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A STUDY OF THE VARIABLES THAT AFFECT HEAT PENETRATION RATES IN GLASS JARS

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

Edward Daniel Schmidt

1965

THESIS

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ABSTRACT

A STUDY OF THE VARIABLES THAT AFFECT HEAT PENETRATION RATES IN GLASS JARS

by Edward D. Schmidt

Heating rate tests were conducted using 16, 26, 32, 48 and 64 ounce glass jars filled with water plus small (3/8" diameter), medium (1/2" diameter) and large (3/4" diameter) size marbles heated in water and in steam plus air mixtures at heating medium temperatures of 165°F, 180°F 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 heating rate of the slowest heating zone in the container. Temperatures were measured using thermocouples located in the jars and recorded using a temperature recording potentiometer. The time vs. temperature data were plotted on semilog paper and f and j values determined.

It was found that: (1) the heating rates were independent of jar size and dependent upon the ratio of the surface area of the jar to the volume of the jar, (2) there was no detectable difference in heating rate due to differences in marble size, (3) the jars containing water plus marbles heated faster than the jars of water, (4) the jars heated faster as the heating medium temperature increased, and (5) the jars heated faster in the water bath at 165°F but faster in the steam air mixtures at 195°F.

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Date Nov 22 1965

A STUDY OF THE VARIABLES THAT AFFECT HEAT PENETRATION RATES IN GLASS JARS

By

Edward Daniel Schmidt

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INTRODUCTION

In the food industry the general practice when designing a heat process is to measure the rate of heating of the product in the container under the actual commercial heat processing conditions. The slowest heating container is customarily used for the heat process design. While this method of measuring and designing the thermal process is ideal there are certain situations where this is not possible. Under these conditions the data for a similar product, container and heating conditions are used for process design. The precision of the judgements depends on the general knowledge of the heating process, the more knowledge there is available the better will be heat processing judgement.

There is a great deal known about the heating of liquid and solid type food products, however relatively little is known about particulate foods. This study was directed toward obtaining data relating thermal process variables of particulate foods in a model type study. The specific objectives were to determine the effect of three sizes of glass marbles in a water marble system, in five sizes of glass containers when heated in a water bath and in steam-air mixtures at 165°, 180° and 195°F.

LITERATURE REVIEW

Ball and Olson (1957) outlined the procedure for making heat penetration tests. A discussion of their recommendations follows. Thermocouples were recommended for measuring temperatures, copper constantan being satisfactory for the temperature range from 40 to 325°F. The optimum size thermocouple is 20 - 26 gage, a heavier wire will tend to conduct heat from the hot junction causing erroneous temperature readings. Thermocouples should be held in cans by receptacles that do not project into the sides of the cans. For a glass jar, the jar cover is punctured in the center to receive the thermocouple assembly. Thermocouples should be connected to a potentiometer for measuring temperatures obtained. Enough thermocouples should be used to provide a complete cycle of readings every 2 or 3 minutes, depending upon the product being tested.

That the data be collected and plotted on semi-logarithmic paper and heat penetration data be evaluated using f and j factors was recommended by Ball and Olson (1957). The rate of heat penetration is affected by the temperature gradient between container and heating medium; the rate becomes slower as the temperature difference decreases with the product temperature asymptotically approaching the retort temperatures (Herson and Hulland, 1963).

The vicinity of the slowest heating point in jars was located by Pflug and Nicholas (1961) and was found to be 10% of the height of fill measuring from the bottom of the jars. Pflug, Blaisdell and Nicholas (1965), working with 16 ounce jars packed with fresh cucumber pickles, found that the slowest heating zone was near the geometric center in the case of conduction heating spears in 50° Brix syrup but moved toward the bottom of the jar for spears and slices in a 30° Brix syrup.

The volume of headspace of a container is important and some provision is usually made for positive control. (Joslyn and Heid, 1963). The container fill requirement under the U. S. Food and Drug Act for products with Standard of Identity and the general requirement by the U. S. D. A. - A. M. S. is 90% of the total capacity.

Blaisdell (1963) used copper and aluminum cylinders as transducers to determine the surface conductance coefficients of water and steam plus air mixtures; the determinations of the film coefficients (h) were made by relating the film coefficients to the basic conduction heat transfer equations.

Varying the heating medium temperatures, Pflug and Nicholas (1961) found that the slope of the heating curves decreases with an increase in heating medium temperature. Pflug and Blaisdell (1961) list the factors which may contribute to the increase rate of heating as: (1) the increase in thermal diffusity and decrease in viscosity of the water with an increase in heating medium temperature, affecting both the water inside and outside the jar, (2) the increase in the convective flow inside the jar produced by the initially larger temperature difference and (3) an increase in the convection heat transfer coefficient with an increase in steam air temperature.

Pflug and Nicholas (1961) found that (1) a steam plus air mixture at zero velocity is a less efficient heating medium than a water bath, water spray or saturated steam when heating glass containers and (2) steam plus air mixtures vary in efficiency according to the percent of steam present, increasing with increasing percentages of steam. Investigating the effect of velocity of steam plus air mixtures, Pflug and Blaisdell (1961) found that with an increased velocity, faster heating occurred.

Mixtures of steam plus air have been used commercially in processing glass containers in retorts, but during the past twenty years this has lost favor completely because of its uncontrollability in retorts of commercial size (Hersom and Hulland, 1963).

The use of surface to volume ratios to predict the f parameter was suggested by Nicholas and Pflug (1961). An increase in fill ratio (ratio of product weight to fluid ounce capacity) and reduced surface to volume ratio caused nearly significant increases in j, but decreases in f (Pflug, Blaisdell and Nicholas, 1965).

Blaisdell (1963) listed the following causes for variation in f and j. (1) the introduction of container capacitance causing an increase in f and j, (2) an increase in surface resistance producing an increase in f but reduction in j, and (3) an increase in f and decrease in j due to thermocouple capacitance.

The heating characteristics of two different size and shaped cucumber products, spears and slices, were studied by Pflug, Blaisdell and Nicholas (1965) and they found that at the slowest heating zone the cucumber received significantly lower lethality values. Hersom and Hulland (1963) postulate that any substance which retards convection currents decreases heat transfer. In liquids, heat transfer takes place primarily by convection. According to Hersom and Hulland (1963), with solids packed in liquids, the ratio of solids to liquids will effect the heating rate. The presence of channels which permit convection currents facilitates the transfer of heat.

EXPERIMENTAL PROCEDURE

Container Preparation

Five sizes of glass containers were evaluated in this series of experiments. These sizes selected are in common use in the food industry and represent a range of sizes that must be dealt with in processing a number of different types of food products.

Jar specifications are shown in Table 1. The data in Table 1 includes specifications interpreted from the manufacturers code stamped on the bottoms of the jars.

To simulate the effect of particles on the rate of heating of water in glass containers, the five sizes of jars in Table 1 were filled with three sizes of marbles; small (3/8" diameter), medium (1/2" diameter), and large size marbles (3/4" diameter). In Table 2 are shown data for the weight of marbles and water in the different size jars; in Table 3 are shown marble specifications and in Table 4 are shown the number of marbles per jar for each of the three sizes of marbles.

TABLE 1

Jar Specifications

	Nominal Size				
	16 oz.	26 oz.	32 oz.	48 oz.	64 oz.
Manufacturer	Brockway	Brockway	Hazel Atlas	Brockway	Brockway
Manufacturers Code	1344	2614	6770-4-X	2613-A	2388
Weight of Empty Jar	7.16 oz.	11.66 oz.	13.95 oz.	19.85 oz.	22.96 oz.
Overflow Capacity	15.99 oz.	27.87 oz.	32.37 oz.	49.31 oz.	66.24 oz.
Height	4.75 in.	5.00 in.	7.125 in.	7.250 in.	8.375 in.
Maximum Diameter	3.125 in.	4.00 in.	3.688 in.	4.625 in.	4.750 in.

TABLE 2

Marble Fill Data

Jar Size		Small Marbles	Medium Marbles	Large Marbles
16 oz.	Wt. of marbles	629 gms.	593 gms.	570 gms.
	Wt. of water	171 gms.	194 gms.	212 gms.
	Totals	800 gms.	787 gms.	782 gms.
	Wt. filled with water	443.9 gms.		
26 oz.	Wt. of marbles	1096.4 gms.	1064.4 gms.	981.4 gms.
	Wt. of water	312.0 gms.	333.0 gms.	376.0 gms.
	Totals	1408.4 gms.	1397.4 gms.	1357.4 gms.
	Wt. filled with water	779.4 gms.		
32 oz.	Wt. of marbles	1256.5	- - - -	1158.5 gms.
	Wt. of water	327.0	- - - -	395.0 gms.
	Totals	1583.5	- - - -	1553.5 gms.
	Wt. filled with water	863.5 gms.		
48 oz.	Wt. of marbles	1931.0 gms.	1909.0 gms.	1801.0 gms.
	Wt. of water	539.0 gms.	542.0 gms.	599.0 gms.
	Totals	2470.0 gms.	2451.0 gms.	2400.0 gms.
	Wt. filled with water	1343.0 gms.		
64 oz.	Wt. of marbles	2696.1 gms.	2575.1 gms.	2492.6 gms.
	Wt. of water	696.0 gms.	749.0 gms.	787.0 gms.
	Totals	3392.1 gms.	3324.1 gms.	3279.6 gms.
	Wt. filled with water	1826.1 gms.		

