into the retort. The temperature within the retort was kept within $\pm 2°$ F. of the desired temperature.

The flow rate of the steam-air mixture through the retort was the same at all three temperatures and was maintained in this dynamic condition by varying the air flow setting of the rotameter for each temperature condition. The air flow rate calculation was based on the assumption that there was no heat loss from the system. This was necessary since the partial pressure of the water vapor in the retort varied with temperature. Gas flow rate calculations are shown in Table 3.

TABLE 3—Air flow rate calculation

Temperature °F.	Steam pressure mm. Hg.	Air pressure mm. Hg.	Steam plus air pressure mm. Hg.	Air flow c. f. m.
165°F.	274	486	760	12.80
180°F.	388	372	760	9.80
195°F.	538	222	760	5.83

Two jars were evaluated at a time; they were first equilibrated at 95° F. and at zero time were placed in the heating medium. The tests ended when the temperatures at the cold point in the jars were within 2° F. of the heating medium temperature. Six to 12 replications were carried out at each condition.

The rate of heating of containers is a function of not only the fluid in the container and particles, but also of the external heat transfer coefficient. To measure the external heat transfer coefficient, copper and aluminum transducers described by Blaisdell (2) were used. The heating rates of both the copper and aluminum transducers were measured under the several heating conditions.

Evaluation of the Data

The time-temperature data for each heating condition were plotted according to the method described by Ball and Olson (1) and the f- and j-values of the straight line portion of the heating curve determined. To evaluate the effect of the three different sizes of marbles, a statistical analysis was carried out on the f-values of the three sizes of marbles.

RESULTS

The overall effect of jar size, heating medium, and the presence or absence of marbles in the jars are summarized in Tables 4 and 5. The average j-value for all tests was 1.36. The effects of marble size on the heating rate are summarized in Table 6. The surface conductance of the two heating media as measured by the copper and aluminum transducers is given in Table 7. The heating data for the three sizes of marbles were analyzed statistically and the results are tabulated in Table 8.

TABLE 4—Summary of the heating rate results in terms of f-values for the several conditions

Jar capacity oz.	Fill	Heating medium	Heating medium temperatures: 165°F. f	165°F. SD(a)	165°F. No.(b)	180°F. f	180°F. SD(a)	180°F. No.(b)	195°F. f	195°F. SD(a)	195°F. No.(b)
16	Water......	Water bath....	12.12	.263	12	11.56	.468	12	10.85	.192	12
		Steam and air .	13.22	.420	6	11.20	.178	6	10.07	.260	6
	Water and marbles	Water bath....	10.52	.444	25	9.41	.390	30	8.85	.309	30
		Steam and air .	11.59	.665	6	9.87	.515	5	9.07	.747	6
26	Water......	Water bath....	15.86	.335	9	14.80	.482	12	14.19	.421	10
		Steam and air .	16.36	.623	4	13.59	.440	6	12.99	.311	6
	Water and marbles	Water bath....	13.25	.397	34	11.55	.334	34	10.91	.296	30
		Steam and air .	13.37	.619	12	11.41	.321	18	9.97	.426	15
32	Water and marbles	Water bath....	13.99	.993	11	12.02	.566	12	11.26	.474	12
		Steam and air .	13.51	.676	12	12.15	.355	12	9.99	.244	11
48	Water......	Water bath....	23.85	.405	8	20.95	.501	12	19.57	.430	12
		Steam and air .	23.12	.552	6	19.55	.570	5	17.03	.252	6
	Water and marbles	Water bath....	17.97	.513	17	16.33	.416	17	15.59	.390	17
		Steam and air .	19.04	.554	6	16.07	.625	6	13.41	.100	6
64	Water......	Water bath....	23.62	.294	9	20.67	.370	12	19.84	.24	12
		Steam and air .	22.64	.700	4	19.95	.552	6	17.23	.421	6
	Water and marbles	Water bath....	18.24	.501	14	16.46	.348	18	15.82	.501	18
		Steam and air .	18.89	.273	4	16.63	.451	6	14.36	.111	6

(a) Standard deviation.
(b) Number of tests conducted.

