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HEAT TRANSFER COEFFICIENTS
OF
CONDENSING VAPORS

BY

CHARLES R. LIPUMA
AND
EARLE A. NIRMAIER

A THESIS
SUBMITTED TO THE FACULTY OF
THE DEPARTMENT OF CHEMICAL ENGINEERING
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ABSTRACT

The film coefficients of heat transfer for vapors condensing on a single horizontal tube have been measured for methyl, i-propyl, and n-butyl alcohols. The equipment used was specifically designed for these studies, and represents an improvement over that used by other investigators. The data collected were analyzed using a modified Wilson method which is based on a rigorous theoretical analysis.

It has been found that the condensing film coefficients for methyl and i-propyl alcohols vary with the heat duty. This is to be expected from the analysis mentioned above. No variation was found for n-butyl alcohol.

The observed values of the heat transfer coefficients have been compared with the values calculated with the Nusselt and Bromley equations. The Bromley equation is a modification of the Nusselt equation and takes into account the effect of the heat capacity of condensate. Excellent agreement between the observed coefficients and those predicted by the Nusselt equation were obtained with methyl and i-propyl alcohols. Good agreement was found with n-butyl alcohol. In all cases the Bromley equation predicted higher values of the condensing film coefficient than did the Nusselt equation.

Close agreement between the observed and theoretical coefficients is a result of the refined theoretical and experimental methods used.

APPROVAL OF THESIS

FOR

DEPARTMENT OF CHEMICAL ENGINEERING

NEWARK COLLEGE OF ENGINEERING

BY

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INTRODUCTION

Investigators have generally used one of two methods for measuring the film coefficients of heat transfer for vapors condensing on single horizontal tubes. These are the embedded thermocouple method as used by Kirkbride (14), Othmer and Berman (18), and Wallace and Davison (24); and the Wilson method (26). Both of these methods have inherent disadvantages.

Rhodes and Younger (23) pointed out that the average wall temperature as measured with thermocouples can be computed only by making certain assumptions that may not be valid. Baker and Mueller (1) later proved that there is no point on a tube wall at which a thermocouple can be located to obtain a truly representative tube wall surface temperature.

Rhodes and Younger (23) showed that some of Wilson's assumptions were not correct. Based on this earlier work, Chu, Flitcraft, and Holeman (6) proposed a unique modification of the Wilson method using a rigorous theoretical analysis. This modified technique has greatly improved the Wilson method.

Chu and associates' proposed technique has been applied to only a limited extent. As a result, this investigation was initiated to test this modified Wilson method using another homologous series of organic compounds. Methyl, i-propyl, and n-butyl alcohols have been selected for these studies. The physical properties of these alcohols have been widely investigated and are more reliable than those of more complex organic compounds. Thus, the predicted condensing film coefficients, which are to be compared with the observed coefficients, can be calculated with a reasonable assurance of reliability.

The predicted coefficients will be calculated using both the Nusselt and Bromley equations. The Bromley equation (4) is a modification of the Nusselt equation and includes a correction for the effect of the heat capacity of condensate. The Bromley equation is to be compared with Nusselt's equation to determine the magnitude of this correction.

The equipment used to measure the heat transfer coefficients was specifically designed for these studies and represents an improvement over that used by the other investigators.

THEORY

The Nusselt equation (15) (17) is generally used to predict the coefficients of heat transfer for the filmwise condensation of pure vapors on a colder surface. Applied to a single, horizontal, cylindrical tube, the equation is

$$h_o = 0.725\ (k_f^3 \rho_f^2 g \lambda / D_o \mu_f \Delta t)^{0.25} \qquad \text{I}$$

which is based on the assumption that streamline flow exists throughout a continuous condensate film, and that gravity alone causes the condensate to flow over the smooth surface. The possible acceleration effect of the vapor velocity upon the film thickness is also neglected.

Many investigators (14) (16) (24) have measured the condensing film coefficients of pure organic vapors with the aid of embedded thermocouples. Inasmuch as the condensate film thickness around the perifery of a cylindrical tube varies, it is to be expected that the film temperature would also vary. Therefore, the measurement of surface temperatures with thermocouples may result in considerable error. Baker and Mueller (1) proved that there is no point on the surface of a cylindrical tube at which a thermocouple can be located to obtain a representative surface temperature.

Investigators (3) (23) have utilized the Wilson method to avoid the difficulties associated with direct temperature measurements. The Wilson method is represented by the following equation

$$R = \sum R_i = R_v + R_w + a/V^{0.8} \qquad \text{II}$$

where R_v is the thermal resistance of the condensate film at a finite cooling water flow rate, and "a" is a constant. This equation is based on the assumption that changes in cooling water rate have no effect upon R_v. Rhodes and Younger (23) pointed out that R_v varied with water rate and postulated that

$$R_v = R_{ve} + b/V^{0.8} \qquad \text{III}$$

Beatty and Katz (3) applied this method to their work with finned tubes, with a modification to allow for the effect of cooling water temperature upon the water film resistance.

Chu, Flitcraft, and Holeman (6) stated that Equation III was empirical, since there is no theoretical justification for setting up R_v as a function of R_{ve} and the cooling water flow rate. They proposed a modification of the Wilson method based on a rigorous theoretical analysis. It was pointed out in their paper and by other investigators (7) (23) that the group $(k_f^3 \rho_f^2 g \lambda / \mu_f)^{0.25}$ appears to remain constant with varying temperature for most organic solvents. Therefore, for steady state heat transfer through a condensing vapor, the following equation has been derived (6).

$$h_e = c\ q^{-1/3} \qquad \text{IV}$$

This equation will result in a straight line with a negative slope equal to one-third on a log-log plot. Thus, Chu and associates (6) have deduced that the condensing film coefficient varies with the heat transferred.

The values of the group $(k_f^3 \rho_f^2 g \lambda / \mu_f)^{0.25}$ for methyl, i-propyl, and n-butyl alcohols are listed in Table 1. Also included in this listing are the values of this group for other organic compounds as reported by Chu and associates (7).

The overall thermal resistance from the condensing vapor to the cooling water side of a condenser tube is represented by

$$\frac{1}{U_oA_o} = \frac{1}{h_oA_o} + \frac{x}{k_wA_{av}} + \frac{D_i^{0.2}}{150\ A_i\ (1+0.011t)\ V^{0.8}} \qquad V$$

From Equation IV it is evident that h_o is constant at constant values of q. Also, the thermal resistance of the tube wall is negligible compared to the other terms of Equation V. Therefore, the first two terms of Equation V are constant at constant values of q. A plot of $1/U_oA_o$ against $1/(1\ \ 0.011t)V^{0.8}$ should result in a straight line at equal values of q. The intercept of this line, equal to $1/h_oA_o\ \ x/k_wA_{av}$, can be used to calculate the condensing film coefficient, h_o, since

$$\frac{1}{U_oA_o} = \frac{T}{q} = \frac{1}{h_oA_o} + \frac{x}{k_wA_{av}} \qquad VI$$

and

$$\frac{1}{h_o} = \frac{1}{U_o} - \frac{x\ A_o}{k_wA_{av}} \qquad VII$$

Several sets of experimental data can be obtained by varying the cooling water flow rate and the pressure in the test condenser vapor space. For any one set, the overall water to vapor temperature difference would be kept constant; and from one set to another the temperature difference changed by readjusting the pressure in the vapor space. Two or more points, at constant q, can be gotten from the above sets of data. These points, when replotted as $1/U_oA_o$ against

TABLE 1

RATIO OF $(k_f{}^3 \rho_f{}^2 g \lambda / \mu_f)^{0.25}$ AT DIFFERENT TEMPERATURES

COMPOUNDS	UPPER TEMP. °F	LOWER TEMP. °F	RATIO
Methyl alcohol	72	63	1.02
i-Propyl alcohol	80	69	1.13
n-Butyl alcohol	98	86	1.09
Ethyl acetate	60	40	1.01
Benzene	60	30	1.03
Toluene	90	40	1.09
Trichloroethylene	60	40	1.02
Nitromethane	80	50	1.02
Bromobenzene	100	50	1.08
n-Hexyl alcohol	100	50	1.07
Perchloroethylene	100	50	1.03
Carbon tetrachloride	60	30	1.11

$1/(1+0.011t)\ V^{0.8}$, yield a straight line. The value of h_o at the constant value of q is then calculated from the intercept of this line.

As previously stated, the Nusselt equation is used to predict condensing film coefficients. Bromley (4) has pointed out that in the basic derivation by Nusselt the effect of the heat capacity of condensate was assumed negligible. This assumption is valid at low pressures. However, at high pressures and large tube wall to saturated vapor temperature differences, sensible heat may significantly affect heat transfer.

This consideration led to the theoretical development of a modified Nusselt equation. The equation for vapors condensing on a single horizontal tube is

$$h_o = 0.728 \left[\frac{k_f^3 \rho_f (\rho_f - \rho_v) g \lambda \left(1 + 0.4 \frac{\Delta t c_p}{\lambda}\right)^2}{D_o \mu_f \Delta t} \right]^{0.25} \qquad \text{VIII}$$

Bromley's equation should predict higher values of h_o than the Nusselt equation.

DESCRIPTION OF APPARATUS

The equipment used in this work, as shown in Figures 1 and 2, consisted basically of a kettle, a single tube horizontal condenser, a cooling water circulation system, and a vacuum pump.

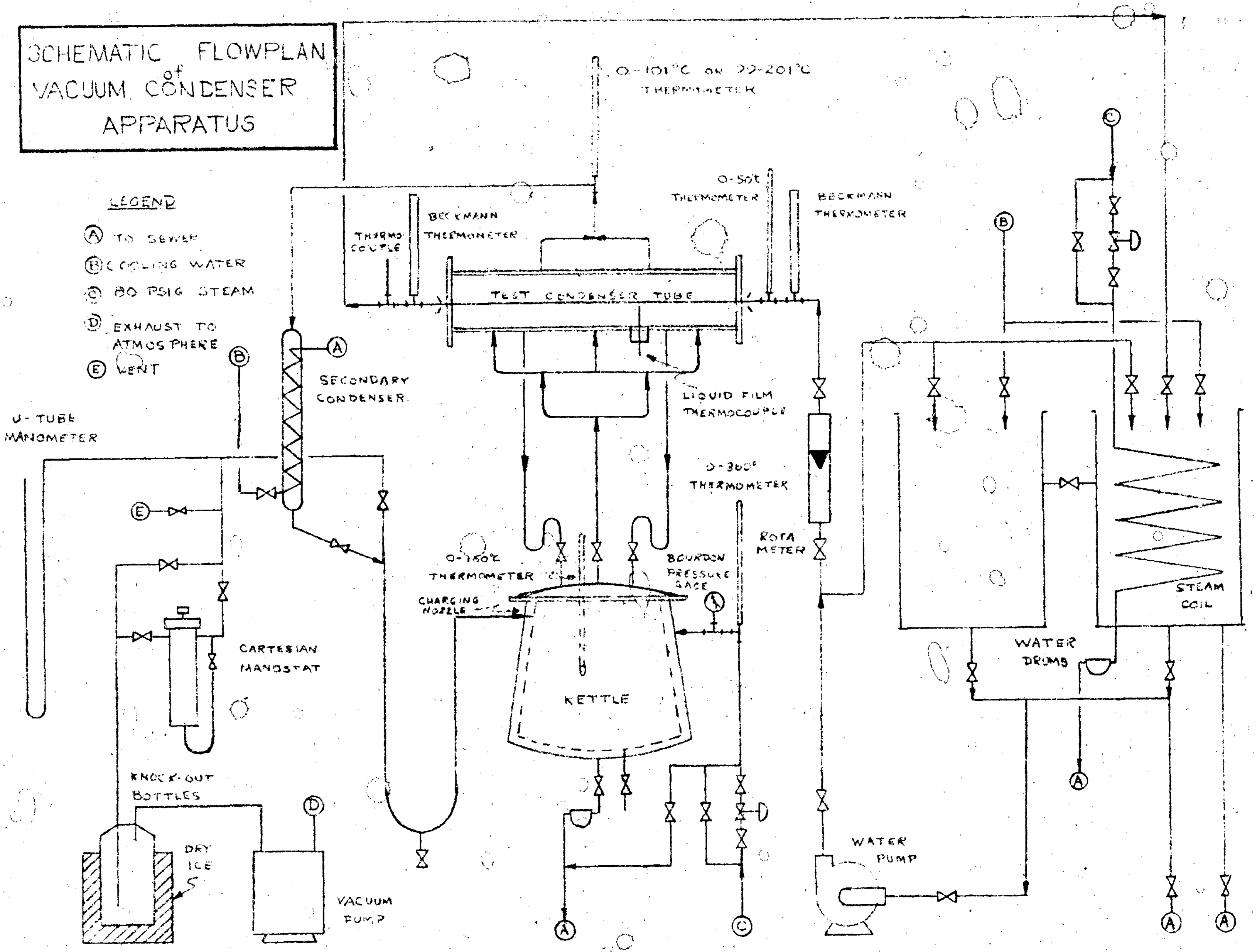
The jacketed kettle was of stainless steel construction and had a five gallon capacity. Steam, at an initial pressure of 90 psig., was introduced into the jacket through a 3 to 15 psig. throttling valve.

The test condenser was a 0.375 inch outside diameter brass tube 24 inches long having a wall thickness of 0.035 inches. The effective outside surface area was 0.196 sq. ft., and the thermal conductivity was 60 Btu/(Hr.) (sq. ft.) (°F/ft.). A 2.5 inch schedule 40 stainless steel pipe, flanged at both ends, was used as the condenser jacket.

Vapor from the kettle entered the jacket through three 0.5 inch diameter distributors. Condensate returned to the kettle by gravity flow through two downcomers and liquid seal traps. The temperature of the uncondensed vapor taken overhead was measured by a -1 to 101°C or 99 to 201°C thermometer graduated in 0.1°C increments. A glass secondary condenser was used to assure that excess vapor was passing the test condenser at all times. Condensate returned to the kettle through a liquid seal trap.