TABLE 3

Marble Specifications

	Average Max. Diam. in.	mm.	Avg. Wt.	Avg. Density
Large Marble	.723	18.36	7.68 gms.	2.396 gm/cc
Medium Marble	.505	12.83	2.73 gms.	2.472 gm/cc
Small Marble	.388	9.86	1.18 gms.	2.356 gm/cc

TABLE 4

Number of Marbles Per Jar

JAR SIZE	LARGE	MEDIUM	SMALL
16 oz.	74	217	535
26 oz.	128	389	932
32 oz.	151	---	1068
48 oz.	235	698	1642
64 oz.	351	942	2293

The data from the marble fill tests were to be compared with data collected where the jars were filled with water and heated. Four sizes of water filled jars were heated: 16 oz., 26 oz., 48 oz., and 64 oz.

Preparing the Temperature Sensing Elements

Temperatures were measured by thermocouples made at the end of duplex 24 gauge copper constantan thermocouple wire introduced into the top of the jars through Ecklund packing glands. A description of the assembly, designed to keep leakage to a minimum and found in Figures 1 and 2, follows; (1) the thermocouple wire, inserted through a hollow fiber rod, is split on the end and each half inserted into grooves of a fiber rod, (2) the grooved fiber rod is secured inside the hollow rod with epoxy resin (Epocast R_{10} - F resin and 10 - F 1951 hardener) and the thermocouple junction is made at the end of the grooved rod, (3) the grooved fiber rod is coated with epoxy resin, (4) pressure fitting B is secured to the lug lid and to secure the rod to pressure fitting B, pressure fitting A is screwed into fitting, expanding a washer. A piece of rubber tubing is fitted over the end of the hollow rod and sealed with epoxy resin. This piece of rubber tubing keeps the flexing of the thermocouple wire at the end of the rod to a minimum.

The fiber rod positioned the thermocouple at the cold point within the jars. In this study the assumption is that the cold point is 1/10 the height of fill measuring from the bottom of the jars. This is the cold point location for liquids in glass jars found by Pflug and Nicholas (1961).

From the jars, the thermocouple wires were connected to input of a Brown 12-point temperature recording potentiometer which printed the temperature every 1.33 minutes.

To make sure that the errors due to a faulty data collecting system, were kept to a minimum, the temperatures being read from the thermocouple system were frequently checked

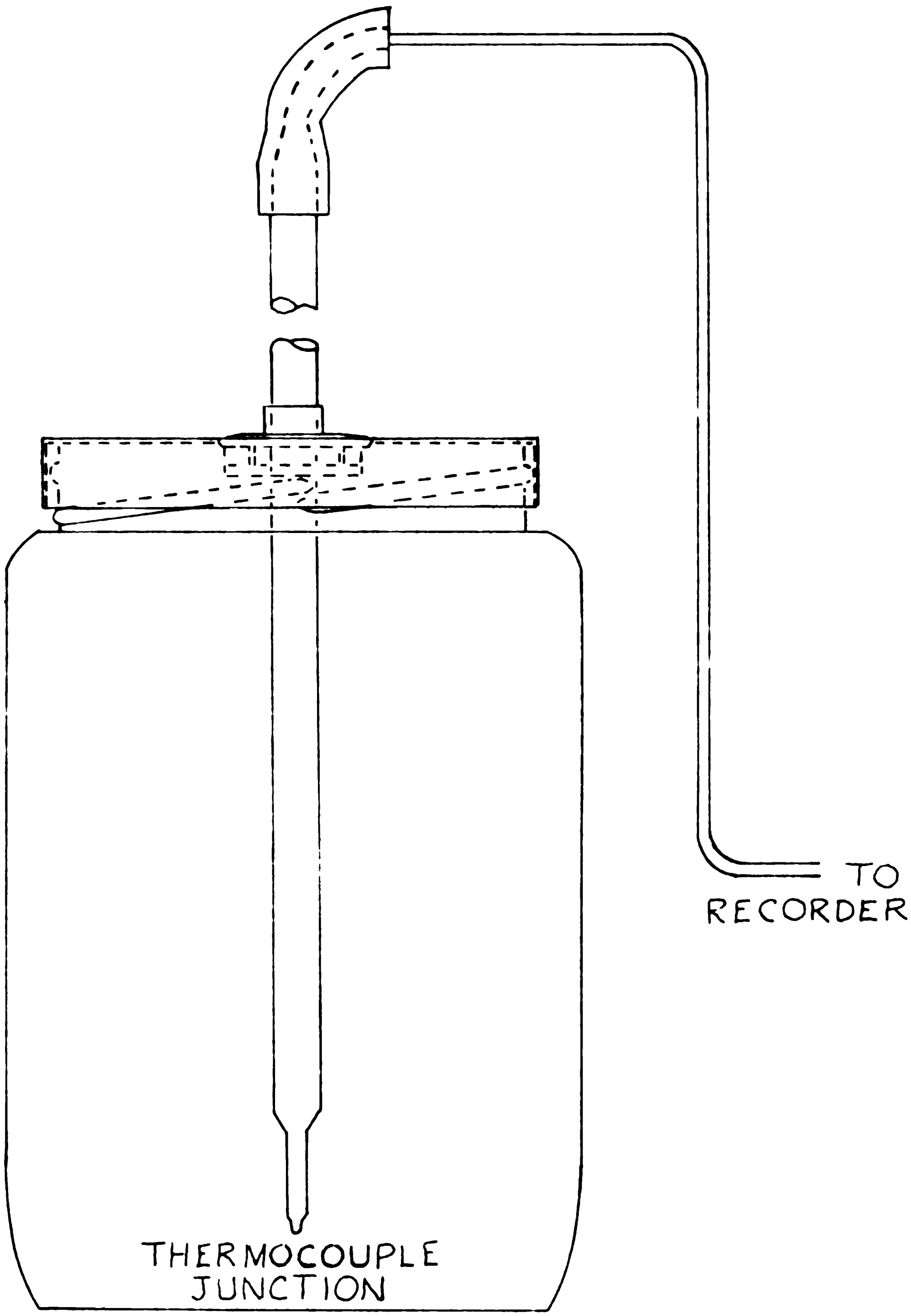

Figure 1. Measuring the temperature at the cold point of 16 oz. jars.

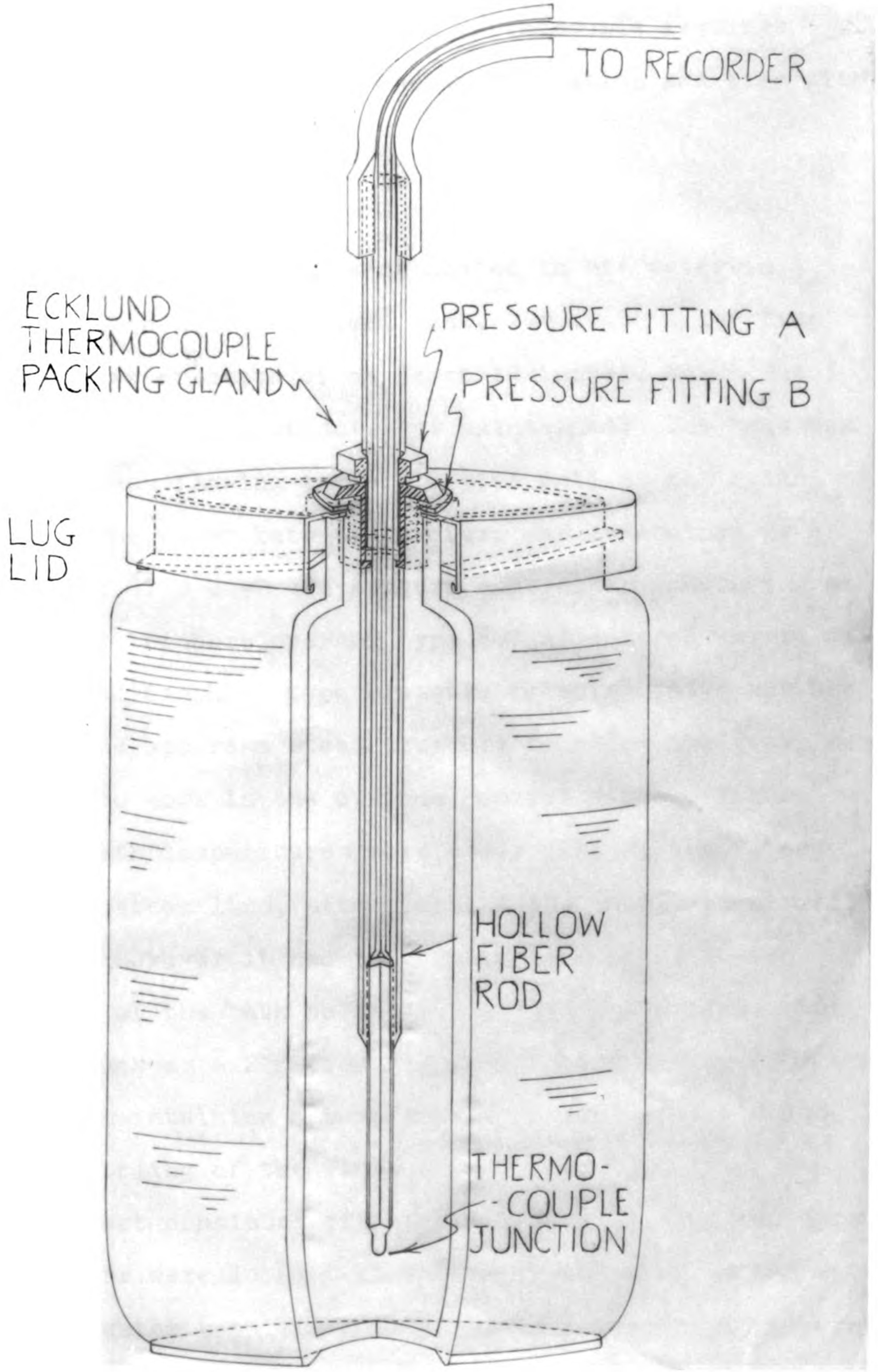

Figure 2. Setup for measuring temperatures in jars.

against temperatures being read from a mercury in glass thermometer. The thermometer and thermocouple readings being compared were taken at the same location and time within the water bath.