TABLE 5—Summary of the heating rate results in terms of the heating curve lag factor j

Jar capacity oz.	Fill	Heating medium	Heating medium temperatures					
			165° F.		180° F.		195° F.	
			f	SD(a)	f	SD(a)	f	SD(a)
16	Water	Water bath	1.37	.087	1.28	.139	1.36	.069
		Steam and air	1.39	.100	1.41	.070	1.54	.205
	Water and marbles	Water bath	1.34	.124	1.34	.124	1.38	.140
		Steam and air	1.24	.062	1.54	.130	1.29	.130
26	Water	Water bath	1.36	.104	1.32	.092	1.28	.098
		Steam and air	1.37	.151	1.43	.179	1.38	.183
	Water and marbles	Water bath	1.25	.104	1.35	.102	1.34	.089
		Steam and air	1.35	.264	1.46	.171	1.36	.170
32	Water and marbles	Water bath	1.36	.089	1.46	.150	1.48	.133
		Steam and air	1.44	.131	1.46	.150	1.49	.137
48	Water	Water bath	1.24	.113	1.28	.060	1.35	.067
		Steam and air	1.29	.117	1.44	.049	1.43	.063
	Water and marbles	Water bath	1.26	.069	1.33	.104	1.30	.116
		Steam and air	1.29	.117	1.44	.049	1.43	.063
64	Water	Water bath	1.14	.074	1.30	.114	1.29	.090
		Steam and air	1.32	.037	1.29	.036	1.53	.205
	Water and marbles	Water bath	1.24	.114	1.31	.098	1.30	.075
		Steam and air	1.36	.154	1.28	.054	1.36	.067

(a) Standard deviation.

DISCUSSION OF RESULTS

Results were analyzed and will be discussed in terms of heating rate or f-value.

Effect of Heating Medium and Heating Medium Temperature

An analysis of the heating medium data in Table 4 shows that, in all instances, as the heating medium temperature increased, the f-value decreased. Tests conducted by Pflug and Nicholas (6) showed this same relationship between f-value and heating medium temperature. Pflug and Nicholas considered the possibility that the larger temperature differentials accompanying the higher processing temperatures produced stronger convection currents responsible for the difference in the heating rate. The data developed in this study verify this observation.

The f-value ratios, ([f in steam-air]/[f in water]) in Table 9 and Figs. 1, 2, and 3 were prepared to aid in comparing the relative heating rates of water and steam-air mixtures. In general, differences are small and only trends can be pointed out.

The effect of the heating medium temperature on the f-value for 16-oz. jars is shown in Fig. 1; 26-oz. jars, Fig. 2; and 48- and 64-oz. jars, Fig. 3. In these figures the relative change in f-value with heating medium type and temperature is evident. In general, the f-value of jars heated in steam-air decreases more with the increase in temperature than the f-value for jars heated in water baths. There may be significance in the fact that the 16-oz. jar of marbles, the smallest jar with the lowest heat capacity, and the 48- and 64-oz. jars of water, the largest jars with the greatest heat capacity, behave differently from the rest of the group.

The results of surface conductance measurements (Table 7) are reflected in the data in Figs. 1, 2, and 3. At 195° F., the h for steam-air f_2 curve is larger than the h for the f_1 curve, the reverse of the water bath results. These data suggest that the steam-air may be more effective at the higher temperature. In general, the results confirm this. The trend (Table 9) is for the steam-air to become more effective as the heating medium temperature goes from 165° to 180° to 195° F.