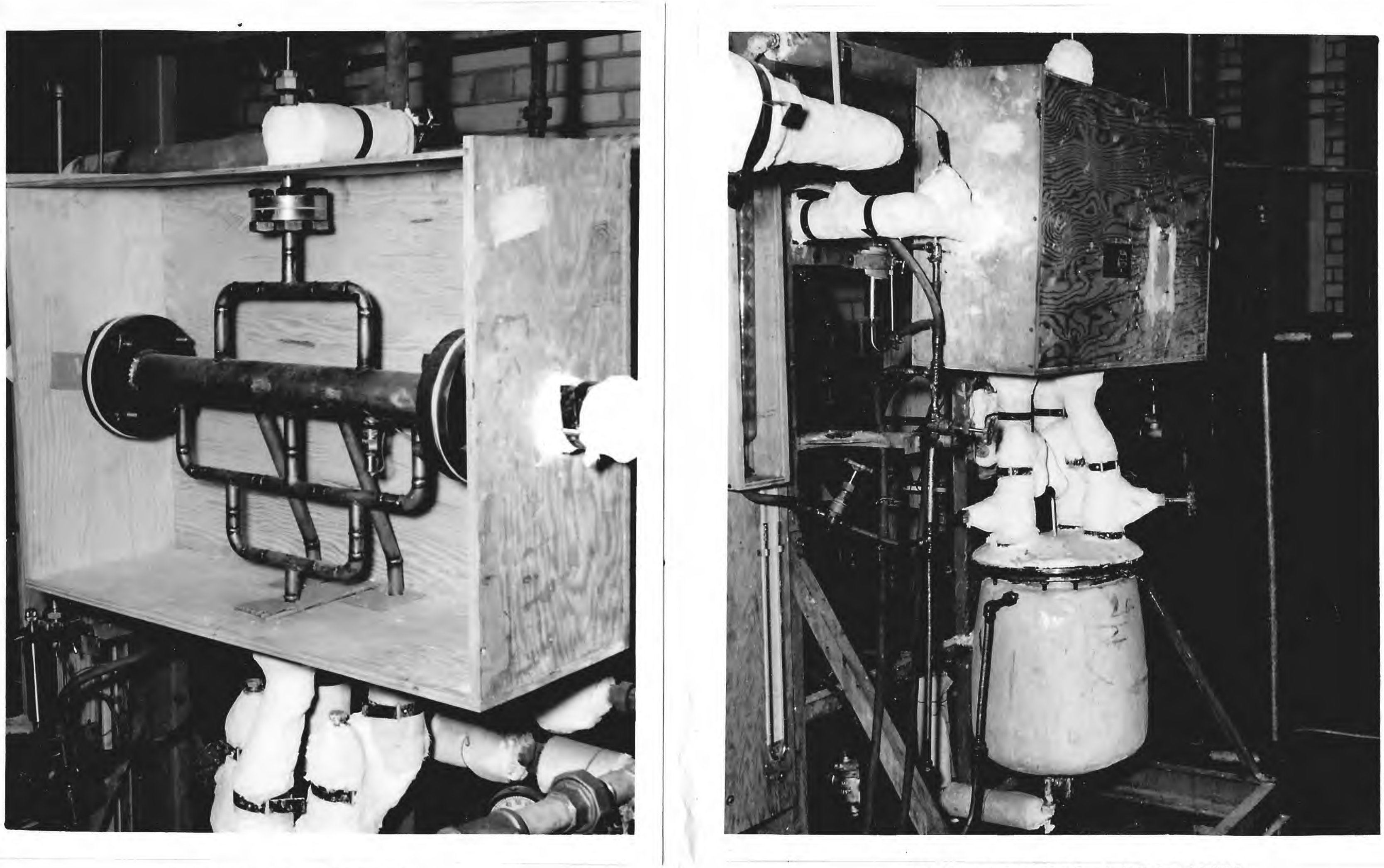
The condenser jacket contained a special thermocouple installation used for measuring bulk condensate temperatures. A finely threaded fitting permitted adjustment of the position of the thermocouple junction.

FIGURE 1



SCHEMATIC FLOWPLAN of VACUUM CONDENSER APPARATUS

FIGURE 2



CONDENSER JACKET

EXPERIMENTAL APPARATUS

The system was evacuated and maintained at low pressures by a Cenco-Hypervac 4 pump of 1.44 cubic ft. per minute free air displacement. The pressure was controlled at the desired level by a cartesian manostat and measured with a U-tube mercury manometer.

The kettle - condenser - vacuum system was checked for leaks. It was considered to be air-tight when no noticeable increase in absolute pressure occurred over a one-half hour period, after evacuation to an absolute pressure level of one inch of mercury.

Water was circulated by a centrifugal pump rated at 25 gallons per minute at 80 ft. head and 1.0 specific gravity. Flow rates were measured with a calibrated Fisher-Porter rotameter rated a 13.6 gallons per minute.

Two 55 gallon drums were used as holdup and constant head supply for the pump. Fresh water flowed to the pump from the supply drum. Heated water from the condenser could be discharged to the second drum and then to the sewer. The secondary drum was equipped with a steam coil which allowed pre-heating of the cooling water.

Condenser inlet water temperatures were measured with a 0 to 50°C thermometer graduated in 0.1°C increments. The outlet water temperature measurements were made with a thermocouple installation. A pair of 0 to 6°C Beckmann thermometers, each of which could be read to 0.002°C, was used to determine the water temperature rise in the test condenser.

The entire kettle-condenser system was well insulated. Magnesia lagging was used on all pipe lines. The condenser jacket was enclosed in a plywood box which was filled with powdered vermiculite. This method of insulation minimised heat losses.

Eighteen gage, copper-constantan thermocouples were used. These thermocouples were factory calibrated at ± 0.8°C up to a temperature of 375°C.

The alcohols used were reagent grade containing a maximum of 0.5 per cent impurities. The boiling ranges were less than 1°C.

EXPERIMENTAL PROCEDURE

The test alcohol was charged to the kettle after the system had been cleaned. Before heating with steam, the cooling water was turned on and the system was allowed to reach a steady state condition. At this point a series of reference readings was taken on the Beckmann thermometers. The rotameter reading and water temperature were also taken. This blank correction on the Beckmann thermometers was used to determine the true water temperature rise in the condenser tube, as discussed in the appendix section "Reference Correction of Beckmann Thermometers".

The system was then evacuated, bypassing the manostat to permit more rapid evacuation. When the absolute pressure decreased to the vapor pressure of the alcohol in the kettle, the pump was turned off and the bypass closed. Steam was then admitted to the kettle jacket. When the system pressure reached the desired level, the manostat was put in operation and the vacuum pump restarted. This method of startup minimized the possibility of non-condensable gases remaining in the system.

Five complete sets of readings were taken at one minute intervals after the system reached equilibrium. The average of these readings was used in the calculations. A set of data consisted of a rotameter reading, absolute inlet and outlet water temperatures, vapor temperature, bulk condensate temperature, kettle pressure, and a simultaneous reading of the Beckmann thermometers. The secondary condenser was constantly checked to assure that excess vapors were present in the test condenser at all times.

After the completion of a run, the water rate was changed. If necessary, the pressure level was readjusted to maintain a constant overall water to vapor temperature difference.

Twenty to thirty minute time intervals were required for the system to return to equilibrium after conditions were changed.

EXPERIMENTAL RESULTS AND TREATMENT OF DATA

The experimental results for methyl, i-propyl, and n-butyl alcohols are presented in Tables 2, 3, and 4, which include the calculated results of $(1 \times 10^3) / (1+0.011t)V^{0.8}$. The data are plotted in Figures 3 to 11. Figures 3, 6, and 9 show the variation of the water flow rate and temperature rise in the test condenser. Figures 4, 7, and 10 are a form of the Wilson plot and represent the heat transferred as a function of $1/V^{0.8}$ at varying overall vapor to cooling water temperature differences.

In determining the heat transfer coefficients, h_o, a series of straight lines were drawn parallel to the abscissae of Figures 4, 7, and 10, intersecting two or more of the constant vapor - water temperature difference lines. These horizontal lines represent constant values of the heat transferred, q. At each intersection, the overall temperature difference, and $(1 \times 10^3) / (1+0.011t)V^{0.8}$ were read. $\Delta T/q$ was calculated and plotted against $(1 \times 10^3) / (1+0.011t)V^{0.8}$ for each value of q. These plots, shown in Figures 5, 8, and 11, yielded straight lines which were extrapolated to the ordinates. The intercepts represent $\Delta T/q$ or $1/U_oA_o$ at infinite water flow. The values of h_o, the condensing film coefficients, are calculated from these intercepts.

TABLE 2
TABULATED RESULTS - METHYL ALCOHOL

RUN NO.	INLET WATER TEMP. °C	WATER TEMP. RISE °C	VAPOR TEMP. °C	OVERALL WATER-VAPOR ΔT, °C	WATER FLOW W LB/HR	HEAT DUTY Q BTU/HR	$\frac{1 \times 10^3 V^{-.8}}{1+0.011t}$
1	5.50	1.759	64.29	57.94	2610	8260	1.24
2	5.80	2.280	64.60	57.65	1950	8010	1.58
3	5.23	1.536	64.93	59.04	3310	9150	1.05
4	6.15	3.108	65.50	57.77	1320	7390	2.11
5	6.72	3.964	64.36	55.62	980	7000	2.65
6	5.50	1.957	64.59	58.13	2270	8000	1.29
7	5.90	2.730	66.14	58.86	1580	7760	1.86
8	7.80	4.491	65.25	55.20	830	6695	2.94
9	7.30	3.449	65.26	56.21	1160	7210	2.30
10	7.15	2.744	55.80	47.19	1250	6175	2.19
11	5.96	1.883	55.81	48.89	2040	6920	1.51
12	5.70	1.462	55.69	49.27	2640	6950	1.23
13	5.70	1.120	55.91	49.70	3310	6670	1.044
14	5.60	1.357	55.86	49.65	2950	7210	1.14
15	5.70	1.802	55.93	49.36	2290	7430	1.39
16	6.13	2.410	56.06	48.72	1550	6720	1.87
17	7.25	3.975	56.98	47.71	850	6080	2.96
18	6.20	1.540	51.65	44.70	2295	6360	1.38
19	6.10	1.338	51.72	45.00	2670	6430	1.225
20	6.04	1.166	51.83	45.28	2960	6220	1.13
21	6.63	1.893	52.63	45.06	1845	6290	1.62
22	6.20	1.146	52.09	45.52	3260	6720	1.033
23	6.46	1.866	52.25	44.42	1910	6410	1.59
24	6.90	2.202	52.43	43.73	1645	6520	1.12
25	7.12	2.650	52.73	42.60	1250	5970	2.20
26	7.65	3.477	52.96	41.02	920	5750	2.78
27	6.40	1.024	45.71	39.10	3350	6175	1.019
28	6.37	1.155	45.65	38.87	2920	6070	1.138
29	6.40	1.262	45.79	38.86	2630	5980	1.23
30	6.50	1.386	45.75	38.56	2350	5860	1.35
31	6.80	1.543	46.36	38.49	2035	5650	1.50
32	7.02	1.897	46.63	38.08	1630	5560	1.79
33	7.43	2.249	47.28	37.66	1315	5325	2.09
34	8.20	3.022	48.03	36.32	930	5060	2.73
35	6.35	1.015	46.23	39.32	3330	6080	1.035

TABLE 2 (Con't)
TABULATED RESULTS - METHYL ALCOHOL

RUN NO.	INLET WATER TEMP. °C	WATER TEMP. RISE °C	VAPOR TEMP °C	OVERALL WATER-VAPOR ΔT, °C	WATER FLOW W LB/HR	HEAT DUTY Q BTU/HR	$\frac{1X10^{3}V^{-.8}}{1+0.011t}$
36	6.50	1.307	60.76	53.61	3330	7800	1.005
37	6.55	1.440	60.76	53.49	2970	7700	1.118
38	6.55	1.633	60.76	53.39	2590	7630	1.243
39	6.60	1.696	60.75	53.30	2345	7165	1.342
40	6.75	2.137	60.80	52.98	1950	7490	1.550
41	6.90	2.478	61.87	53.73	1660	7410	1.757
42	7.20	2.983	61.89	53.20	1300	6985	2.11
43	7.40	3.357	62.09	53.11	1150	6950	2.32
44	7.60	3.897	62.56	53.01	970	6805	2.62
45	7.80	4.330	62.69	52.72	840	6545	2.92