Heating Medium

Water Bath. The jars were heated in hot water in a rectangular, uninsulated steel tank, 24" x 48" x 18" (see Fig. 3). A water depth of at least 12 inches, which was 5 inches above the tallest jar, was maintained. The tank was heated by steam flowing through a pipe coil at the bottom of the tank. The water bath temperature was maintained by a Taylor Model 87 R U 47 temperature controller modulating an air operated (Fisher-Governor type 667 A) control valve. A hand operated diaphram type pressure reducing valve was used to adjust the upstream steam pressure to allow the steam control valve to work in the optimum control range. Three different bath temperatures were used: 165°F, 180°F, and 195°F. The steam line, after leaving the tank, was normally left open. However it had to be throttled to raise the temperature of the bath to 195°F. At 195°F the temperature cycled as much as ± 2°F from the mean, which was greater than found when maintaining a temperature of 180° or 165°F due to the throttling of the line.

Each test consisted of heating two jars. The two jars for all tests were located at the same positions in the water bath. The water bath was not agitated; the average temperature between the two positions was 3°F.

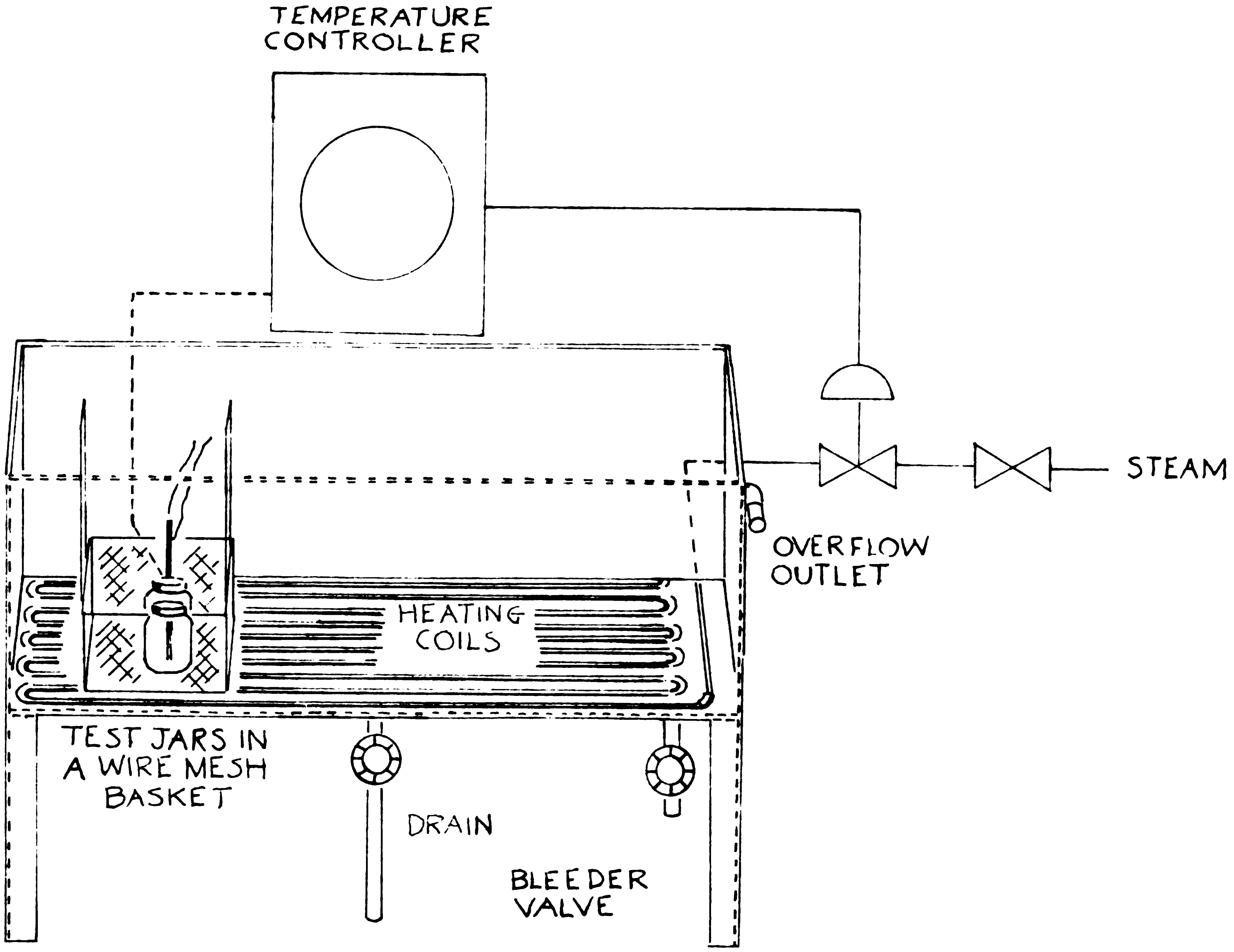

Figure 3. Diagram of the water bath system used.

Steam plus Air Mixture. The desired steam air mixture was developed inside a laboratory retort (see Fig. 4) whose pressure was maintained at one atmosphere by means of a pipe venting the system outside of the building and the lid of the retort not clamped closed but left open $\frac{1}{4}$ inch.

The temperature in the retort was controlled by an air operated valve. A steam line pressure reducing valve was located upstream to the control valve to facilitate final control. The baffles and arrangement of flow through the retort were designed to minimize the velocity effect and to eliminate, as much as possible, air pockets or steam pockets within the retort. Air flowed to the retort through a rotameter, a hand valve being used to control air flow to the retort; the air and steam line joined outside the retort. The temperature within the retort was kept within $\pm$ $2^{o}F$ 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 system by varying the air flow settings of the rotameter. The steam pressure varied with temperature, and in order to keep the flow in the retort constant, the air flow was adjusted. Calculations used to determine water pressures, air pressures and air flows were as follows:

a. $165^{o}F$ - 5.335 psi - absolute pressure at saturation

b. $\frac{5.335}{14.7 \text{ atmosphere pressure}} = .36$ or 36% steam in mix

100 - 36 = 64% air in mix

c. .36 x 760 mm Hg = 274 mm Hg water pressure

.64 x 760 mm Hg - 486 mm Hg air pressure

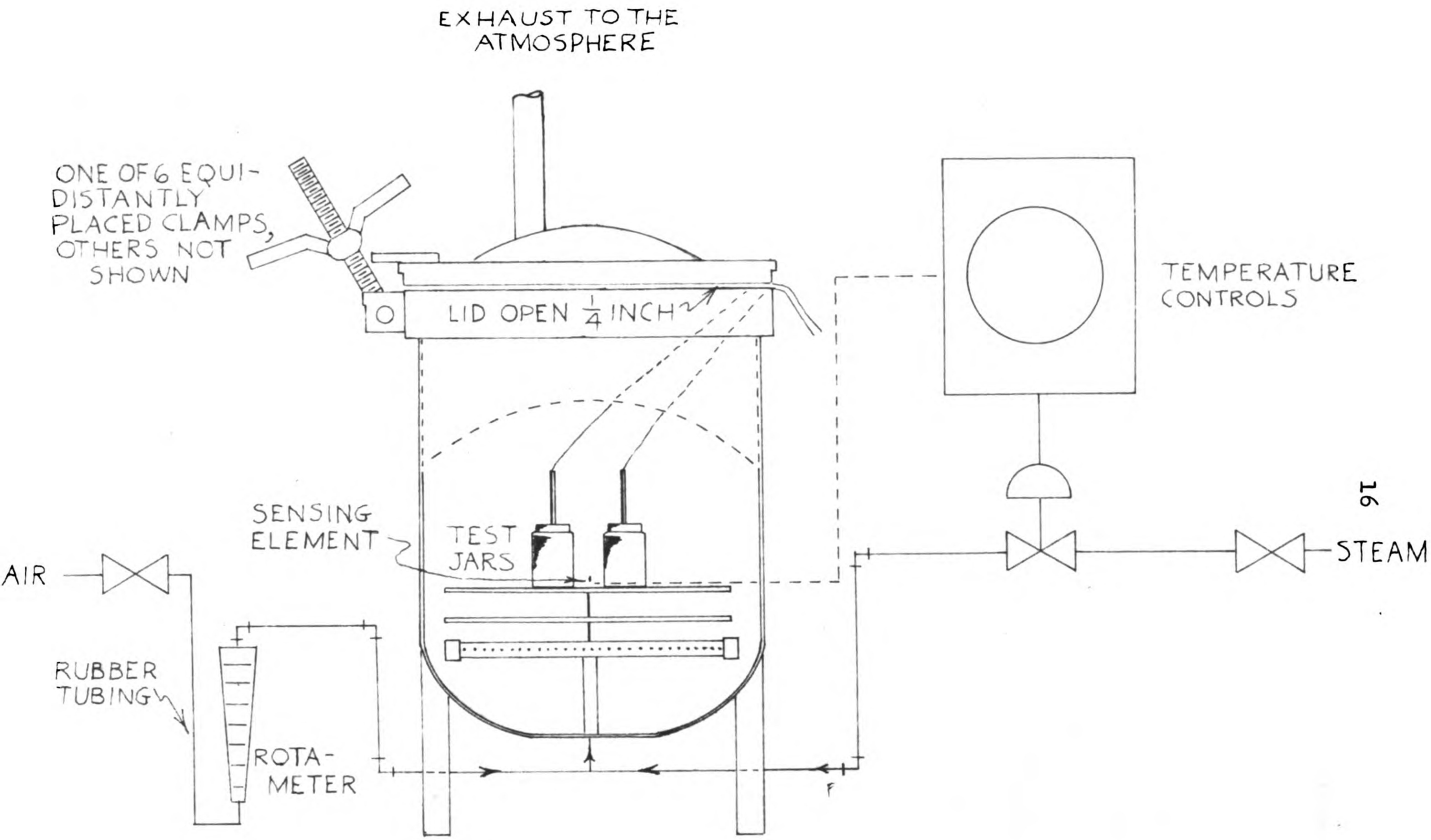

Figure 4. Diagram of the laboratory retort system used.

d. A total change flow of 20 cfm is adequate, allowing for $2\frac{1}{2}$ changes in the retort per minute. 20 x .64 - 12.80 cfm - rate of air flow.

e. $12.80 \text{ cfm} \times \frac{1}{1.235}$ (*K value) = 10.35 (rotameter reading)

where *K = temperature correction, the rotameter was calibrated at 10^{o}F and is being used at room temperature.

i.e. $K - \frac{\text{The rotameter reading at room temperature}}{\text{The assumed rotameter reading at T}}$

(For details of the calculations involved see Coulson and Richardsen (1956)). Table 5 summarizes the pressures, air flows and rotameter settings.

TABLE 5

Temperature ^{o}F (T)	Steam Press. mm Hg.	Air Press mm Hg.	Steam plus Air Press. mm Hg.	Air Flow cfm at T	K	Rota-meter Reading
165^{o}F	274	486	760	12.80	1.235^{-1}	10.35
180^{o}F	388	372	760	9.80	1.265^{-1}	7.73
195^{o}F	538	222	760	5.83	1.295^{-1}	4.45

Testing Procedure

Two jars containing either water or water plus marbles were equilibrated at 95^{o}F, and at 0 time (the start of the tests) were placed in the heating medium bath. The heating tests were ended when the temperatures in the jars were within two degrees of the heating medium temperature. A series of tests consisted of heating from 6 - 12 jars.

In the first series of tests, water alone was used in the jars. At the end of these experiments, the tests were conducted using water plus marbles to determine if particle size affects the heating rates inside jars. A series of tests were conducted filling the 16, 26, 48 and 64 ounce jars with first a small (3/8 in. diameter), then a medium (1/2 in. diameter) and then a large (3/4 in. diameter size marble fill, and heating the jars in water.

The decision to conduct tests using 32 oz. jars came during the later part of the testing period; therefore, the above tests were repeated heating 32 ounce jars with just two different size marble fills, small and large. To compare heating marble filled jars in water and a steam air mixture, the above tests were repeated heating 26 ounce jars, with the three different size marble fills, and the 32 ounce jars, with a small and large marble fill, in a steam and air mixture. Prior to being heated, water was added to the marble fill in the jars. The jars were filled until an air space equal to 10% of the total volume of the jars remained. The lid was placed on the jars and the thermocouple positioned by the rod secured to the lid. Each size jar with each size fill was heated while the temperature of the water and steam air mediums were maintained at 165, 180, and 195°F.

The rate of heating of containers is a function not only of the fluid and particles in the container, but also of the external heat transfer coefficient. To measure the external heat transfer coefficient, the transducers developed by Blaisdell (1963) were used. The surface conductance coefficients were determined the first time by using an aluminum cylinder and as a check a second time, using a copper cylinder (see Table 6), each cylinder being 3 inches in diameter and 4 1/2 inches long.

Duplex 24 gauge copper constantan thermocouple wires were imbedded in the cylinders to measure heating rates. (For a more detailed description of the construction of the cylinders see Blaisdell (1963)). Heating rate of the cylinders in each heating medium and for each temperature range 95 - 165°, 95 - 180°, and 95 - 195°F were determined using the same procedures used to determine the f values for the jars. Upon computing the f values, the surface conductances were determined from the transducer calibration curves developed by Blaisdell (1963).

Evaluation of Data

An f value for each jar heated was obtained by plotting the time temperature data on semi-logarithim paper and then by determining the time in minutes required for the straight line portion of the heating curve to cross one log cycle on the temperature scale (see Fig. 5). The data were taken off the recorder charts and were plotted on semi-log paper as a function of print cycle. The f value measured from the semi-log plot was in terms of print cycles which was multiplied by 1.33 min. to convert from print cycles to minutes. The j factor for each size jar was calculated applying the relationship

$$\frac{\text{retort temp. - theoretical initial temp.}}{\text{retort temp. - actual initial temp.}}$$

The fill data presented in Table 2 were obtained by subtracting the weights of the jars when empty from the jars when full with either marbles, marbles and water, or water.

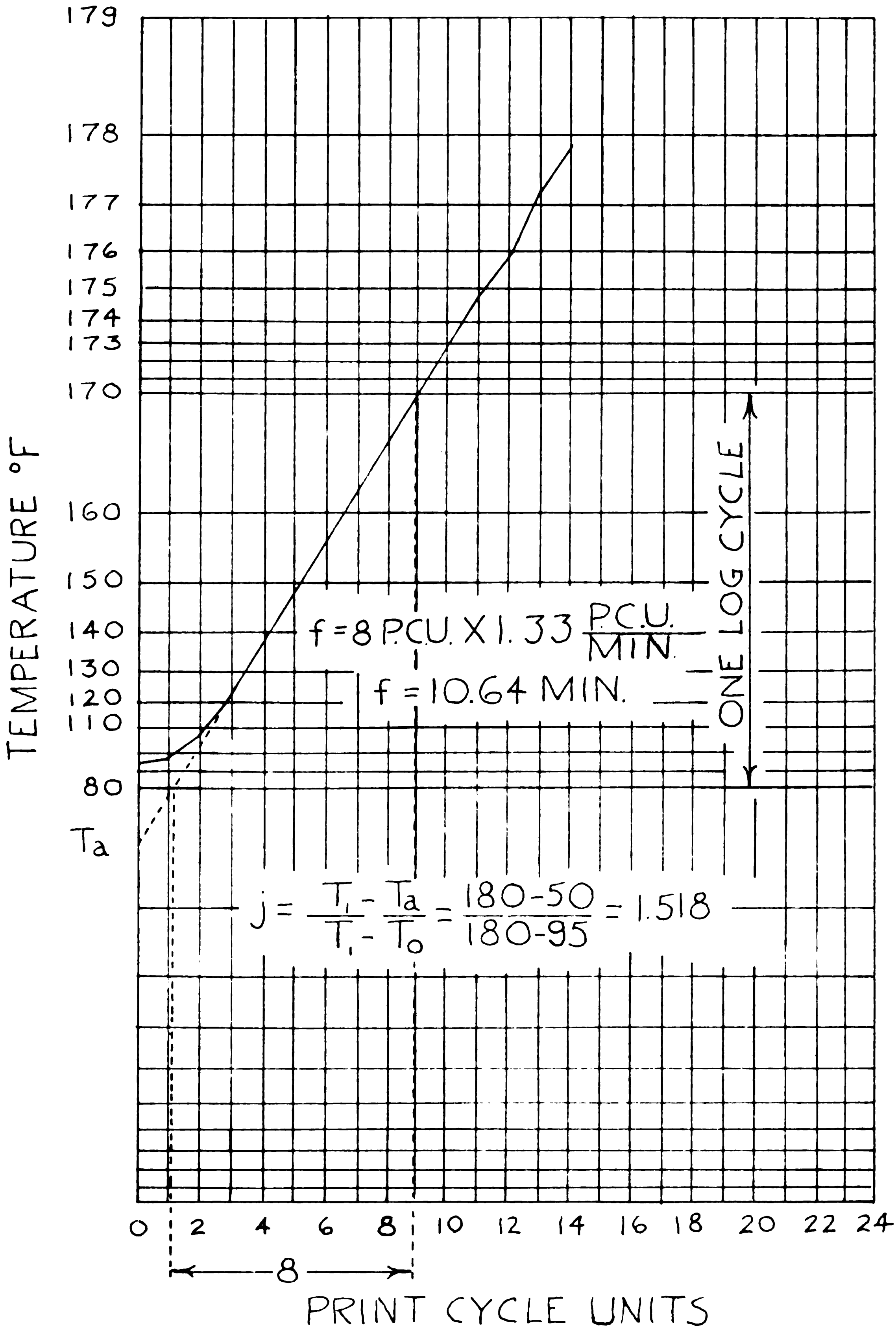

Figure 5. Determining f and j factors.