The f-values ratios for the two heating media appear roughly to

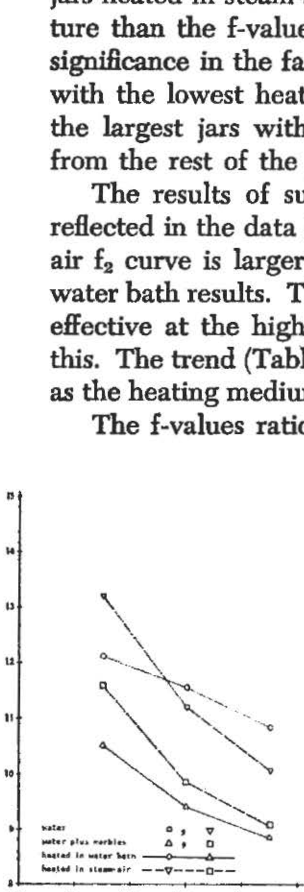

Fig. 1. The relation of f-value and heating medium temperature for 16-ounce jars heated in a non-agitated water bath and in steam-air mixtures.

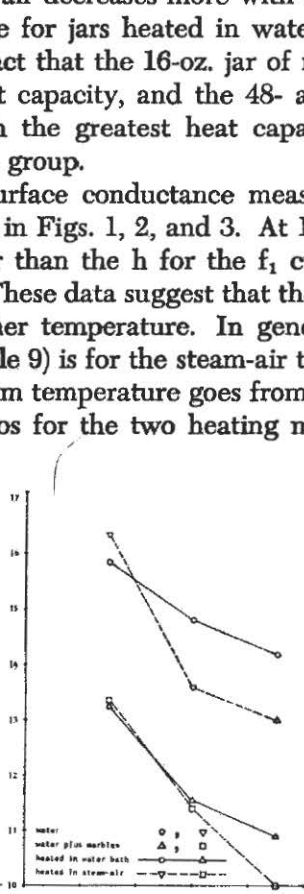

Fig. 2. The relation of f-value and heating medium temperature for 26-ounce jars heated in a non-agitated water bath and in steam-air mixtures.

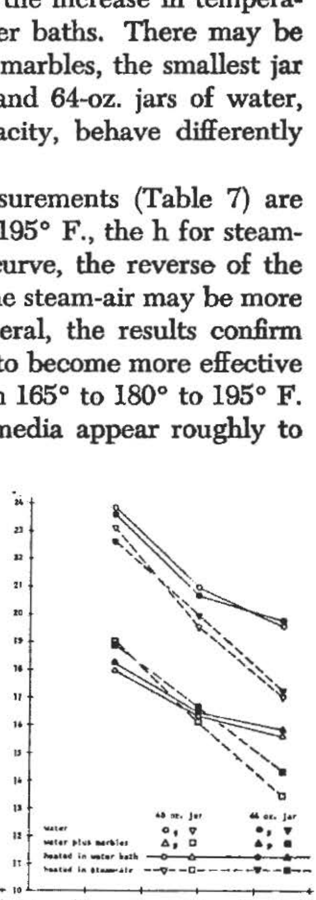

Fig. 3. The relation of f-value and heating medium temperature for 48- and 64-ounce jars heated in a non-agitated water bath and in steam-air mixtures.

group themselves by jar surface-to-volume ratios; at lower surface-to-volume ratios, 0.49 compared to 0.62 or 0.66, the f-value heating medium ratio for water in jars appears to be smaller, whereas for water plus marbles the difference is less pronounced or there is no difference. For both water and water plus marbles there appears to be a decrease in the f-value ratio as temperature increases, which suggests that the relative effect of the surface film of water vs. steam plus air, changes with heating medium temperature.