FIGURE 3

VARIATION OF WATER TEMPERATURE RISE WITH FLOW RATE METHYL ALCOHOL

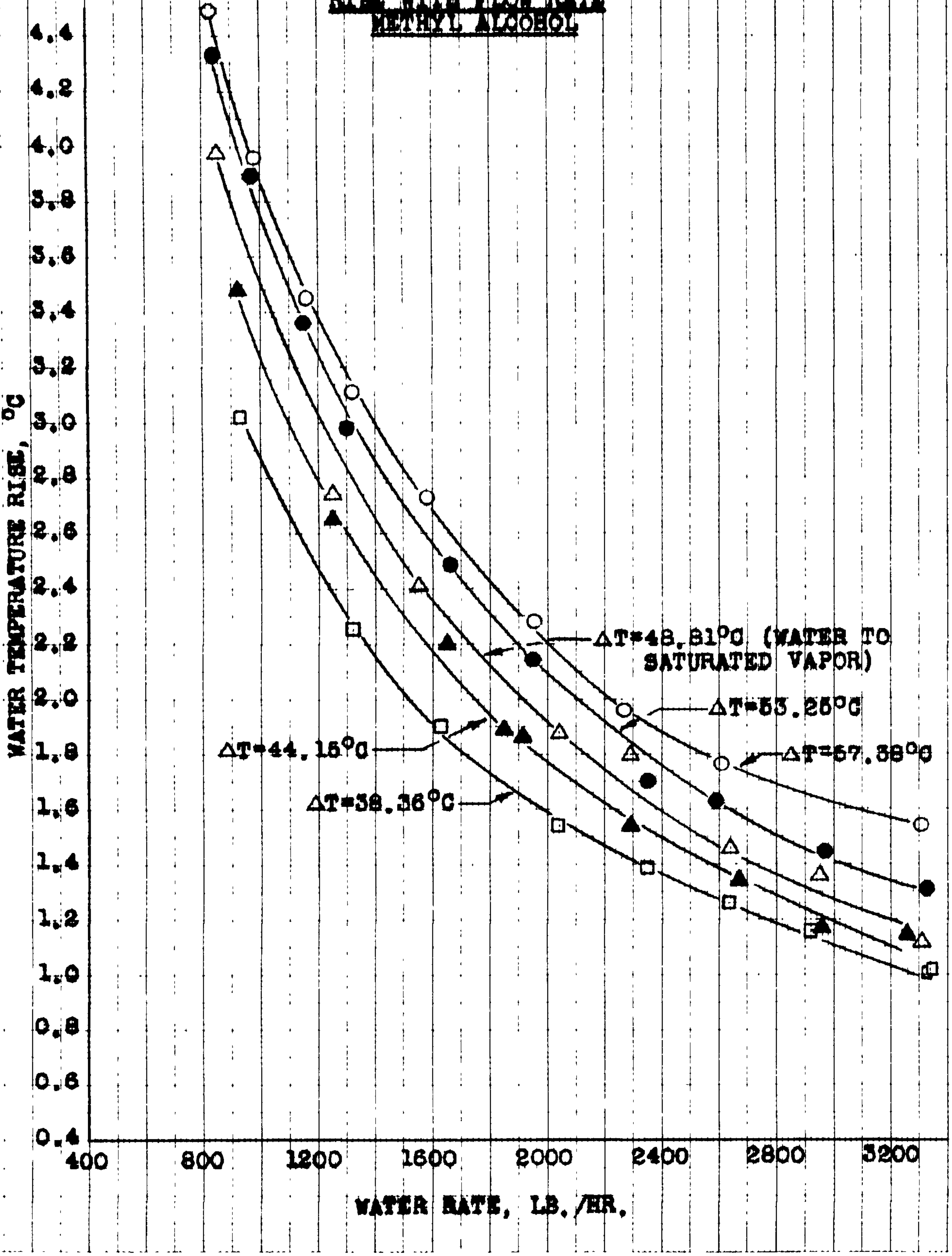


FIGURE 4

VARIATION OF HEAT TRANSFER RATE WITH WATER FLOW RATE

METHYL ALCOHOL

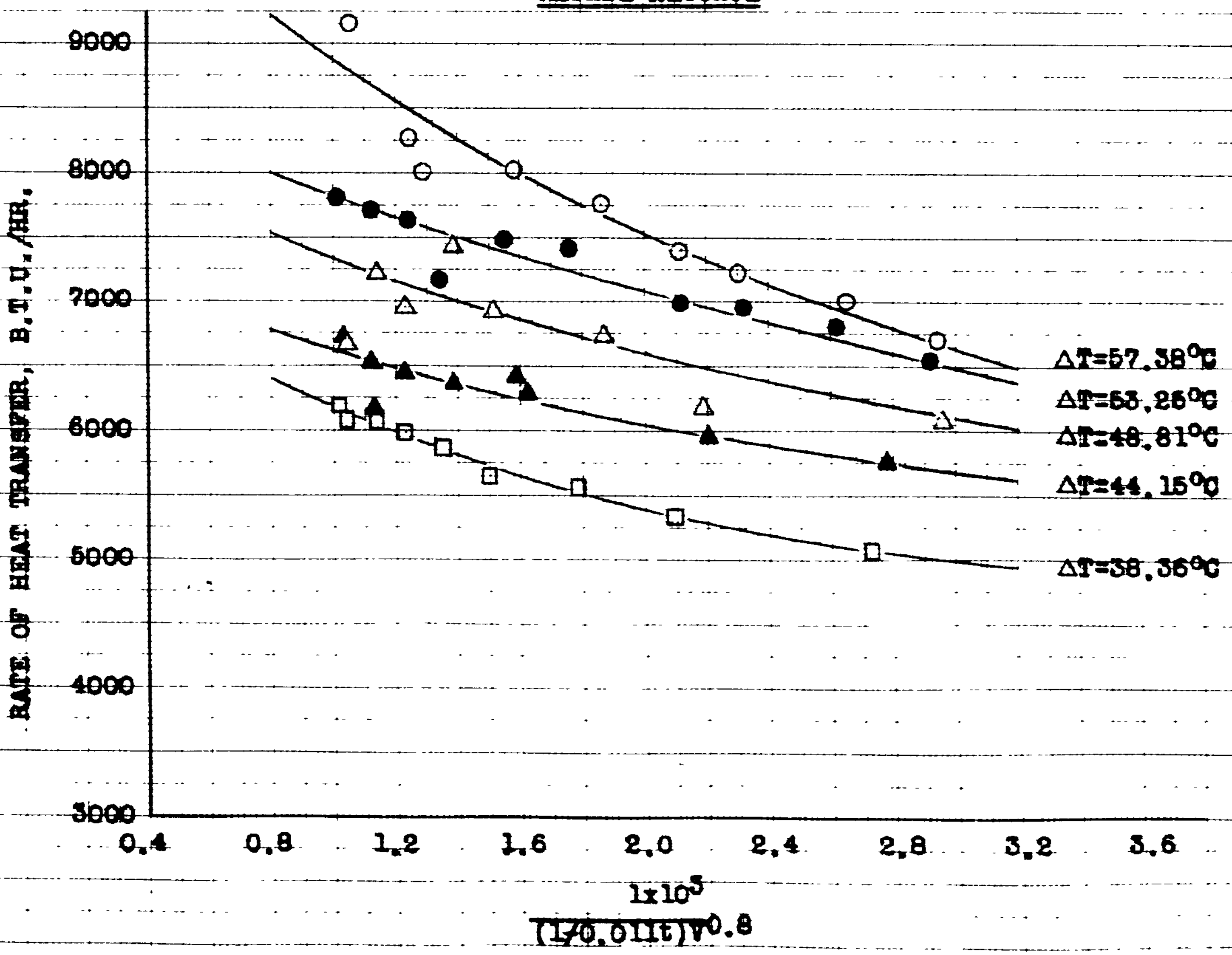


FIGURE 5- RELATION BETWEEN OVER-ALL THERMAL RESISTANCE AND WATER FLOW RATE

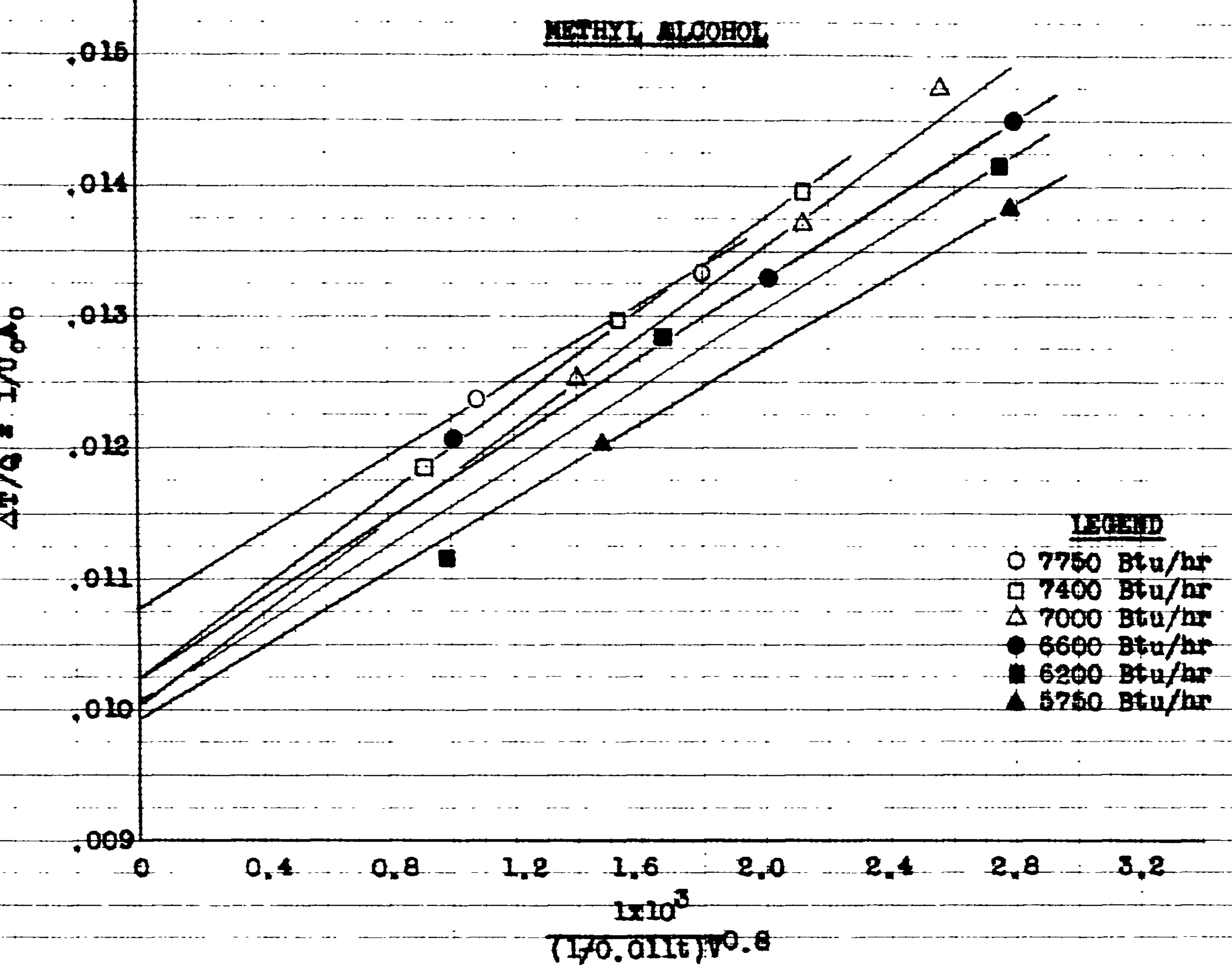


TABLE 3
TABULATED RESULTS - ISOPROPYL ALCOHOL

RUN NO.	INLET WATER TEMP. °C	WATER TEMP. RISE °C	VAPOR TEMP °C	OVERALL WATER-VAPOR ΔT, °C	WATER FLOW W LB/HR	HEAT DUTY Q BTU/HR	$\frac{1x10^3 V^{-.8}}{1+0.011t}$
46	7.15	2.080	83.13	74.94	1320	4940	2.10
47	6.80	1.405	82.80	75.30	2010	5080	1.523
48	6.70	1.169	82.77	75.49	2370	4980	1.338
49	6.70	1.032	82.30	75.08	2670	4970	1.200
50	7.35	2.653	82.37	73.69	980	4675	2.63
51	7.00	2.286	82.36	74.22	1155	4760	2.33
52	7.73	3.605	82.35	72.82	680	4420	3.48
53	5.97	.876	82.40	75.99	3255	5120	1.05
54	5.90	1.038	82.40	75.98	2720	5080	1.30
55	6.60	2.444	71.03	63.21	990	4360	2.65
56	6.90	2.952	71.78	63.40	810	4300	3.08
57	7.32	3.572	72.35	63.24	650	4180	3.64
58	5.98	1.475	69.24	62.52	1700	4510	1.775
59	5.75	1.277	69.71	63.32	1980	4550	1.575
60	5.60	1.093	69.57	63.42	2300	4530	1.388
61	5.50	.973	69.70	63.72	2675	4680	1.282
62	5.50	.861	69.43	63.50	3010	4660	1.123
63	5.60	.803	69.18	63.18	3240	4680	1.052
64	6.52	2.221	70.43	62.80	1100	4440	2.42
65	6.70	1.822	65.29	57.68	1245	4085	2.205
66	7.00	2.327	66.22	58.06	975	4090	2.68
67	7.40	2.576	67.71	59.02	830	3840	3.00
68	7.90	3.183	68.71	59.22	660	3780	3.59
69	6.51	1.421	65.48	58.26	1650	4220	1.788
70	6.30	1.159	64.05	57.17	1990	4150	1.547
71	6.25	.998	64.62	57.87	2310	4150	1.382
72	6.10	.820	64.41	57.90	2785	4110	1.190
73	6.00	.714	64.74	58.38	3220	4140	1.060
74	5.90	.913	59.09	52.71	2300	3780	1.385
75	6.00	1.095	59.46	52.91	1930	3800	1.590
76	5.80	.774	58.28	52.09	2705	3760	1.220
77	5.75	.636	57.76	51.69	3240	3710	1.060
78	6.24	1.329	59.98	53.07	1540	3680	1.89
79	6.50	1.582	60.44	53.15	1270	3620	2.20
80	6.87	1.945	61.09	53.25	1070	3750	2.50
81	7.20	2.439	61.51	53.07	830	3640	3.15
82	8.40	3.735	62.44	52.17	505	3400	4.46
83	7.63	2.883	61.58	52.51	660	3420	3.58