Surface to volume ratios, Table 10, were calculated from the jar volumes, water fill data, and jar surface areas evaluated. The number of marbles per jar, Table 4, were estimated by dividing the average marble weight into the marble fill weight. Analysis of varience tests, t and F tests, were used when determining the effect of marble size on heating rates.

RESULTS

The overall effect of jar size, heating medium, and the presence or absence of marbles in the jars are summarized in Tables 6 and 7. In Tables 6 and 7, average values for the heating rate of the three sizes of marbles are given. The effects of marble size on the heating rate at the different temperatures for the different size containers in the two different heat transfer media are summarized in Table 8. The surface conductance of the two heating media as measured by the copper and aluminum transducers is given in Table 9. The heating data for the three sizes of marbles were analyzed statistically and the results of the statistical analysis are tabulated in Table 10. The average j-value for all tests was 1.36.

Discussion of Results

The results were analyzed and will be discussed in terms of heating rate or f-value. The j-values were measured but the meaningfulness of the j-value in convection heating is not fully known. Since the significance of the f-value is understood and is in general independent of j, it will be used in the analysis.

Effect of Heating Medium and Heating Medium Temperature. An analysis of the heating medium data in Table 6 shows that in all instances as the heating medium temperature increased, the f-value decreased. Tests conducted by Pflug and Nicholas (1961) 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 which were responsible for the difference in the rate of heating. The data developed in this study verify this observation.

The f value ratios, f in steam-air/f in water in Table 11 and Figures 6, 7, and 8 were prepared to aid in the 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 heating medium temperature on the f value for 16 oz jars is shown in figure 6; 26 oz jars, figure 7, and for 48 and 64 oz jars figure 8. In these figures the relative change in f value with heating medium type and temperature is evident. The f value of jars heated in steam-air decreases more with the increase in temperature then the f value for jars heated in water baths. Probably, there is 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 then the rest of the group.

The results of surface conductance measurements (data in Table 9) reflect the data in Figures 6, 7 and 8 that at 195°F there should be essentially no difference in heating

TABLE 6. Summary of the heating rate results in terms of f-values for the several conditions.

Jar Size	Fill	Heating medium	165°F f	165°F SD*	165°F No.	180°F f	180°F SD*	180°F No.	195°F f	195°F SD*	195°F No.
16 oz.	water	water bath	12.12	.263	12	11.56	.468	12	10.85	.192	12
16 oz.	water	steam & air	13.22	.420	6	11.20	.178	6	10.07	.260	6
16 oz.	water & marble	water bath	10.52	.444	25	9.41	.390	30	8.85	.309	30
16 oz.	water & marble	steam & air	11.59	.665	6	9.87	.515	5	9.07	.747	6
26 oz.	water	water bath	15.86	.336	9	14.80	.482	12	14.19	.421	10
26 oz.	water	steam & air	16.36	.623	4	13.59	.440	6	12.99	.311	6
26 oz.	water & marble	water bath	13.25	.397	34	11.55	.334	34	10.91	.296	30
26 oz.	water & marble	steam & air	13.37	.619	12	11.41	.321	18	9.97	.426	15
32 oz.	water & marble	water bath	13.99	.993	11	12.02	.566	12	11.26	.474	12
32 oz.	water & marble	steam & air	13.51	.676	12	12.15	.355	12	9.99	.244	11
48 oz.	water	water bath	23.85	.405	8	20.95	.501	12	19.57	.430	12
48 oz.	water	steam & air	23.12	.552	6	19.55	.570	5	17.03	.252	6
48 oz.	water & marble	water bath	17.97	.513	17	16.33	.416	17	15.59	.390	17
48 oz.	water & marble	steam & air	19.04	.554	6	16.07	.625	6	13.41	.100	6

(continued on page 25)

TABLE 6 (continued)

Jar size	Fill	Heating medium	165°F f	165°F SD*	165°F No.	180°F f	180°F SD*	180°F No.	195°F f	195°F SD*	195°F No.
64 oz.	water	water bath	23.62	.294	9	20.67	.370	12	19.84	.24	12
64 oz.	water	steam & air	22.64	.700	4	19.95	.552	6	17.23	.421	6
64 oz.	water & marbles	water bath	18.24	.501	14	16.46	.348	18	15.82	.501	18
64 oz.	water & marble	steam & air	18.89	.273	4	16.63	.451	6	14.36	.111	6

Heating medium temperatures

No. = Number of tests conducted

* = Standard Deviation

TABLE 7. Summary of the heating rate results in terms of the heating curve lag factor j.

Jar sizes	Fill	Heating medium	Heating medium temperatures 165°F j	SD*	180°F f	SD*	195°F f	SD*
16 oz.	water	water bath	1.370	.0870	1.282	.1388	1.357	.0689
16 oz.	water	steam and air	1.390	.1002	1.410	.0697	1.540	.2053
16 oz.	marble & water	water bath	1.339	.1236	1.336	.1240	1.380	.1399
16 oz.	marble & water	steam and air	1.241	.0616	1.541	.1296	1.288	.1304
26 oz.	water	water bath	1.361	.1044	1.319	.0919	1.281	.0976
26 oz.	water	steam & air	1.370	.1508	1.430	.1785	1.380	.1825
26 oz.	marble & water	water bath	1.252	.1043	1.352	.1023	1.339	.0887
26 oz.	marble & water	steam & air	1.352	.2643	1.460	.1713	1.357	.1703
32 oz.	marble & water	water bath	1.360	.0893	1.455	.1495	1.483	.1330
32 oz.	marble & water	steam & air	1.439	.1313	1.455	.1496	1.485	.1370
48 oz.	water	water bath	1.242	.1127	1.283	.0600	1.348	.0667
48 oz.	water	steam & air	1.290	.1170	1.440	.0490	1.430	.0626
48 oz.	marble & water	water bath	1.255	.0693	1.333	.1036	1.295	.1157
48 oz.	marble & water	steam & air	1.290	.1170	1.440	.0490	1.430	.0626

(continued on page 27)

TABLE 7 (continued)

Jar size	Fill	Heating medium	Heating Medium Temperature 165°F j	165°F SD*	180°F j	180°F SD*	195°F j	195°F SD*
64 oz.	water	water bath	1.139	.0738	1.302	.1139	1.293	.0895
64 oz.	water	steam & air	1.320	.0374	1.290	.0363	1.530	.2053
64 oz.	marble & water	water bath	1.244	.1135	1.307	.0978	1.299	.0754
64 oz.	marble & water	steam & air	1.360	.1539	1.280	.0540	1.360	.0667

* = Standard Deviation

TABLE 8. Rearrangement of the f-value data to make possible comparison of the f-values for the three sizes of marbles.

Water bath medium		Small f min.	No.*	Medium f min.	No.*	Large f min.	No.*
16 oz. jars	165°F	10.45	11	10.53	10	10.67	4
	180°F	9.31	12	9.39	12	9.64	6
	195°F	8.72	12	8.80	12	9.24	6
26 oz. jars	165°F	13.37	12	12.89	11	13.49	11
	180°F	11.74	12	11.33	12	11.57	10
	195°F	10.74	12	10.94	12	11.17	6
32 oz. jars	165°F	14.05	6			13.94	5
	180°F	12.24	6			11.79	6
	195°F	11.31	6			11.22	6
48 oz. jars	165°F	18.00	6	18.02	6	17.88	5
	180°F	16.34	6	16.25	6	16.41	5
	195°F	15.74	6	15.54	5	15.47	6
64 oz. jars	165°F	18.22	4	18.49	4	18.09	6
	180°F	16.45	6	16.40	6	16.54	6
	195°F	15.87	6	15.74	6	15.85	6

(Marble size)

*No. = Number of tests conducted

Marble Size

Steam plus Air Medium		Small f min.	No.	Medium f min.	No.	Large f min.	No.
26 oz. jars	165°F	13.48	4	13.43	4	13.20	4
	180°F	11.35	6	11.37	6	11.50	6
	195°F	9.92	5	10.17	4	9.87	6
32 oz. jars	165°F	14.05	6			12.97	6
	180°F	12.22	6			12.08	6
	195°F	10.19	5			9.82	6

TABLE 9. Average surface conductance of the transducers in the two heating mediums at the three temperatures. (These data are the averages of surface conductances determined using the copper and the aluminum cylinders in the heating mediums at the respective temperatures; the curves were broken, the first f value (f_1) and the second f value (f_2) were treated separately.