Steam plus air becomes relatively more effective, f is smaller, as temperature increases from 165 to 195° F. Comparing the h values at 165° and 195° F. we find that the h_1 ratios are 0.38 (56/147) and

TABLE 6—Rearrangement of the f-value data to make possible comparison of the f-values for the three sizes of marbles

Jar capacity	oz.	Heating medium temperature °F.	Marble size: Small f min.	Small No.(a)	Medium f min.	Medium No.(a)	Large f min.	Large No.(a)
	16	165	10.45	11	10.53	10	10.67	4
		180	9.31	12	9.39	12	9.64	6
		195	8.72	12	8.80	12	9.24	6
	26	165	13.37	12	12.89	11	13.49	11
		180	11.74	12	11.33	12	11.57	10
		195	10.74	12	10.94	12	11.17	6
Water bath	32	165	14.05	6			13.94	5
		180	12.24	6			11.79	6
		195	11.31	6			11.22	6
	48	165	18.00	6	18.02	6	17.88	5
		180	16.34	6	16.25	6	16.41	5
		195	15.74	6	15.54	5	15.47	6
	64	165	18.22	4	18.49	4	18.09	6
		180	16.45	6	16.40	6	16.54	6
		195	15.87	6	15.74	6	15.85	6
	26	165	13.48	4	13.43	4	13.20	4
		180	11.35	6	11.37	6	11.50	6
Steam plus air		195	9.92	5	10.17	4	9.87	6
	32	165	14.05	6			12.97	6
		180	12.22	6			12.08	6
		195	10.19	5			9.82	6

(a) Number of tests conducted.

TABLE 7—Average surface conductance of the transducers in the two heating media at the three temperatures. (These data are the averages of surface conductances determined using the copper and the aluminum cylinders in the heating medium at the respective temperatures; the heating curves were broken, the first f value (f_1) and the second f value (f_2) were treated separately to yield the respective h values.)

Temperature °F.	Water bath		Steam plus air	
	h_1 for f_1	h_2 for f_2	h_1 for f_1	h_2 for f_2
165	147	128	56	66
180	168	150	72	93
195	189	167	143	192

0.76 (143/189) and the h_2 ratios are 0.52 (66/128) and 1.15 (192/167), respectively. This h ratio comparison would seem to explain the change in f ratio. This result suggests that the rate of heating of water in jars is more dependent on the heat transfer coefficient than the rate of heating of water plus marbles; this is true even though the f-value of water plus marbles is smaller than the f-value of water. (The relative heat capacity of the jar of water is sufficiently larger than the heat capacity of the jar of water plus marbles to make this possible.) It follows that in jars of water plus marbles, flow resistance within the jar is probably the limiting factor as far as rate of heating is concerned.

Results of these experiments appear to fit into the overall pattern of steam-air heating. Pflug and Nicholas (6), using a nonflow relatively quiescent steam-air heating system, found that steam-air mixtures at very low velocity were not as efficient as a water bath in cases when the external film coefficient had a controlling influence. Pflug and Blaisdell (5) established that the effectiveness of steam-air mixtures varies directly with velocity, that at the low velocities used by Pflug and Nicholas (6) steam-air mixtures can be very ineffective, but at higher velocities the differences between steam-air mixtures and water are small.

The experiments in this project were carried out under controlled steam-air velocity conditions selected to approximate commercial flow conditions. Obviously under the steam-air flow conditions evaluated the steam-air was in general less effective than water at 165° and more effective than water at 195°F.

Water vs. Water Plus Marbles

The effect of water vs. water plus marbles is shown graphically in Figs. 4 and 5 where regardless of heating medium or fill ratio the f-values are smaller for the water plus marbles than for the water. Rephrasing in terms of heating rates: the jars containing water plus marbles heat more rapidly than jars of water.