FIGURE 5

VARIATION OF WATER TEMPERATURE RISE WITH FLOW RATE

ISO-PROPYL ALCOHOL

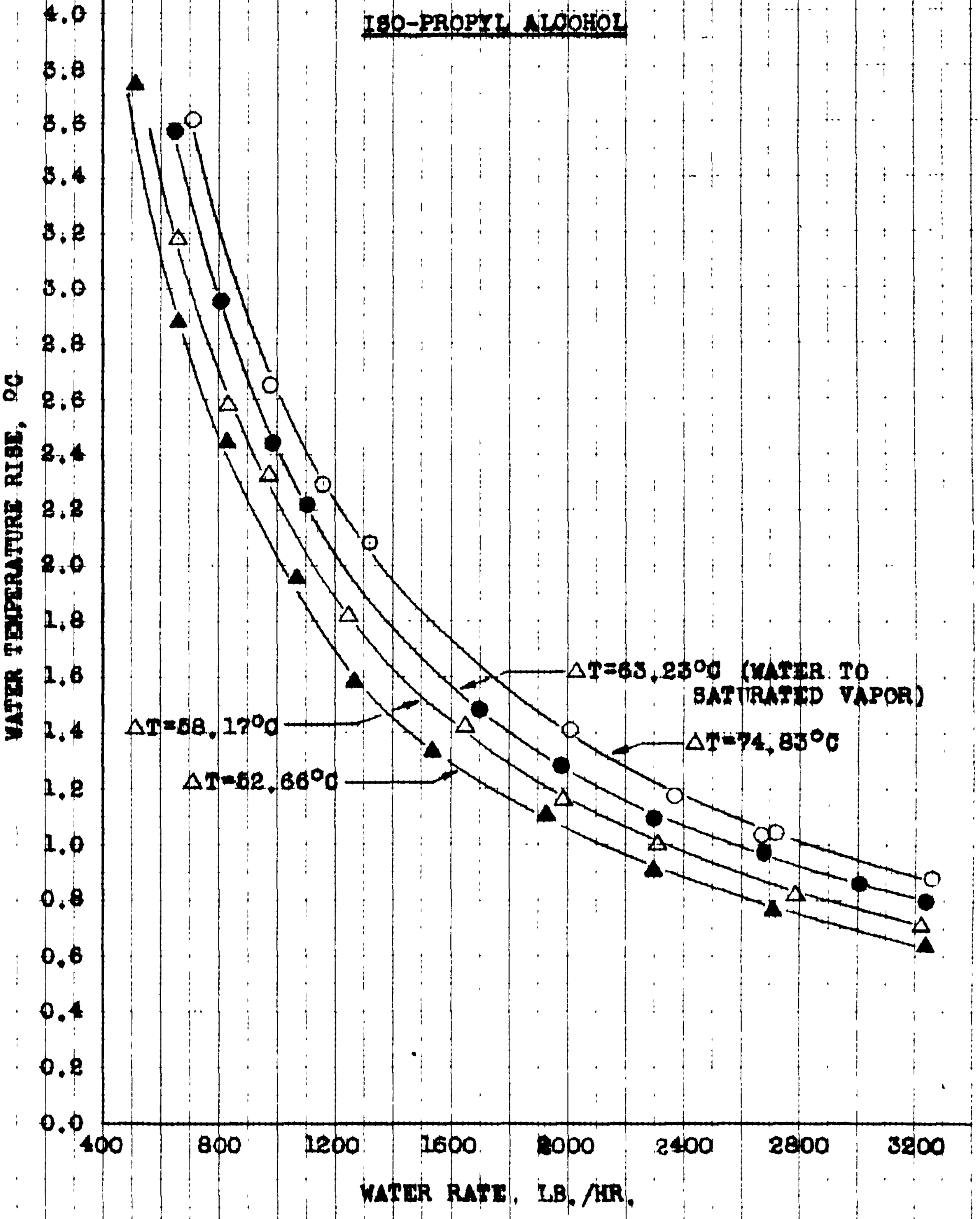


FIGURE 7-VARIATION OF HEAT TRANSFER RATE WITH WATER FLOW RATE

ISO-PROPYL ALCOHOL

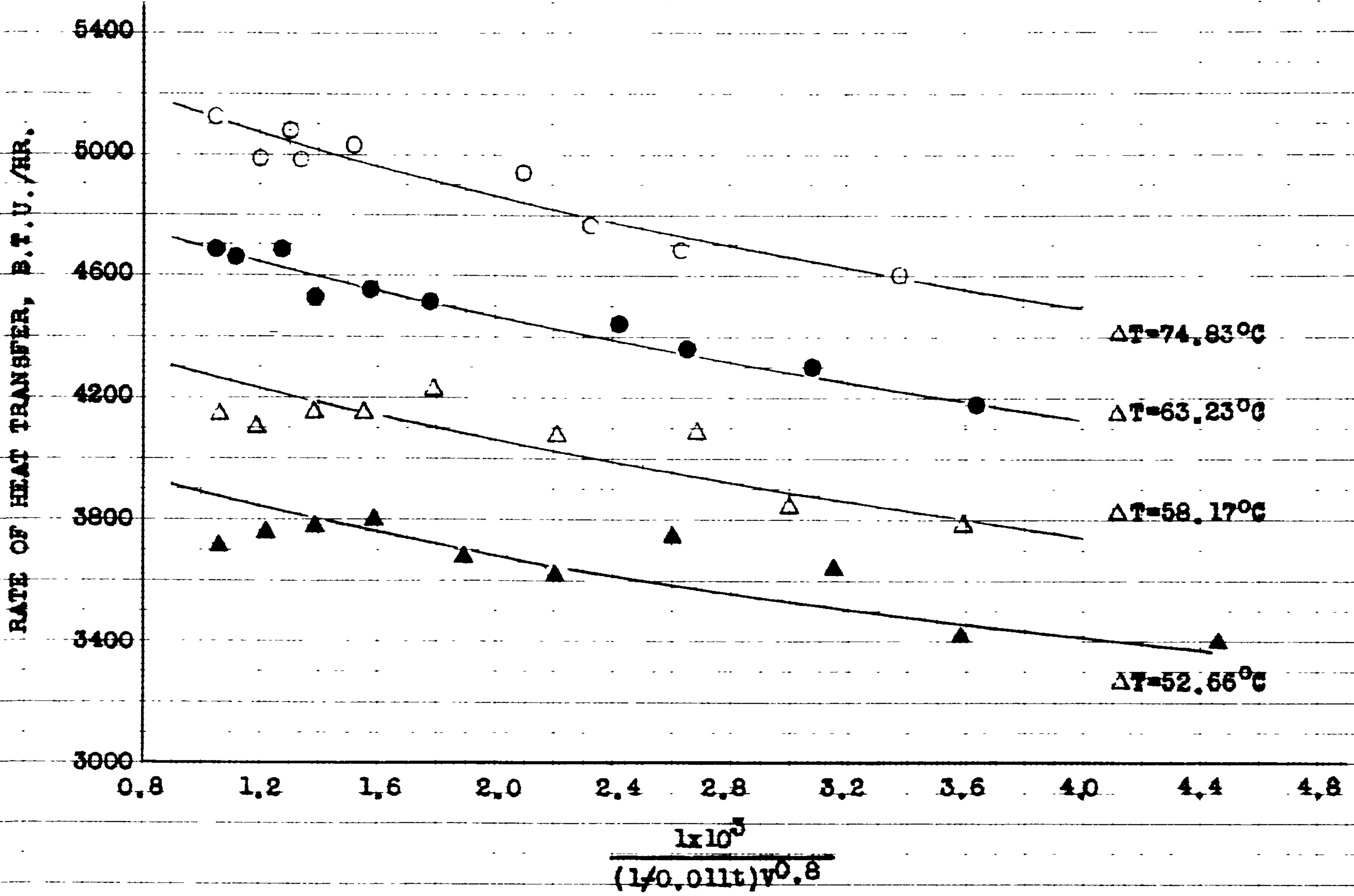
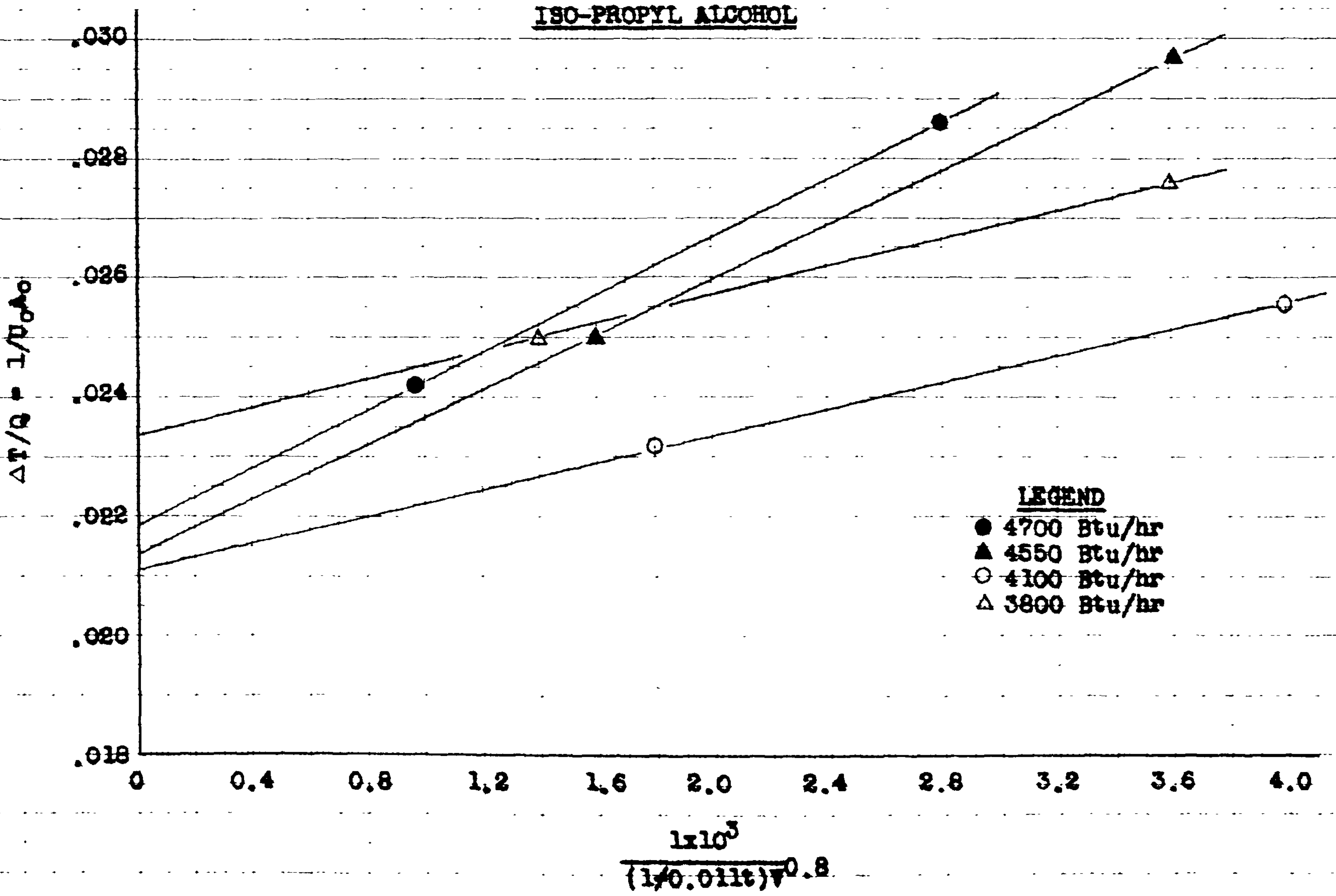


FIGURE 8 - RELATION BETWEEN OVER-ALL THERMAL RESISTANCE AND WATER FLOW RATE



ISO-PROPYL ALCOHOL

TABLE 4
TABULATED RESULTS - N-BUTYL ALCOHOL

RUN NO.	INLET WATER TEMP. °C	WATER TEMP. RISE °C	VAPOR TEMP. °C	OVERALL WATER-VAPOR ΔT, °C	WATER FLOW W LB/HR	HEAT DUTY Q BTU/HR	$\frac{1X10^3 V^{-.8}}{1+0.011t}$
84	7.50	2.251	95.14	86.51	1400	5665	2.00
85	8.10	3.378	95.86	86.07	930	5660	2.72
86	7.30	1.958	95.45	87.17	1680	5920	1.74
87	7.20	1.685	94.01	85.97	1980	6010	1.53
88	7.02	1.425	94.01	86.28	2345	6020	1.34
89	7.00	1.255	94.06	86.43	2680	6050	1.20
90	7.18	1.030	93.45	85.75	3235	6000	1.04
91	9.00	4.399	97.25	86.05	700	5540	3.34
92	8.90	4.358	97.14	86.06	720	5650	3.26
93	7.72	2.484	99.27	90.31	1365	6100	2.03
94	8.25	3.570	99.53	88.69	955	6140	2.62
95	8.88	4.427	100.23	89.14	750	5980	3.16
96	7.50	1.057	98.65	90.62	3240	6170	1.03
97	7.58	1.331	98.55	90.30	2595	6220	1.23
98	8.04	2.250	98.61	89.44	1515	6140	1.86
99	7.80	1.688	99.10	90.46	2040	6210	1.47
100	7.96	1.623	104.07	95.30	2265	6630	1.36
101	8.11	1.866	104.10	95.06	1940	6520	1.53
102	8.37	2.304	104.40	94.88	1595	6610	1.78
103	8.80	2.635	105.78	95.66	1400	6630	1.96
104	9.30	3.782	106.60	95.41	960	6540	2.59
105	9.50	4.253	107.07	95.44	830	6350	2.89
106	6.48	5.371	103.85	94.68	650	6290	3.64
107	8.00	1.169	103.65	95.07	3210	6750	1.03
108	8.00	1.299	103.80	95.15	2840	6640	1.13
109	8.00	1.420	108.67	99.96	2740	7010	1.17
110	7.98	1.220	108.38	100.40	3210	7050	1.03
111	8.30	1.714	109.35	100.19	2270	7000	1.35
112	8.35	1.901	109.79	100.49	1980	6790	1.50
113	8.50	2.422	110.45	100.74	1620	7060	1.75
114	8.80	2.992	110.44	100.49	1310	7050	2.06
115	6.67	5.517	108.60	99.17	665	6610	3.63
116	8.23	1.237	108.78	99.93	3210	7150	1.03
117	9.30	4.605	111.31	99.71	800	6640	3.03
118	8.80	3.406	111.07	100.57	1120	6860	2.31

TABLE 4 (Con't)
TABULATED RESULTS - N-BUTYL ALCOHOL

RUN NO.	INLET WATER TEMP. °C	WATER TEMP. RISE °C	VAPOR TEMP. °C	OVERALL WATER-VAPOR ΔT, °C	WATER FLOW W LB/HR	HEAT DUTY Q BTU/HR	$\frac{1X10^3 V^{-.8}}{1+0.011t}$
119	8.80	3.658	116.25	105.62	1115	7340	2.33
120	8.40	2.137	116.01	106.54	1995	7670	1.49
121	8.60	2.659	116.14	106.21	1580	7560	1.78
122	8.80	3.180	116.71	106.29	1310	7500	2.05
123	9.30	4.496	117.37	105.82	990	7370	2.69
124	7.86	5.768	116.79	106.00	665	6910	3.53
125	7.43	5.479	116.27	106.10	705	6950	3.37
126	8.81	5.056	116.54	105.20	775	7060	3.06