The Surface Conductance in the Two Heating Mediums

	Water Bath		Steam Plus Air	
	h for f_1	h for f_2	h for f_1	h for f_2
165 deg. F.	147.24	127.50	56.25	65.75
180 deg. F.	168.33	150.33	71.80	93.00
195 deg. F.	189.17	167.00	143.25	192.50

TABLE 10. Results of the statistical analysis of the f-value data for jars containing marbles.

Significance of Marble Fill Data When Heating the Jars in a Water Bath

Jar size	Heating temperature range	F-value	Level of significance
1. 16 oz.	95-165° F	1.289	None
2. 16 oz.	95-180° F	3.092	None
3. 16 oz.	95-195° F	19.992	99%
4. 26 oz.	95-165° F	7.214	99%
5. 26 oz.	95-180° F	6.247	99%
6. 26 oz.	95-195° F	14.591	99%
7. 48 oz.	95-165° F	.118	None
8. 48 oz.	95-180° F	.336	None
9. 48 oz.	95-195° F	.693	None
10. 64 oz.	95-165° F	2.056	None
11. 64 oz.	95-180° F	.11[illegible]	None
12. 64 oz.	95-195° F	.254	None
		T-value	
13. 32 oz.	95-165° F	.982	None
14. 32 oz.	95-180° F	3.221	None
15. 32 oz.	95-195° F	.934	None

Significance of marble fill data when heating jars in steam and air

Jar size	Heating temperature range	F value	Level of significance
1. 26 oz.	95-165° F	.358	None
2. 26 oz.	95-180° F	.369	None
3. 26 oz.	95-195° F	.940	None
		T value	
4. 32 oz.	95-165° F	8.200	99%
5. 32 oz.	95-180° F	1.129	None
6. 32 oz.	95-195° F	1.001	None

TABLE 11

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

Jar size	Surface to volume ratio	f value (steam plus air)/ f value (water) 165° F	180° F	195° F
Water fill				
16 oz.	.1027	1.091	.969	.928
26 oz.	.0967	1.032	.918	.915
32 oz.	.0956	-----	----	----
48 oz.	.0761	.969	.933	.870
64 oz.	.0764	.958	.965	.868
Water plus marble fill				
16 oz.	.1027	1.102	1.049	1.025
26 oz.	.0967	1.009	.988	.914
32 oz.	.0956	.966	1.011	.887
48 oz.	.0761	1.060	.984	.860
64 oz.	.0764	1.036	1.010	.908

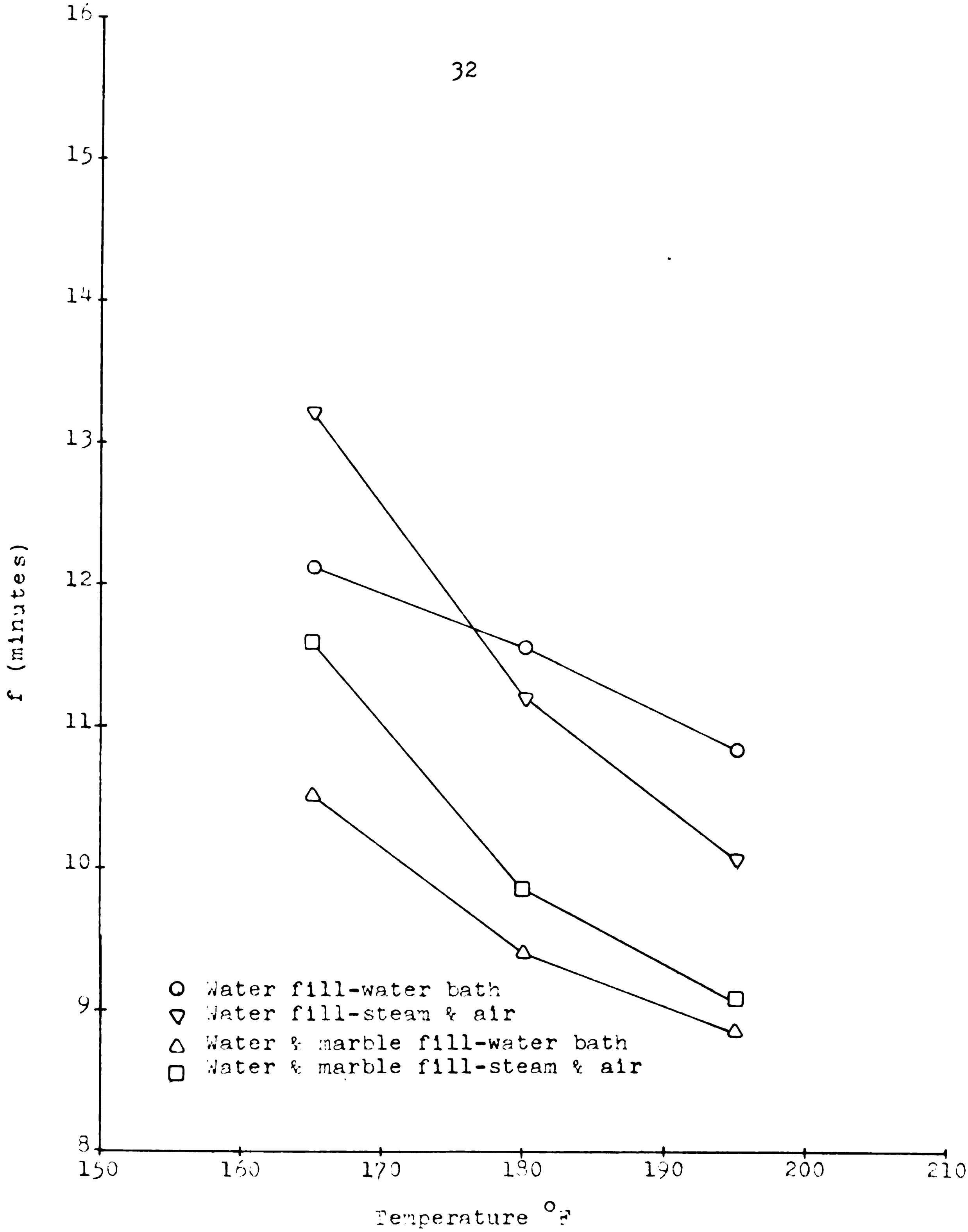

Figure 6. The relation of f-value and heating medium temperature for 16 oz jars heated in a non-agitated water bath and in steam plus air mixtures.

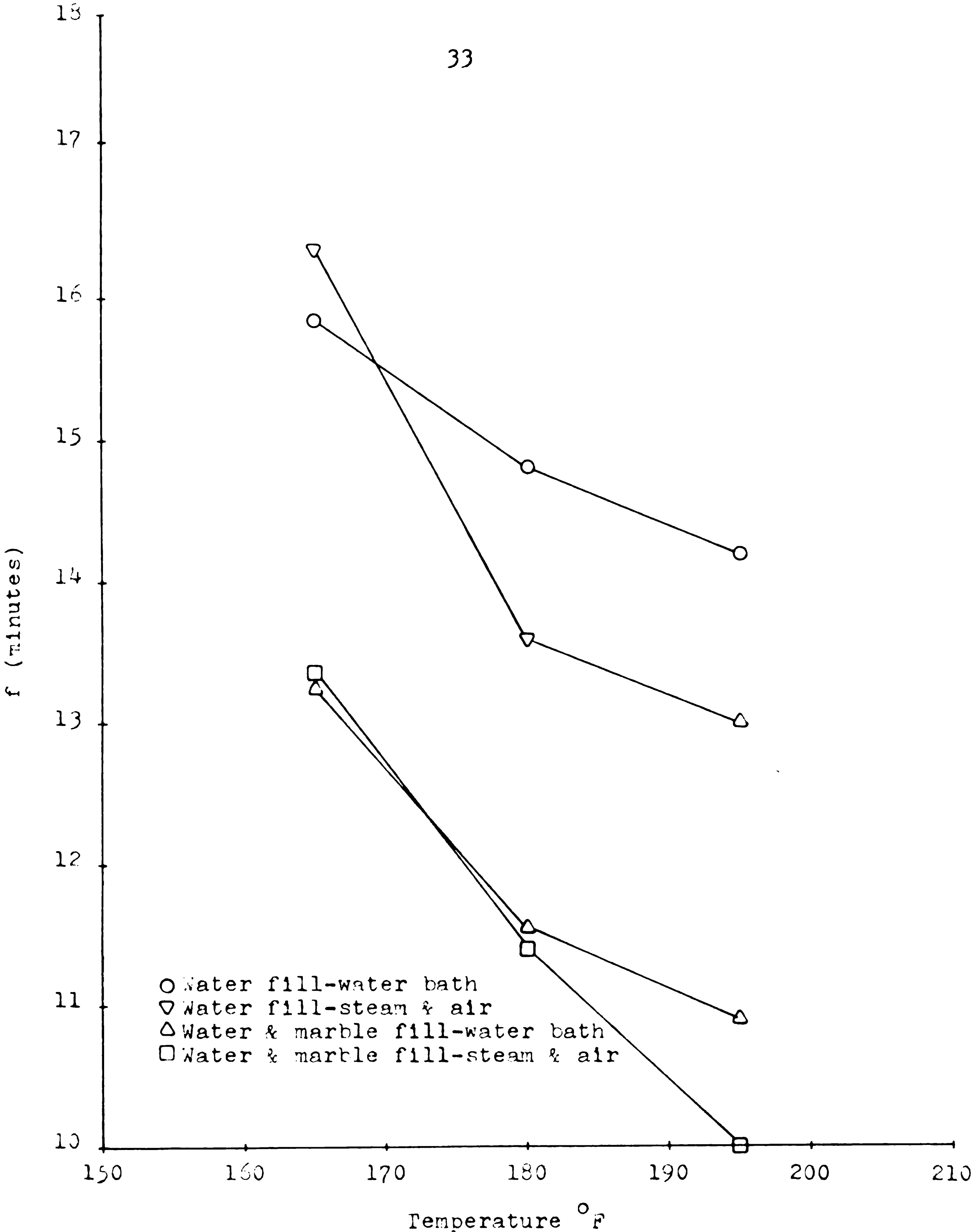

Figure 7. The relation of f-value and heating medium temperature for 26 oz jars heated in a non-agitated water bath and in steam plus air mixtures.