In jars of water plus marbles the heat capacity of the system is smaller than for water alone due to the relative difference of density x specific heat of glass, (150 lb./ft.^{3} x 0.18 BTU/lb. °F. = 27) compared with water, (62.4 lb./ft.^{3} x 1.0 BTU/lb. °F. = 62.4). The solid glass marble heats by conduction. Therefore not only is the final heat capacity of the system reduced 56.7 percent for that part of the volume replaced by glass, but the glass portion of the system will absorb heat at a lower rate than the water portion (the temperature of the glass will lag the temperature of the water). Since the surface area of the jar remains constant, we are theoretically increasing the surface-to-

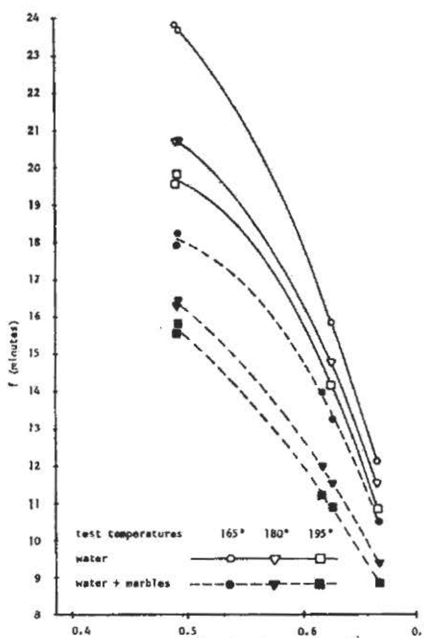

Fig. 4. The relation of f-value and surface-to-volume ratio for jars heated in steam-air mixtures.

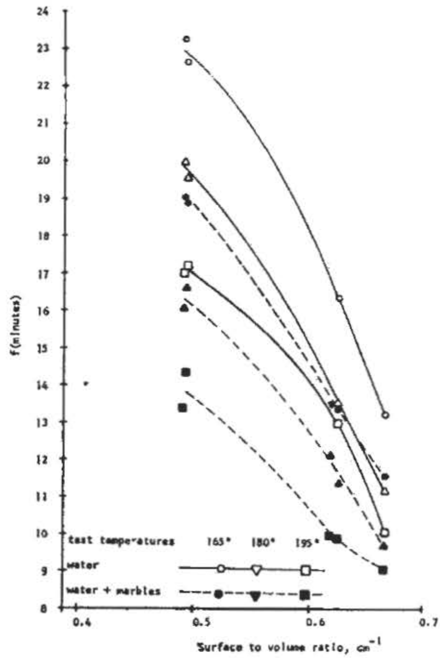

Fig. 5. The relation of f-value and surface-to-volume ratio for jars heated in a non-agitated water bath.

volume ratio, which produces faster heating (smaller f-values). Obviously we are not reducing the f-value linearly as we theoretically increase the surface-to-liquid volume ratio.

In the jar of water plus marbles, the water will be flowing through a series of small channels (spaces between the marbles). Therefore the resistance to flow will be higher than in jars of water. The velocity of the convection fluid flow will be a function of the flow resistance or friction drag; consequently heating should be faster in a water-filled jar than in a jar with water plus marbles.

In the convection heating system, the convection flow driving force, temperature difference, which is a function of the heat transfer rate to the jar, is going to be about the same for jars of water plus marbles as for jars of water since water contact surface area will be only slightly reduced by the point contact of the marbles with the jar. The result is probably that there is sufficiently more convective flow pressure in jars with water plus marbles to overcome the increased friction. If the size of marble is reduced to a point where the friction becomes quite large the result would be slower heating.

It can be concluded that since spherical particles do not block the flow when heating the liquid mass and since they make only point contact, the addition of particles in the range of ⅜- and ¾-inch diameter to a liquid system should not appreciably affect the rate of heating. If the particles are large and have flat sides that can prevent liquid wall contact in a significant surface area, the heating rate will be reduced. For example, cucumber spears in brine in 26-oz. jars where the cut product surface is flat against the container wall we find average f-values of 22.0 to 24.7 minutes (4).