FIGURE 9 - VARIATION OF WATER TEMPERATURE RISE WITH FLOW RATE

N-BUTYL ALCOHOL

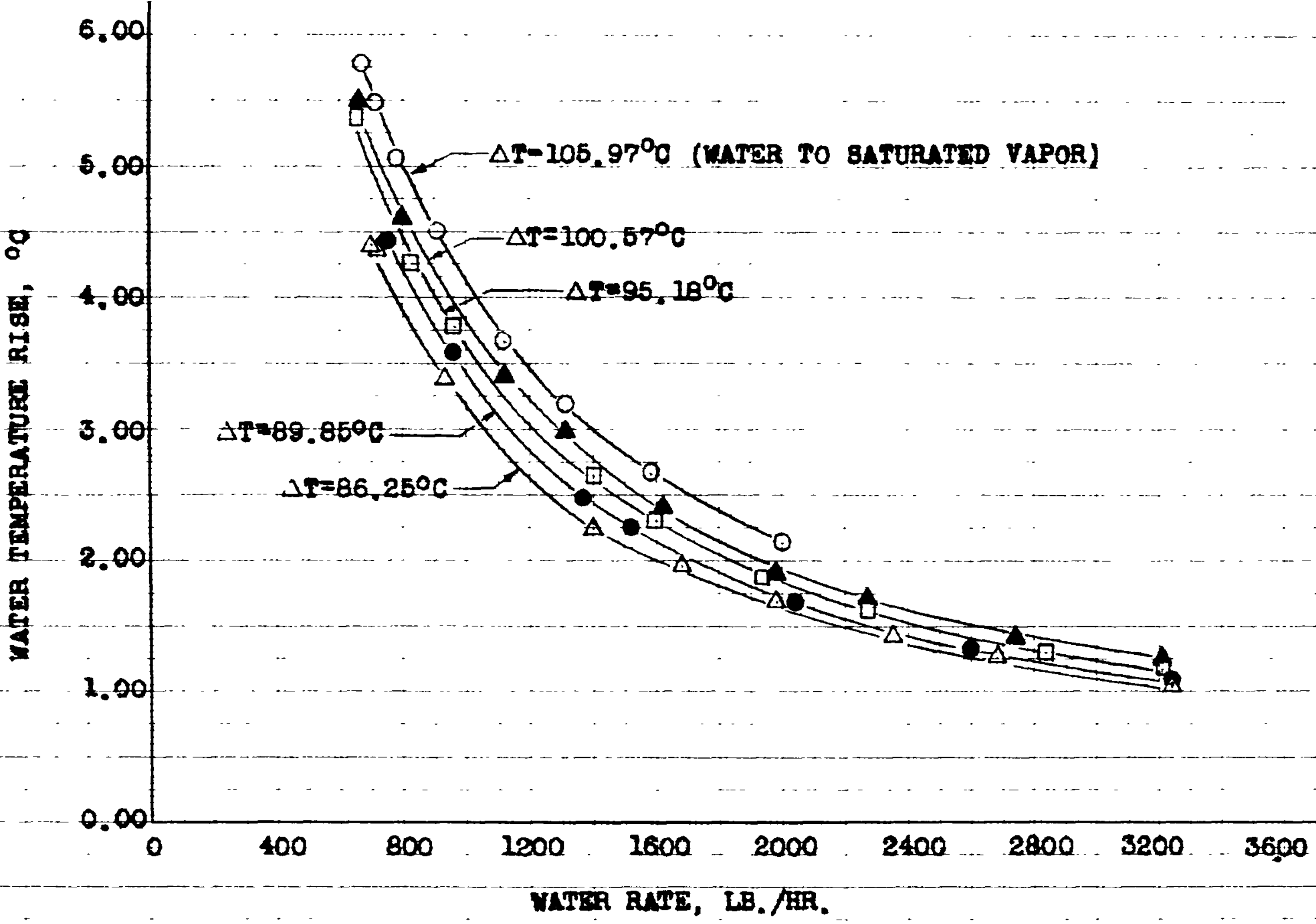


FIGURE 10 - VARIATION OF HEAT TRANSFER RATE WITH WATER FLOW RATE

N-BUTYL ALCOHOL

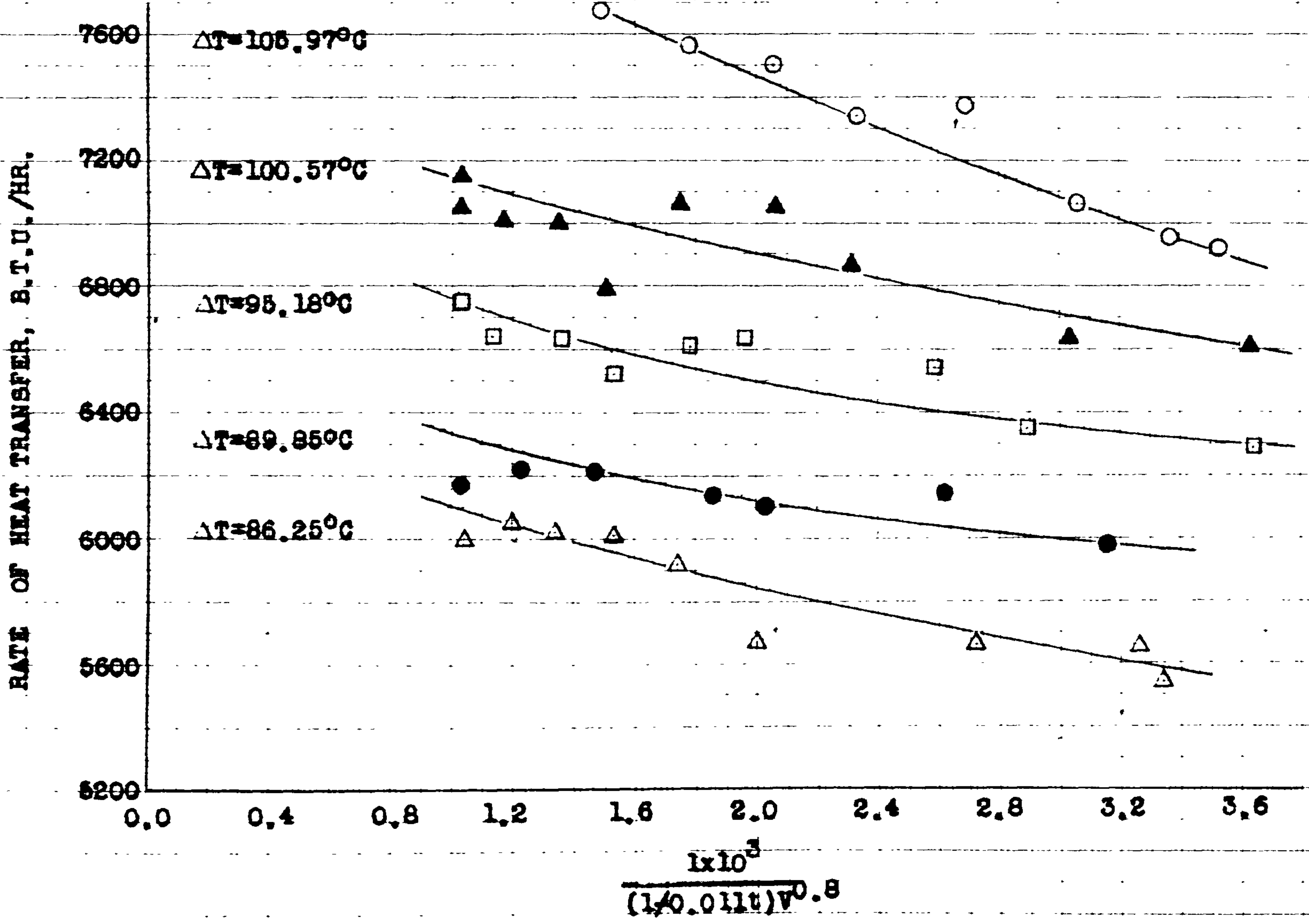


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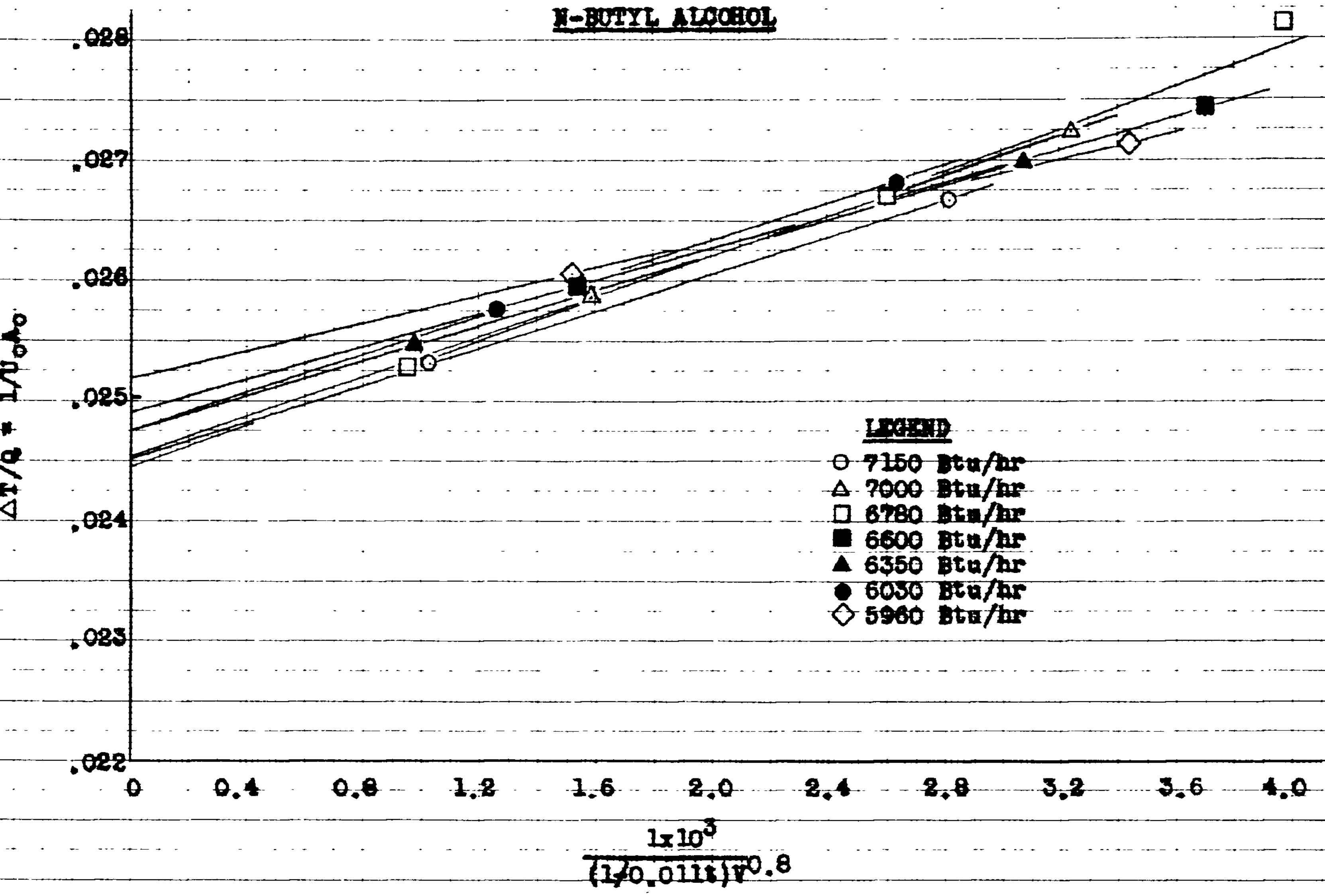
FIGURE 11 - RELATION BETWEEN OVER-ALL THERMAL RESISTANCE AND WATER FLOW RATE



N-BUTYL ALCOHOL

DISCUSSION

It has been found that the value of h_o varies with q for methyl and i-propyl alcohols. No variation was found for n-butyl alcohol. The values of h_o for methyl alcohol ranged from 485 to 527 with q varying from 7750 to 5750. For i-propyl alcohol, h_o varied from 221 to 250 with q changing from 4700 to 3800. The value of h_o for n-butyl alcohol was 208 with q ranging from 7150 to 5960.

The h_o values were determined from lines drawn through two or three points. Most of the values for methyl alcohol were obtained from three points and most of those for the other alcohols from two points. It is desirable to obtain as many points as possible. However, this is not always practicable. As is evident from Figures 4, 7, and 10, the number of points determined is dependent upon the slopes and spacing of the curves. The slopes of the curves are a function of each individual alcohol; the spacing is an experimental variable.

The data of Chu, et. al.; (7) indicate that the slopes of the above mentioned curves become very steep at high cooling water flow rates. Pump head limitations in this work prevented the experimental determination of the steep end of these curves. Investigation at high water rates would have provided additional points for the determination of h_o.

Reducing the spacing between curves to obtain more points was impracticable due to data overlap. This overlap is best demonstrated on Figures 3, 6, and 9.

It would have been desirable to make investigations over wider ranges of q. Limitations of the pressure controller made it impossible to obtain lower values of this parameter.

Since many of the values of h_o were determined from only two points, it is necessary to discuss the accuracy of these pairs of points. For the most part, these points were obtained from the head of one curve and the tail of another. (Figures 4, 7, and 10.) The head, or high cooling water rate end, was usually well defined by a large number of data points. The tail, or low water rate end, was usually defined by fewer points, tending to make this end of the curve less reliable. Also, as the overall temperature difference decreased, the curves became flatter. This was to be expected since from a theoretical consideration, q will equal zero when the overall temperature difference is zero, no matter what the rate of cooling water flow. A slight change in slope of these flat curves can make a large difference in the intercept selected to calculate h_o. Therefore, the points obtained from low water rates and/or low overall temperature differences are least reliable.

The water flow rate variation was less than one per cent, except at low flows where it was occasionally as high as three per cent. It is believed, therefore, that the value of q is correct to within ±3 per cent. The Beckmann thermometers could be read to within

0.002 °C. Since the minimum cooling water temperature rise was about 0.800 °C the maximum error involved in reading these thermometers is ±0.5 per cent. The average variation of the overall water to vapor temperature difference is ±1 per cent. This variation was kept to a minimum by adjusting vapor temperature as water temperature changed. The overall error of the observed condensing film coefficients is estimated to be 5 to 10 per cent.

As shown in a previous section, the relation of h_e and q is such that a log-log plot of h_e and q should give a straight line with a slope of minus one-third. This plot is shown in Figure 12 and the data listed in Table 5. The data on methyl and i-propyl alcohols confirm this theoretical relationship. The slope for methyl alcohol was -0.278 and for i-propyl alcohol was -0.405. The deviation of these slopes from -0.333 is within the accuracy of the graphical techniques involved. No variation of h_e and q was found for n-butyl alcohol. The reasons for this are unknown at this time.

The value of h_e at the lowest measured value of q for i-propyl alcohol is inconsistent with the other determinations. As discussed above, this inconsistency is probably a result of the inaccuracies inherent in the determination of h_e at low values of q.