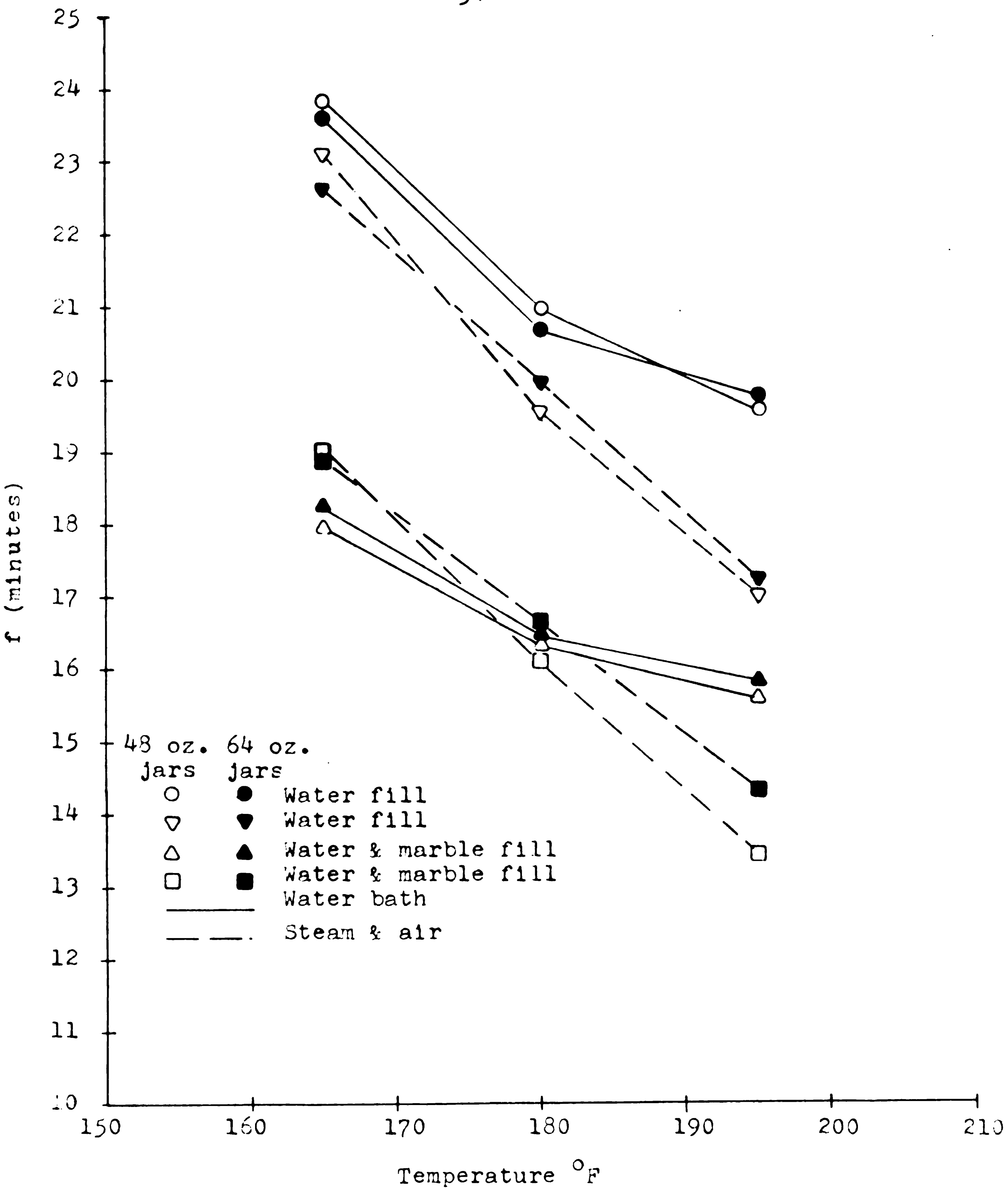

Figure 8. The relation of f value and heating medium temperature for 48 and 64 oz jars heated in a non-agitated water bath and in steam plus air mixtures.

TH

rate between water bath and steam-air mixture with some difference expected at 165°F and 180°F. In general the results confirm this; the trend in Table 11 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 mediums appear roughly to group themselves with jar surface to volume ratios; at lower surface to volume ratios, 0.076 compared to 0.096 or 0.103, the f-value heating medium ratio for water in jars appear 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 we go from 165 to 195°F. Comparing the h values at 165° and 195°F we find that the h_1 ratios are 56/147 and 143/139 and the h_2 ratios are 65/127 and 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 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 is probably the limiting factor as far as rate of heating is concerned.

The results of these experiments appear to fit into the overall pattern of steam-air heating. Pflug and Nicholas (1961) using a non flow 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 (1961) established that the effectiveness of steam-air mixtures varies directly with velocity, that at the low velocities used by Pflug and Nicholas (1961) steam-air mixtures can be very bad but at higher velocities the differences between steam-air mixtures and water are small. The experiments in this thesis 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 efficient than water at 165 and more effective than water at 195°.

Water vs. water plus marbles. The effect of water vs. water plus marbles is shown graphically in Figures 9 and 10 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

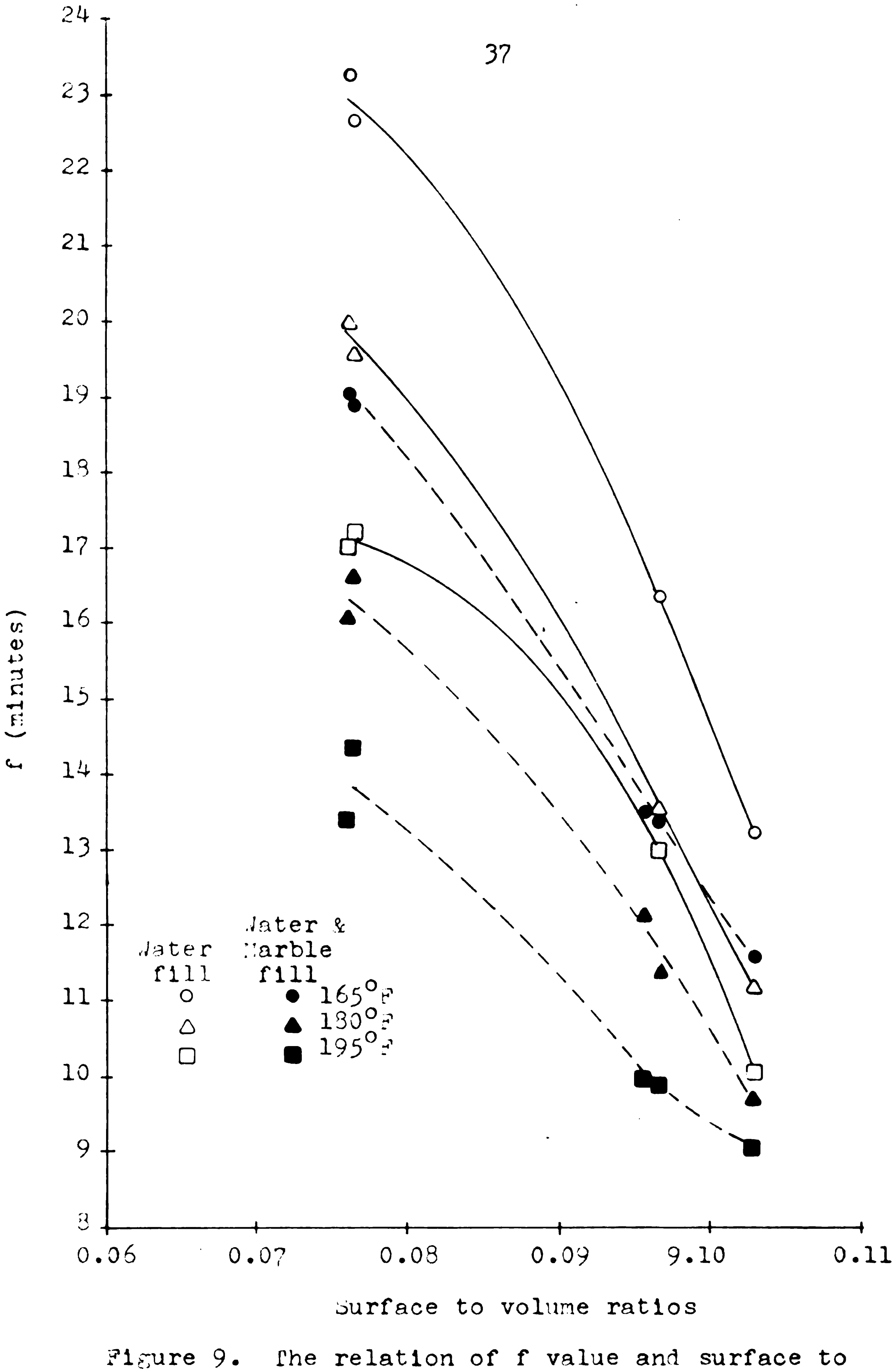

Figure 9. The relation of f value and surface to volume ratio for jars heated in steam plus air mixtures.