Effect of Jar Size

In Figs. 4 and 5 the f-value data from Table 4 are shown as a function of the surface-to-volume ratios. The rate of heating increased consistently (f-value decreased) as the surface-to-volume ratio increased. Nicholas and Pflug (3) showed that correlation of heating rates with surface-to-volume ratios are more meaningful than correlation of heating rates with jar capacity. The rather good agreement of different sized containers with similar surface-to-volume ratios in Figs. 4 and 5 (for example, the 48- and 64-oz. jars have similar surface-to-volume ratios, 0.49, and have similar f-values when the type of fill and heating medium are the same) suggest that the heating rates of water or water plus marbles in jars with other surface-to-volume ratios can be predicted if in the same overall range of conditions.

Effect of Marble Size

The effect of marble size is shown in Table 6. A statistical analysis was made to determine if the differences in Table 6 were significant; the results of the statistical analysis are shown in Table 8. It was found that the f-value deviation of replicate runs was greater than the difference in f-value due to marble size variation for 16 of the 21 comparisons.

It can be shown that ¾-inch marbles heat about ¼ as fast as ⅜-inch marbles. Therefore jars of water plus the ¾-inch marbles should heat faster because the rate of heat removal is smaller plus the fact that the flow path in the ⅜-inch marbles should have a higher resistance. Since in these experiments there appear to be no major differences in the rate of heating of the jars with either large (¾-inch) or small

TABLE 8—Results of the statistical analysis of the f-value data for jars containing marbles

Jar capacity		Heating temperature range (°F.)	F-value	Level of significance
	16	95-165	1.289	None
	16	95-180	3.092	None
	16	95-195	19.992	99%
	26	95-165	7.214	99%
	26	95-180	6.247	99%
	26	95-195	14.591	99%
	48	95-165	.118	None
Water bath	48	95-180	.336	None
	48	95-195	.693	None
	64	95-165	2.056	None
	64	95-180	.119	None
	64	95-195	.254	None
	32	95-165	.982(*a*)	None
	32	95-180	3.221(*a*)	None
	32	95-195	.934(*a*)	None
	26	95-165	.358	None
	26	95-180	.369	None
	26	95-195	.940	None
Steam-air	32	95-165	8.200(*a*)	99%
	32	95-180	1.129(*a*)	None
	32	95-195	1.001(*a*)	None

(*a*) t-values.

(⅜-inch) marbles, it must be concluded that neither of these effects are significant in this range of conditions. Decreasing the size of marbles to ¼- or $\frac{3}{16}$-inch might change the results dramatically.

TABLE 9—Calculated ratios, f-value (steam plus air) / f-value (water), and ratios of surface area to volume for the five jar sizes

Jar capacity oz.		Surface-to-volume ratio cm⁻¹	f value (steam plus air)/f value (water)		
			165°F.	180°F.	195°F.
	16	.66	1.091	.969	.928
	26	.62	1.032	.918	.915
Water	32	.62	.....	....	.....
	48	.49	.969	.933	.870
	64	.49	.958	.965	.868
	16	.66	1.102	1.049	1.025
	26	.62	1.009	.988	.914
Water plus marbles	32	.62	.966	1.011	.887
	48	.49	1.060	.984	.860
	64	.49	1.036	1.010	.908

It can be concluded that the effect of the size of particle over the range tested in this experiment does not produce significant change in f. These data should not be extrapolated to smaller sizes or other shapes because there is certainly a critical particle size that has a significant effect on heating rate.

CONCLUSIONS

The following conclusions can be drawn with respect to heating 16- to 64-oz. jars in a water or steam-air from 95 to 165°, 95 to 180°, or 95 to 195°F.

1. The f-values correlate well with surface-to-volume ratios rather than jar size; the f-values decrease with increasing surface-to-volume ratio.
2. As the heating medium temperature increases, the f-value decreases.
3. No difference in the f-value was detected due to differences in the size of the marbles.
4. Jars with water plus marbles heat faster than jars of water, (smaller f-values).
5. Water was in general more efficient at 165° F. with steam-air being more more efficient at 195° F. at the flow rates studied.

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