As discussed in the "Theory", Bromley re-derived the Nusselt equation, taking into account the effect of the heat capacity of condensate. The observed results of the condensing film coefficients of heat transfer have been compared to those predicted by both the

Nusselt and Bromley equations. These results are presented in Table 5.

The agreement between the observed values of h_o and those predicted by the Nusselt equation is excellent for methyl and i-propyl alcohols. The ratio of h_{obs}/h_{calc} ranges from 0.975 to 1.020 for methyl alcohol and from 0.975 to 0.992 for i-propyl alcohol, with a ratio of 0.863 for the one inconsistent data point for i-propyl alcohol. The agreement between the observed and the predicted values of n-butyl alcohol is good, the ratio ranging from 0.879 to 0.934. For the most part, for the alcohols studied, the observed values of h_o were lower than the theoretical values.

The condensing film coefficients predicted by the Bromley equation are higher than those predicted by the Nusselt equation. Bromley's predictions were 2% higher for methyl alcohol, 4 to 5 per cent higher for i-propyl alcohol, and 6 to 7 per cent higher for n-butyl alcohol. This equation, although supposedly better than Nusselt's at high pressures, apparently overpredicts coefficients at low and reduced pressures. It can be concluded from these observations that the Nusselt equation satisfactorily predicts condensing film coefficients at low pressures where the effect of the heat capacity is negligible.

The values of h_o were calculated at constant values of q. Since the variations of latent heats were small over the range investigated in this work, the tube loadings and film thicknesses for any one alcohol remained essentially constant for these values of h_o. Also, the acceleration effects of the vapor on the condensate film were minimized by using a large condenser jacket. These are further reasons for the agreement between the observed and theoretical results predicted by the Nusselt equation.

This study shows that the ratio of h_{obs}/h_{calc} decreases as the molecular weight of the alcohol increases. The average of the ratios for the three alcohols in order of increasing molecular weight are 0.997, 0.950, and 0.910. It should be noted that the work of Chu, et. al., (7) indicates a ratio of 0.420 for n-hexyl alcohol.

It has been suggested in the past that sub-cooling of condensate occurs and effects the experimental results. In order to measure the effect of sub-cooling, if any, a thermocouple was installed to measure the condensate temperature. These temperature data are listed in Tables 8, 9, and 10.

In all cases the measured condensate temperatures were about 5 to 10°C lower than the saturated vapor temperatures. Since this measured bulk condensate temperature is higher than any average calculated with the equation recommended by Mc Adams (15), $t_f = t_{sv} - 0.75\ (t_{sv} - t_s)$, it is felt that sub-cooling did not effect the experimental results of this work. Furthermore, excess vapors were present in the test condenser at all times.

Another possible source of error is the presence of non-condensable gases in the condensing vapor. The experimental technique, as described in a previous section, precludes this possibility.

The fouling of a condenser tube surface effects the condensing film coefficients. Rhodes and Younger (23) found that the apparent thermal resistance of a fouled tube can be 10 to 20 per cent higher than that of a cleaned tube. This may partially account for the fact that the ratios of h_{obs}/h_{calc} were usually less than unity.

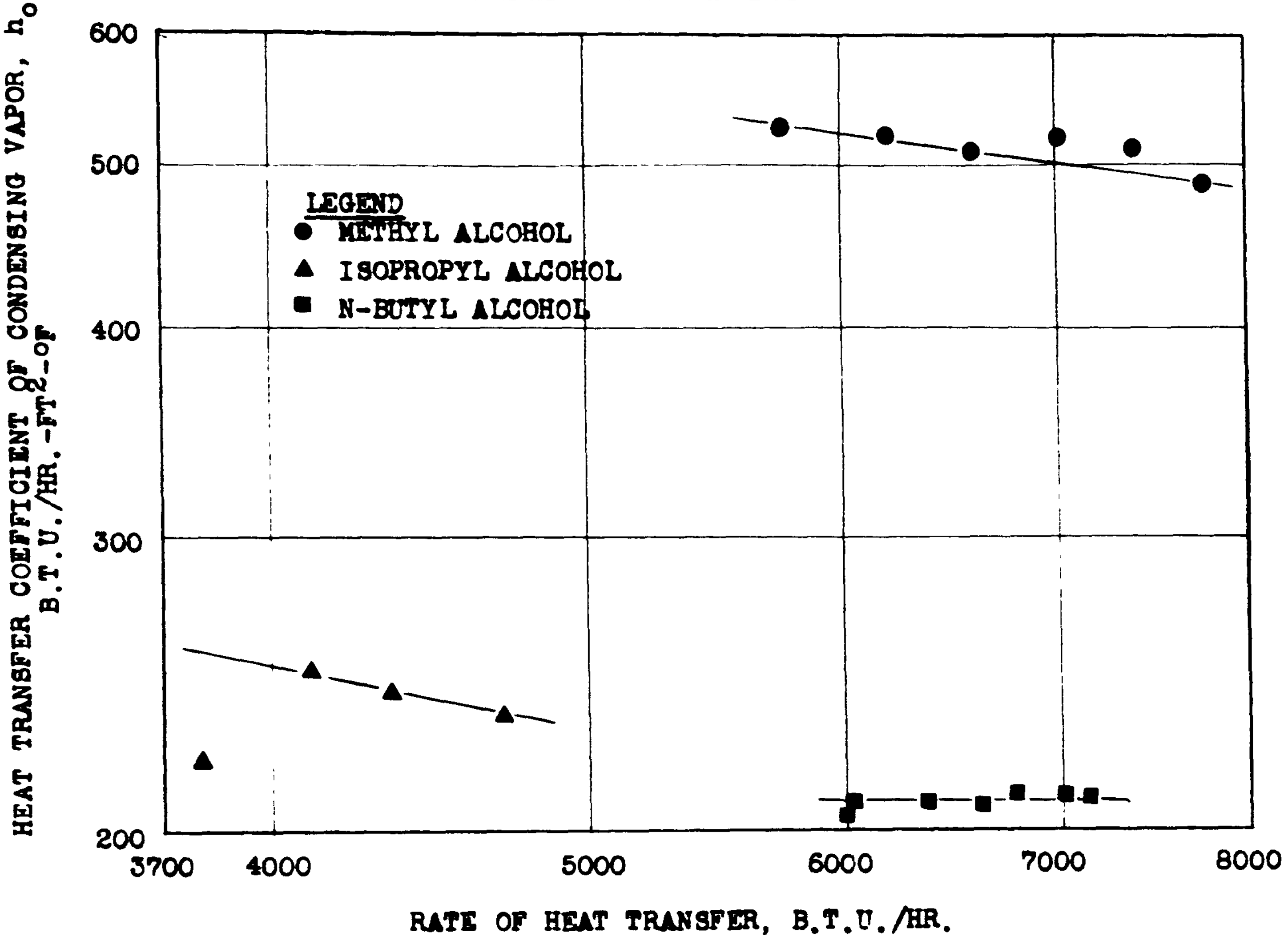
The predicted condensing film coefficients are always affected by the physical property data used. The properties of the alcohols used in this work were obtained from the <u>International Critical Tables</u> (10) and from other, more recent, literature (2) (8) (9) (15) (21). There is considerable inconsistency in these data, especially for thermal conductivity.

TABLE 5
COMPARISON BETWEEN OBSERVED AND CALCULATED HEAT TRANSFER COEFFICIENTS OF CONDENSING VAPOR

q	Temp. Diff. Across Cond.	ho Observed	ho Theoretical Nusselt	ho Theoretical Bromley	Ratios of Obs. to Theoretical ho	
BTU/HR	°F	(a)	(b)	(c)	(a)/(b)	(a)/(c)
			METHYL ALCOHOL			
7750	103	485	493	504	.984	.962
7400	96	511	502	512	1.020	.998
7000	87	521	515	525	1.012	.992
6600	87	511	513	524	.997	.975
6200	80	520	525	535	.991	.972
5750	69	527	540	549	.975	.960
			ISOPROPYL ALCOHOL			
4700	135	236	242	255	.975	.925
4550	114	242	248	260	.975	.931
4100	105	250	252	262	.992	.954
3800	96	221	256	266	.863	.831
			NORMAL BUTYL ALCOHOL			
7150	192	210	225	242	.934	.868
7000	181	210	228	243	.921	.864
6780	181	211	228	243	.926	.868
6600	172	207	229	244	.904	.848
6350	172	208	229	244	.908	.852
6030	162	208	230	245	.904	.849
5960	156	204	232	246	.879	.829

FIGURE 12

THE VARIATION OF HEAT TRANSFER COEFFICIENT OF CONDENSING VAPOR WITH RATE OF HEAT TRANSFER



CONCLUSIONS

The technique of Chu, Flitcraft, and Holeman, for measuring the film coefficients of condensing vapors, has been checked with methyl, i-propyl, and n-butyl alcohols. Chu and associates concluded that

$$h_o = c\, q^{-1/3}$$

The work on methyl and i-propyl alcohols presented in this paper substantiate their conclusion. No variation of h_o and q was found for n-butyl alcohol.

The theoretical condensing film coefficients calculated from the Nusselt and Bromley equations were compared with the observed values. The Nusselt equation predicted values of h_o closer to those observed than did the Bromley equation. Excellent agreement of theoretical and observed coefficients was found for methyl and i-propyl alcohols, and good agreement was found for n-butyl alcohol. In all cases the Bromley equation predicted higher values of h_o than did the Nusselt equation. It can be concluded from these observations that the Nusselt equation satisfactorily predicts condensing film coefficients at low pressures where the effect of the heat capacity of condensate is negligible.

The close agreement between the theoretical and observed coefficients is attributed to 1) the rigorous theoretical analysis of the Wilson method, as presented by Chu and associates, eliminating variables not previously considered and 2) the use of equipment, designed specifically for this work, which represents an improvement over apparatus used by other investigators.

RECOMMENDATIONS

The following recommendations are forwarded:

1. Continue investigations with the aliphatic alcohols. Determine the relationship, if any, between the ratio of h_{obs}/h_{calc} and molecular weight.

2. Investigate other homologous series of organic compounds.

3. Conduct investigations over a wider range of cooling water flow rates. Initiate studies at positive pressures.

NOMENCLATURE

a, b, c = constants

A_o, A_i, A_{av} = external, inside, and average surface area of a tube perpendicular to the flow of heat, sq. ft.

C_p = heat capacity of condensate, Btu/lb. -°F.

D_i, D_o = inside, outside diameter of tube, ft.

g = gravitational constant, 4.17×10^8 ft./(hr)^2

h_o, h_{obs}, h_{calc} = film coefficient, observed film coefficient and calculated film coefficient of condensate outside of a tube, Btu/(hr) (°F) (sq.ft.)

k_f = thermal conductivity of condensate film, Btu/(hr) (sq.ft.) (°F/ft.)

k_w = thermal conductivity of tube wall, Btu/(hr.) (sq.ft.) (°F/ft.)

q, Q = rate of heat transfer, Btu/hr.

R = thermal resistance, (°F) (hr.)/Btu. R_w for tube wall, R_v for condensing vapor, R_{vo} for condensate at infinite rate of flow of water, and R for total resistance ($= 1/U$)

t = temperature, °F or °C. t for water bulk, t_f for condensate film, t_s for outside tube surface, t_{sv} for saturated vapor.

Δt = temperature difference across condensate, °F.

ΔT = overall (water bulk to saturated vapor) temperature difference, °F.

U_o = overall heat transfer coefficient based on outside tube surface area Btu/ (hr.) (°F) (sq.ft.)

V = average velocity of flow, ft./sec. based on a water density of 62.3 lb./cu. ft. ($V =$ lb/hr. in the calculation procedures).

x = thickness of tube wall, ft.

λ = latent heat of vaporization, Btu/lb.

ρ_f, ρ_v = condensate film, vapor density, lb./cu. ft.

μ_f = absolute viscosity of condensate film, lb./(hr.) (ft.)