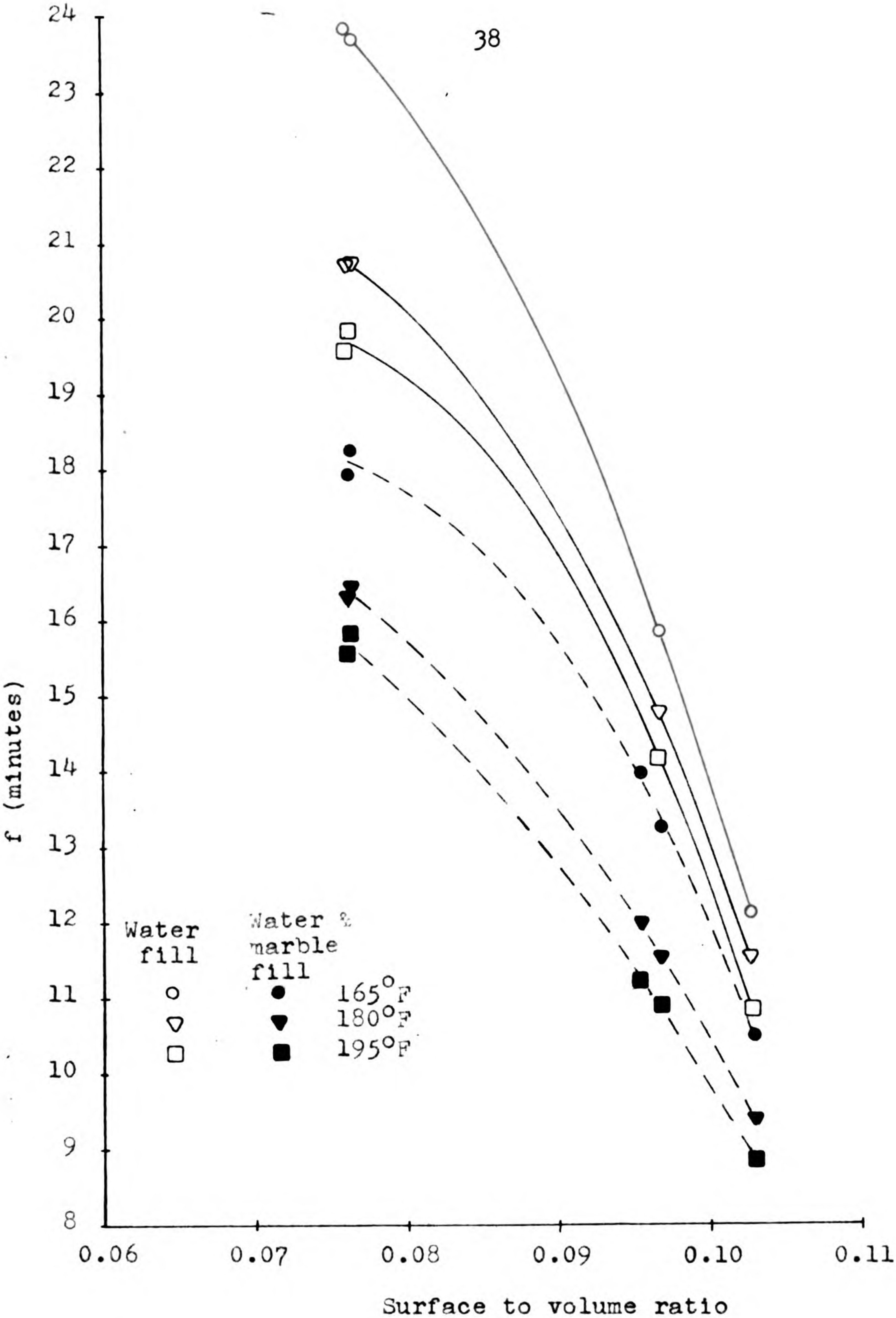

Figure 10. The relation of f value and surface to volume ratio for jars heated in a non-agitated water bath.

x 0.18 BTU/lb ^{o}F = 27, compared with water, 62.4 lb/ft^{3} x 1.0 BTU/lb ^{o}F = 62.4. The solid glass marble heats by conduction, therefore not only is the final heat capacity of the system reduced 56.7% 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 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 3/8 to 3/4 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.

Effect of jar size. In figures 9 and 10 the f-value data from Table 6 are shown as a function of the surface to volume ratios. The rate of heating increased consistantly (f-value decreased) as the surface to volume ratio increased. Nicholas and Pflug (1961) 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 Figure 7 (for example, the 48 and 64 oz. jars have similar surface to volume ratios, 0.0761 and 0.0764, 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 8. A statistical analysis was made to determine if the differences in Table 8 were significant; the results of the statistical analysis are shown in Table 10. It was found 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.

A 0.75 marble should heat at a rate 25% as fast as a 0.375 marble therefore jars of water plus the 0.75 marbles should heat faster because the rate of heat removal is smaller plus the fact that the flow path in the 0.375 marbles should have a higher resistance which would slow the rate of heating. Since in these experiments there appear to be no major differences in the rate of heating of the jars with either large or small marbles, it must be concluded that neither of these effects are significant in this range of conditions. Decreasing the size of marbles to 0.25 or .1875 inch may change the results dramatically.

It can be concluded that the effect of the size of particle over the range tested in this experiment do not produce significant effects as a function of particle size. These data cannot be extrapolated since there is certainly a critical particle size that has a significant effect on heating rate.

SUMMARY

A study was made of the heating characteristics of water and water plus marbles in five sizes of glass containers in water and steam air mixtures at 165, 180 and 195°F.

Glass jars in common use in the food science industry having 16, 26, 32, 48 and 64 fluid oz capacity were studied filled with water, water plus 3/8 in. diameter, water plus 1/2 in. diameter and water plus 3/4 in. diameter glass marbles to determine the effect of the particulate objects on the heating rate. The jars were heated in a water bath and in steam - air mixtures at 165, 180 and 195°F. The temperature - time heating characteristics were determined by thermocouples located at the slowest heating zone in the container. The temperature-time data were plotted and the resulting curves analyzed for f and j values. The effect of jar size, water vs. marbles, marble size, water bath vs steam-air, and heating medium temperature were determined as a function of the heating rate.

The results of the study showed a good correlation between the surface to volume ratio of the container and the heating rate. The rate of heating of the jar increased (f value decreased) as the surface to volume ratio increased.

There was no detectable difference in the rate of heating

for the three size marbles. Jars with the water plus marbles heated faster than jars of water.

All jars heated faster with increasing heating medium temperature. Greater changes in heating rate were observed in steam-air mixtures then in a water bath. The difference between water bath and steam-air mixtures was small due to the relatively high flow rate of the steam-air mixtures; however, the water bath was more effective at 165° F with the steam air more effective at 195° F.

CONCLUSIONS

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

1. As the heating medium temperature increases the f value decreases.
2. In these tests water was in general more efficient at 165°F with steam plus air being more efficient at 195°F.
3. The f values correlate well with surface to volume ratios rather than jar size, the f value decreases with an increasing surface to volume ratio.
4. Jars with water plus marbles heat faster than jars of water.
5. No difference in the rate of heating was detected due to differences in the three sizes, 3/8", 1/2", or 3/4" of marbles.

APPENDIX

Nomenclature

F is the time required to produce a given sterlization effect at 250 degrees F.

j is the log factor computed from $\frac{T_1 - T_a}{T_1 - T_o}$

T_1 is heating medium temperature in degrees F.

T_0 is the initial temperature in degrees F.

T_a is the temperature at $t_h = 0$; the intercept value of the straight line asymptote in degrees F.

t_h indicates heating time, the time the container is subject to a given heating medium temperature.

f is the time required, in minutes, for the asymptote of the heating or cooling curve to cross one log cycle, i.e., the time required for a 90% change in temperature on the linear portion of the curve. Subscripts are used to denote successive values if more than one linear portion is used to describe a heating or cooling curve.

h is the surface heat transfer coefficient in BTU/hr. $(ft.)^2$ $^\circ$F.

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