APPENDIX

APPENDIX CONTENTS

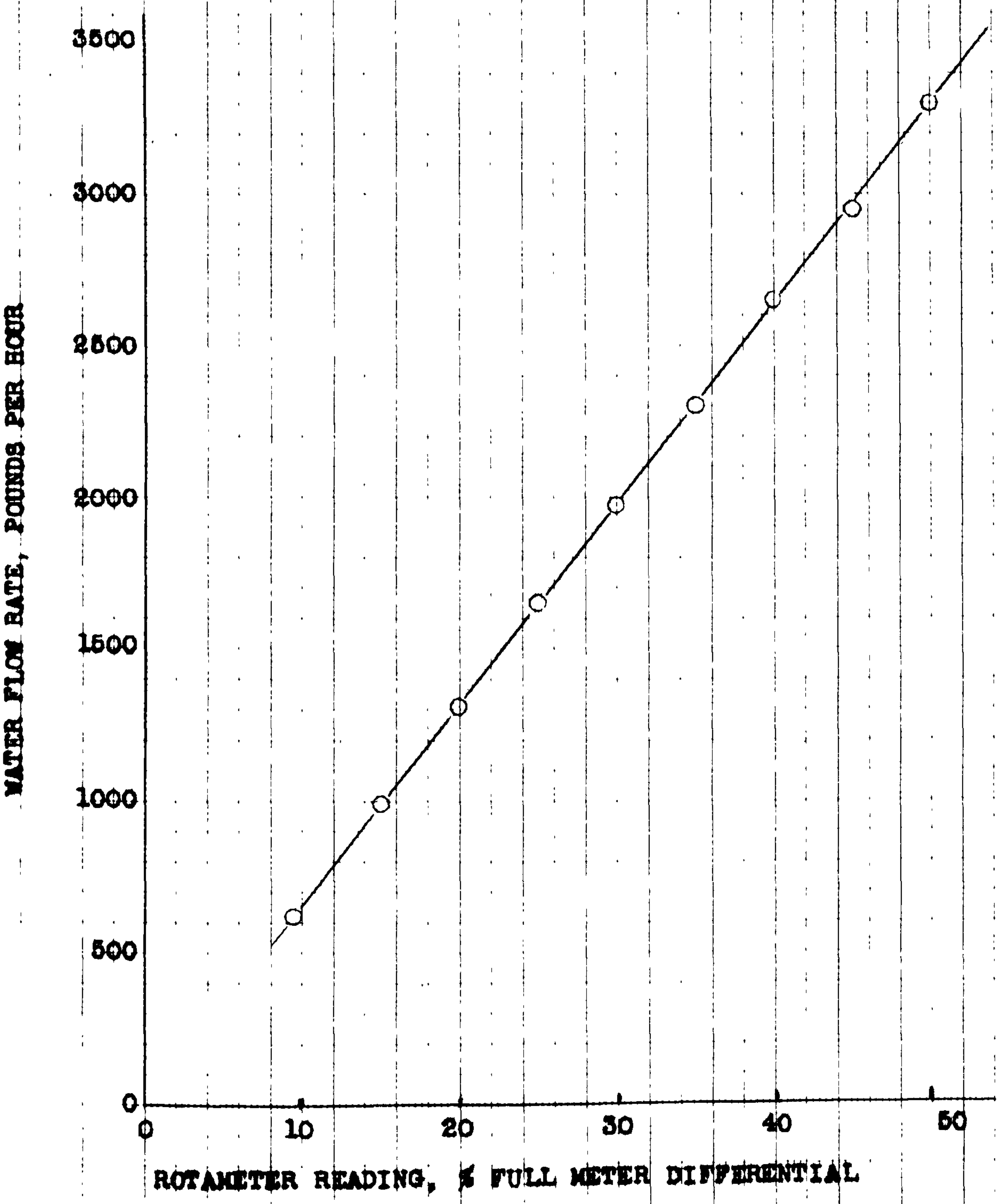
TABLE 6

ROTAMETER CALIBRATION - ORIGINAL DATA

POINT NO.	ROTAMETER READING %FMD	TIME MIN.	WEIGHT DELIVERED LBS.	WATER TEMP. °C	WATER FLOW LB/HR
1	9.5	5.78	60.0	10.3	623
2	15.0	2.425	40.0	11.0	990
3	20.0	3.66	80.0	10.5	1311
4	25.0	2.91	80.0	10.0	1650
5	30.0	2.43	80.0	9.9	1975
6	35.0	2.08	80.0	10.0	2305
7	40.0	1.815	80.0	9.0	2645
8	45.0	1.630	80.0	8.5	2945
9	50.0	1.452	80.0	8.4	3300

FIGURE 13

ROTAMETER CALIBRATION CURVE



REFERENCE CORRECTION OF BECKMANN THERMOMETERS

Two Beckmann thermometers were used to measure the cooling water temperature rise. No attempt was made to adjust the mercury columns to the same scale reading. However, both mercury levels were adjusted to the lower ends of the scales at the prevailing cooling water temperatures for maximum utilization of the scales.

Since the mercury columns in the Beckmann thermometers were not preset to the same scale reading, the indicated temperature difference at zero heat duty had to be determined. This was accomplished by pumping water through the condenser tube at a constant rate until the system reached equilibrium. The temperature difference was then read. This reading, or "blank", was algebraically added to the indicated temperature rise at a finite heat duty to obtain the true increase.

It was found that there was a small, but measurable, rise in water temperature due to friction in the condenser tube. This temperature rise increased with increasing water flow rate. A calibration curve was developed to determine the magnitude of this effect. This curve is shown in Figure 14. It is evident that this temperature rise would have a significant effect upon temperature differences measured under test conditions. Therefore, a correction for the friction effect, as shown in Figure 14, was employed.

It is convenient to illustrate the use of the correction factors with an example. Assume that a "blank" was established for the Beckmann thermometers at a rotameter reading of 50 per cent. At this water rate, a temperature difference of 0.500°C was indicated. Under test conditions at the same flow rate, say the temperature difference was 1.700°C. The actual temperature difference in the condenser tube would then be 1.700 - 0.500 or 1.200°C. As shown by Figure 14, the increase due to friction alone was 0.262°C. Therefore, the true temperature difference resulting from the condensing vapor is 1.200 - 0.262°C or 0.938°C.

All differential temperature data presented in this work were corrected in the above manner.

TABLE 7

TEMPERATURE RISE DUE TO FRICTION
CONDENSER TUBE BLANK

RUN NO.	ROTA-METER RDG %	INLET WATER TEMP. °C	INLET BECK-MANN TEMP. °C	OUTLET BECK-MANN TEMP. °C	ΔT BECK-MANN °C	RELA-TIVE ΔT °C
C1	50.0	6.20	2.102	0.412	1.690	0.262
C2	40.00	6.30	2.217	0.615	1.602	0.174
C3	30.0	6.75	2.597	1.066	1.531	0.103
C4	19.0	7.40	3.228	1.757	1.471	0.043
C5	9.0	9.20	5.091	3.659	1.432	0.004
C6	14.9	8.00	3.889	2.434	1.455	0.027

FIGURE 14

VARIATION OF THE RELATIVE WATER TEMPERATURE RISE DUE TO FRICTION WITH FLOW RATE

CONDENSER TUBE BLANK

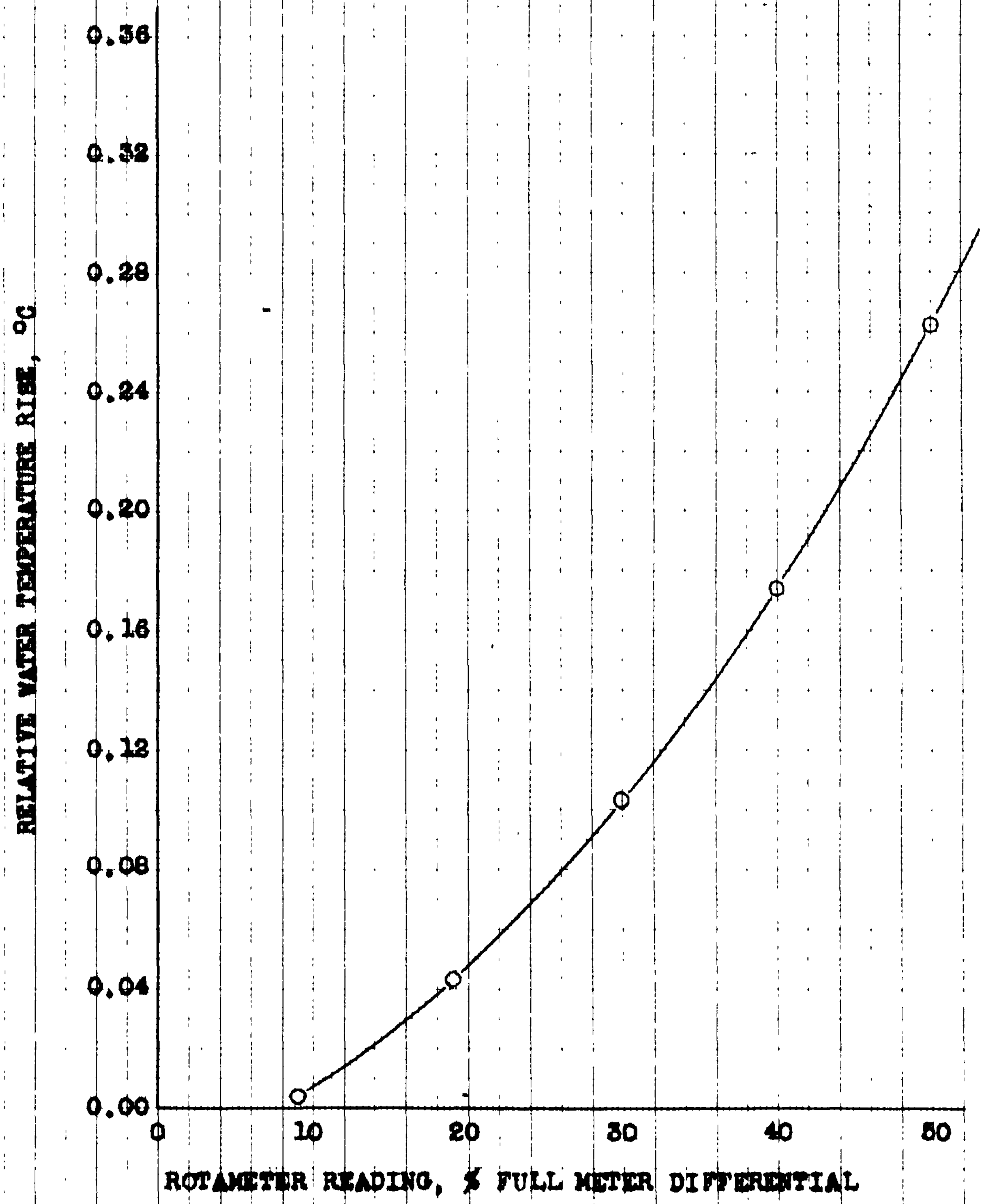


TABLE 8

ORIGINAL DATE - METHYL ALCOHOL

RUN NO.	ROTA-METER RDG	INLET WATER TEMPERATURE		OUTLET WATER TEMPERATURE		VAPOR TEMP.	FILM TEMP.	
	%	ABSO-LUTE °C	BECK-MANN °C	ABSO-LUTE MV	BECK-MANN °C	°C	MV	°C
C	45.0	5.60	2.301		0.627			
1	39.5	5.50	2.153	0.266	2.191	64.29	2.42	58.8
2	29.7	5.80	2.517	0.300	3.146	64.60	2.44	59.3
C	50.0	5.20	2.451		0.804			
3	50.0	5.23	1.954	0.195	1.631	64.93	2.40	58.4
C	28.4	6.20	2.440		0.823			
4	20.1	6.15	2.860	0.310	4.398	65.50	2.46	59.8
5	15.0	6.72	3.437	0.370	5.853	64.36	2.44	59.3
6	34.5	5.50	2.235	0.240	2.535	64.59	2.40	58.4
7	24.0	5.90	2.615	0.296	3.754	66.14	2.45	59.5
C	13.7	7.70	3.468		1.621			
C	31.3	6.70	2.399		0.465			
8	12.7	7.80	3.575	0.450	6.222	65.25	2.50	60.6
9	17.7	7.30	3.032	0.384	4.618	65.26	2.48	60.2
C	45.2	6.00	0.887		1.158			
10	19.0	7.15	1.926	0.347	5.118	55.80	2.07	50.9
C	37.0	5.70	1.468		0.423			
11	31.0	5.96	1.608	0.258	2.488	55.81	2.07	50.9
12	40.0	5.70	1.400	0.242	1.795	55.69	2.06	50.7
13	50.0	5.70	1.393	0.244	1.428	55.91	2.07	50.9
C	26.3	6.10	2.166		0.552			
14	44.7	5.60	1.844	0.222	1.453	55.86	2.05	50.4
15	34.7	5.70	1.885	0.248	1.919	55.93	2.06	50.7
16	23.5	6.13	2.315	0.288	3.127	56.06	2.08	51.1
17	13.0	7.25	3.416	0.392	2.424	56.98	2.14	52.5
C	27.2	6.50	2.531		0.846			
18	34.8	6.20	2.302	0.260	2.107	51.65	1.90	46.9
19	40.4	6.10	2.236	0.250	1.796	51.72	1.92	47.4
20	46.3	6.04	2.214	0.246	1.552	51.83	1.92	47.4
21	28.0	6.63	2.715	0.295	2.918	52.63	1.95	48.1
C	40.0	6.40	2.310		0.471			
22	49.3	6.20	2.269	0.236	1.496	52.09	1.93	47.7
23	29.0	6.46	2.463	0.272	2.544	52.25	1.94	47.9
24	25.0	6.90	2.885	0.302	3.350	52.43	1.95	48.3
C	14.2	7.65	3.629		2.031			

TABLE 8 (con't)
ORIGINAL DATE - METHYL ALCOHOL

RUN NO.	ROTA-METER RDG	INLET WATER TEMPERATURE		OUTLET WATER TEMPERATURE		VAPOR TEMP.	FILM TEMP.	
		ABSOLUTE	BECKMANN	ABSOLUTE	BECKMANN			
	%	°C	°C	MV	°C	°C	MV	°C
25	19.0	7.12	3.108	0.346	4.140	52.73	1.98	48.8
26	14.1	7.65	3.657	0.400	5.536	52.96	2.01	49.5
C	50.0	6.30	2.415		0.633			
27	50.6	6.40	2.422	0.240	1.664	45.71	1.62	40.2
28	44.2	6.37	2.375	0.246	1.802	45.65	1.63	40.4
29	39.8	6.40	2.365	0.248	1.936	45.79	1.65	40.9
30	35.7	6.50	2.430	0.258	2.157	45.75	1.65	40.9
C	30.9	6.80	2.940		1.361			
31	30.9	6.80	2.750	0.280	2.714	46.36	1.72	42.6
32	24.8	7.02	2.973	0.300	3.328	46.63	1.74	43.1
33	20.0	7.43	3.336	0.333	4.088	47.28	1.77	43.8
34	14.2	8.20	4.133	0.400	5.663	48.03	1.81	44.8
35	50.3	6.35	2.360	0.250	1.640	46.23	1.71	42.4
C	50.0	6.50	2.352		0.692			
36	50.3	6.50	2.417	0.256	2.061	60.76	2.27	55.4
37	45.0	6.55	2.432	0.264	2.256	60.76	2.27	55.4
38	39.3	6.55	2.408	0.270	2.473	60.76	2.27	55.4
39	35.6	6.60	2.468	0.276	2.624	60.75	2.27	55.4
40	29.6	6.75	2.579	0.300	3.217	60.80	2.28	55.7
41	25.2	6.90	2.709	0.320	3.714	61.87	2.32	56.6
42	19.8	7.20	3.038	0.352	4.577	61.89	2.33	56.8
C	13.7	7.70	3.468		1.621			
C	31.3	7.60	2.399		0.465			
43	17.5	7.40	3.172	0.394	4.667	62.09	2.36	57.5
44	14.8	7.60	3.367	0.412	5.413	62.56	2.39	58.2
45	12.9	7.80	3.540	0.440	6.025	62.69	2.40	58.4

TABLE 9
ORIGINAL DATA - ISOPROPYL ALCOHOL

RUN NO.	ROTA-METER RDG	INLET WATER TEMPERATURE		OUTLET WATER TEMPERATURE		VAPOR TEMP.	FILM TEMP.	
		ABSOLUTE	BECKMANN	ABSOLUTE	BECKMANN			
	%	°C	°C	MV	°C	°C	MV	°C
C	37.4	6.65	2.445		0.452			
C	19.0	7.20	2.968		1.077			
46	20.1	7.15	2.920	0.320	3.104	83.13	3.15	75.3
47	30.5	6.80	2.567	0.280	2.029	82.80	3.15	75.3
48	35.9	6.70	2.494	0.264	1.682	82.77	3.12	74.7
C	46.2	6.80	2.576		0.552			
C	23.5	7.10	2.803		0.948			
49	40.4	6.70	2.444	0.262	1.501	82.30	3.10	74.2
50	15.0	7.35	3.042	0.352	3.880	82.37	3.13	74.9
51	17.6	7.00	2.703	0.342	3.163	82.36	3.13	74.9
52	10.9	7.73	3.456	0.410	5.260	82.35	3.15	75.3
C	40.1	6.30	1.925		0.080			
53	49.2	5.97	1.658	0.235	0.611	82.40	3.12	74.7
54	41.2	5.90	1.591	0.240	0.774	82.40	3.10	74.2
C	19.4	6.65	2.287		0.576			
55	15.1	6.60	2.206	0.316	2.957	71.03	2.69	65.0
56	12.4	6.90	2.495	0.350	3.764	71.78	2.74	66.1
57	10.0	7.32	2.956	0.390	4.850	72.35	2.75	66.4
58	25.8	5.98	1.576	0.250	1.305	69.24	2.60	62.9
C	19.7	6.17	1.768		0.017			
59	30.1	5.75	1.379	0.230	0.846	69.71	2.60	62.9
60	35.0	5.60	1.261	0.220	0.510	69.57	2.60	62.9
61	40.5	5.50	1.232	0.210	0.319	69.70	2.60	62.9
62	45.5	5.50	1.243	0.210	0.176	69.43	2.58	62.5
63	49.0	5.60	1.326	0.210	0.170	69.18	2.58	62.5
64	17.0	6.52	2.152	0.300	2.643	70.43	2.65	64.1
C	40.1	6.70	1.925		0.080			
C	19.0	6.30	2.270		0.543			
65	19.0	6.70	2.296	0.290	2.391	65.29	2.45	59.5
66	14.9	7.00	2.636	0.340	3.254	66.22	2.50	60.6
67	12.7	7.40	3.027	0.350	3.902	67.71	2.55	61.8
68	10.2	7.90	3.576	0.400	5.065	68.71	2.60	62.9
69	25.0	6.51	2.159	0.270	1.821	65.48	2.45	59.5
70	30.3	6.30	1.932	0.250	1.301	64.05	2.38	57.9
71	35.1	6.25	1.869	0.250	1.060	64.62	2.40	58.4

TABLE 9 (Con't)
ORIGINAL DATE - ISOPROPYL ALCOHOL

RUN NO.	ROTAMETER RDG	INLET WATER TEMPERATURE		OUTLET WATER TEMPERATURE		VAPOR TEMP.	FILM TEMP.	
		ABSOLUTE	BECKMANN	ABSOLUTE	BECKMANN			
	%	°C	°C	MV	°C	°C	MV	°C
72	42.2	6.10	1.748	0.230	0.705	64.41	2.40	58.4
73	48.7	6.00	1.714	0.220	0.509	64.74	2.40	58.4
C	41.0	5.90	1.468		1.405			
74	35.0	5.90	1.475	0.230	2.372	59.09	2.20	53.9
75	29.3	6.00	1.580	0.240	2.697	59.46	2.20	53.9
76	41.0	5.80	1.366	0.210	2.077	58.28	2.16	53.0
77	49.0	5.75	1.363	0.210	1.867	57.76	2.15	52.7
78	23.4	6.24	1.752	0.250	3.138	59.98	2.24	54.8
79	19.3	6.50	1.994	0.275	3.653	60.44	2.26	55.2
C	18.9	6.70	2.251		0.495			
80	16.3	6.87	2.464	0.300	2.665	61.09	2.31	56.3
81	12.7	7.20	2.823	0.340	3.531	61.51	2.32	56.6
82	7.8	8.40	4.098	0.445	6.117	62.44	2.36	57.5
83	10.2	7.63	3.225	0.375	4.384	61.58	2.33	56.8

TABLE 10
ORIGINAL DATA - NORMAL BUTYL ALCOHOL

RUN NO.	ROTAMETER RDG	INLET WATER TEMPERATURE		OUTLET WATER TEMPERATURE		VAPOR TEMP.	FILM TEMP.	
		ABSOLUTE	BECKMANN	ABSOLUTE	BECKMANN			
	%	°C	°C	MV	°C	°C	MV	°C
C	21.3	7.45	2.884		1.219			
84	21.3	7.50	2.933	0.35	3.519	95.14	3.47	82.4
85	14.2	8.10	3.514	0.40	5.258	95.86	3.53	83.8
86	25.5	7.30	2.761	0.325	3.031	95.45	3.54	84.0
87	30.1	7.20	2.660	0.305	2.629	94.01	3.53	83.8
88	35.6	7.02	2.505	0.29	2.176	94.01	3.53	83.8
89	40.6	7.00	2.498	0.28	1.960	94.06	3.53	83.8
90	48.9	7.18	2.691	0.27	1.857	93.45	3.52	83.6
C	20.0	7.70	3.128		0.571			
91	10.7	9.00	4.378	0.48	6.256	97.25	3.56	84.4
92	11.1	8.90	4.293	0.48	6.129	97.14	3.56	84.4
93	20.75	7.72	3.107	0.37	3.031	99.27	3.55	84.2
94	14.6	8.25	3.647	0.43	4.683	99.53	3.62	85.8
95	11.5	8.88	4.269	0.48	6.172	100.23	3.67	86.9
C	40.8	7.50	2.927		0.211			
96	49.0	7.50	3.006	0.30	1.276	98.65	3.55	84.2
97	39.3	7.58	3.022	0.31	1.649	98.55	3.56	84.4
98	23.0	8.04	3.438	0.365	3.092	98.61	3.65	86.4
99	31.0	7.80	3.180	0.33	2.224	99.10	3.60	85.4
C	38.0	7.90	3.224		0.059			
100	34.4	7.96	3.351	0.34	1.836	104.07	3.88	91.6
101	29.5	8.11	3.506	0.35	2.267	104.10	3.88	91.6
102	24.2	8.37	3.728	0.395	2.958	104.40	3.90	92.0
C	21.3	8.80	4.136		1.078			
103	21.3	8.80	4.149	0.42	3.699	105.78	4.00	94.0
104	14.75	9.30	4.638	0.48	5.364	106.60	4.05	95.1
105	12.7	9.50	4.924	0.51	6.128	107.07	4.11	96.4
106	10.0	6.48	1.794	0.42	4.123	103.85	4.01	94.2
107	48.5	8.00	3.488	0.32	1.377	103.65	3.92	92.4
108	43.0	8.00	3.440	0.32	1.507	103.80	3.90	92.0
109	41.5	8.00	3.444	0.335	1.644	108.67	4.10	96.2
110	48.5	7.98	3.444	0.32	1.383	108.38	4.07	95.5
111	34.5	8.30	3.675	0.355	2.223	109.35	4.13	96.8
112	30.1	8.35	3.715	0.37	2.481	109.79	4.15	97.2
113	24.6	8.50	3.868	0.40	3.195	110.45	4.19	98.1

TABLE 10 (con't)

ORIGINAL DATE - NORMAL BUTYL ALCOHOL

RUN NO.	ROTA-METER RDG	INLET WATER TEMPERATURE		OUTLET WATER TEMPERATURE		VAPOR TEMP.	FILM TEMP.	
		ABSO-LUTE	BECK-MANN	ABSO-LUTE	BECK-MANN			
	%	°C	°C	MV	°C	°C	MV	°C
114	20.0	8.80	4.149	0.435	4.062	110.44	4.23	99.0
115	10.2	6.67	1.965	0.45	4.440	108.60	4.25	99.4
116	48.5	8.23	3.692	0.35	1.649	108.78	4.12	96.6
C	30.1	8.40	3.512		0.340			
117	12.2	9.30	4.696	0.525	6.213	111.31	4.22	98.8
118	17.1	8.80	4.168	0.45	4.467	111.07	4.20	98.3
119	17.0	8.80	4.167	0.45	4.719	116.25	4.48	104.4
C	30.1	8.40	3.783		0.661			
120	30.3	8.40	3.766	0.38	2.780	116.01	4.44	103.5
121	24.0	8.60	3.951	0.415	3.524	116.14	4.50	104.8
122	20.0	8.80	4.137	0.45	4.252	116.71	4.55	105.9
123	13.9	9.30	4.673	0.52	6.130	117.37	4.62	107.4
124	10.2	7.86	3.213	0.52	5.953	116.79	4.58	106.5
C	27.0	8.60	3.933		0.840			
125	10.8	7.43	2.763	0.45	5.223	116.27	4.43	103.3
126	11.9	8.81	4.151	0.52	6.185	116.54	4.44	103.5

SAMPLE CALCULATIONS

I. RUN NO. 2 - METHYL ALCOHOL

1. **Rate of Heat Transfer, q**

Water flow rate = 1950 lb./hr.

Water temperature rise = 2.280°C

Heat capacity of water = 1.0 Btu/(lb) (°F)

$q = 1950\ (1.0)\ (2.280)\ (1.8) = 8010$ Btu/hr.

2. **Water Bulk Temperature, °F**

Inlet water temperature = 7.60°C

Water temperature rise = 2.280°C

Bulk temp. (°C) = 5.80 $\frac{2.280}{2}$ = 6.94°C

Bulk temp. (°F) = (6.94) (1.8) + 32 = 44.6°F

3. **Overall Water to Vapor Temperature Difference, °C**

Water bulk temperature = 6.94°C

Saturated vapor temperature = 64.60°C

Overall temp. difference = 64.60 - 6.94 = 57.66°C

4. $\underline{\dfrac{1\times 10^3}{(1+0.011t)V^{0.8}}}$

Water bulk temperature = 44.6°F

Water flow rate, V = 1950 lb./hr.

$$V^{0.8} = 425$$

$$\frac{1\times 10^3}{(1+0.011t)V^{0.8}} = \frac{1\times 10^3}{[1+0.011(44.6)]\ (425)} = 1.58$$

II. METHYL ALCOHOL AT $q = 7400$ Btu/hr

1. Observed Heat Transfer Coefficient, h_o

From Figure 4 at q = 7400 Btu/hr

ΔT, °C	$\frac{1 \times 10^3}{(1+0.011t)V^{0.8}}$	ΔT, °F	$\Delta T/q$ (°F) (hr)/(Btu)
57.38	2.12	103.3	0.01396
53.25	1.53	95.9	0.01296
48.81	0.92	87.8	0.01186

$\Delta T/q$ vs $\frac{1 \times 10^3}{(1+0.011t)V^{0.8}}$ is plotted in Figure 5.

at $\frac{1 \times 10^3}{(1+0.011t)V^{0.8}} = 0$, $\quad \frac{\Delta T}{q} = 0.01025$

Tube wall thickness, x = 0.00292 ft.

Outside tube surface area = 0.1962 sq.ft.

Inside tube surface area = 0.1596 sq.ft.

Tube thermal conductivity, k = 60 Btu/(hr) (sq.ft.) (°F/ft)

Average tube surface area, $A_{av} = \frac{0.1962 - 0.1596}{\ln \frac{0.1962}{0.1596}} = 0.1772$

$$\frac{x}{k\,A_{av}} = \frac{0.00292}{60(0.1772)} = 0.00027$$

$$\frac{1}{U_oA_o} = \frac{\Delta T}{q} = \frac{1}{h_oA_o} + \frac{x}{k\,A_{av}}$$

$$h_o = \frac{1}{0.1962(0.01025 - 0.00027)} = 511 \text{ Btu/(hr) (sq.ft.)(°F)}$$

2. Theoretical Heat Transfer Coefficient, h_o

At infinite water flow rate, water bulk temp = inlet water temp = 7.0°C (Figure 4 at T = 53.25°C)

Saturated vapor temp., $t_{sv} = 61.5$°C

Thermal resistance from water to vapor = 0.01025

Thermal resistance of tube wall = 0.00027

Water to saturated vapor temp. diff. = 61.5 - 7.0 = 54.5°C

Tube surface temp., $t_s = 7.0 + 54.5 \left[\frac{0.00027}{0.01025}\right] = 8.4$°C

Film temp., $t_f = t_{sv} - 0.75\,(t_{sv} - t_s)$

$= 61.5 - 0.75\,(61.5 - 8.4) = 21.7$°C

Temp. drop across condensate film = 61.5 - 8.4 = 53.1°C

At $t_f = 21.7$°C

Thermal conductivity, $k_f = 0.1235$ Btu/(hr)(sq.ft.)(°F/ft)

Liquid density, $\rho_f = 49.2$ lb/cu.ft.

Latent heat, $\lambda = 503$ Btu/lb.

Viscosity, $\mu = 1.40$ lb/(hr)(ft.)

Heat capacity, cp = 0.601 Btu/(lb) (°F)

Gravitational constant, $g = 4.17 \times 10^8$ ft/hr^2

Outside tube diameter, $D_o = 0.03125$ ft.

Temp. drop across condensate film = 95.7°F

(a) h_o by Nusselt equation

$$h_o = 0.725 \sqrt[4]{\frac{k_f^3 \rho_f^2 g \lambda}{D_o \mu_f \Delta t}}$$

$$h_o = 0.725 \sqrt[4]{\frac{(0.1235)^3\ (49.2)^2\ (4.17\text{x}10^8)\ (503)}{0.03125\ (1.40)\ (95.7)}}$$

$$= 502 \quad \text{Btu/(hr) (sq.ft.) (}^{\circ}\text{F)}$$

(b) h_o by Bromley Equation

$$h_o = 0.728 \sqrt[4]{\frac{k_f^3 \rho_f (\rho_f - \rho_v)\ g\lambda \left(1 + 0.4\ \frac{\Delta t C_p}{\lambda}\right)^2}{D_o \mu_f \Delta t}}$$

$$h_o = 0.728 \sqrt[4]{\frac{(0.1235)^3 (49.2)^2 (4.17\text{x}10^8) \left[1 + 0.4\ \frac{(95.7)(0.601)}{503}\right]^2}{0.03125\ (1.40)\ (95.7)}}$$

$$= 512 \quad \text{Btu/(hr) (sq.ft.) (}^{\circ}\text{F)}$$

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