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HEAT TRANSFER COEFFICIENTS
OF
CONDENSING VAPORS

BY

JAMES J. BRODERICK
AND
HAROLD E. DEVANEY

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

Several experimental methods have been developed for the determination of the rate of heat transfer between a pure condensing organic vapor and a cold surface. The experimental results of the earliest method, the so-called "embedded thermocouple" approach, have not been in good agreement with heat transfer values predicted by the theoretical Nusselt equation, nor has good agreement been found among the individual data. The alternate method was an indirect approach developed by Wilson and was based on the effect of cooling water velocity. Wilson's method provided values in close agreement with the values predicted by the Nusselt equation but was empirical in nature. Both methods have been subject to criticism.

Chu, Flitcraft and Holeman developed and tested a modification of the Wilson method based on a rigorous theoretical analysis which postulated that the film coefficient was an inverse function of the heat transferred and could be determined by graphical means. With a few exceptions, notably toluene, this technique has provided values in good agreement with the predicted theoretical coefficients.

The purpose of this work was three-fold: to enlarge the span of operating conditions investigated with particular reference to extension of the cooling water velocity range; to determine whether the modified Wilson method was applicable to n-propyl and n-amyl alcohol; and to investigate n-butyl alcohol which was previously tested and did not exhibit a variation of the film coefficient with the heat transferred.

The experimental results of this investigation showed the values obtained for the three alcohols to be in conformance with the behavior

expected by Chu and were in good agreement with the predicted values. The Chu method was also found to be applicable over the larger water flow range tested. In addition, the extended range provided data that allowed more accurate charting of the graphical method. The inclusion of this data was instrumental in determining the variation of the heat transfer coefficient, h_o, with q for the n-butyl alcohol where none was found previously. It is felt that a similar investigation over the extended range of water flow would clarify the variation of h_o for toluene, the only presently know exception to Chu's method.

APPROVAL OF THESIS

FOR

DEPARTMENT OF CHEMICAL ENGINEERING

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BY

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NEWARK, NEW JERSEY

JUNE, 1957

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The authors would like to express their sincere appreciation to Professor George C. Keeffe for his assistance in obtaining required equipment and guidance in preparing this paper; and to Mr. William Furmadge for his assistance in the mechanical construction of the equipment used in this work.

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INTRODUCTION

The Nusselt equation (19) is generally used in predicting the rate of heat transfer between a cold surface and pure condensing vapors. However, the equation has not been widely checked for a large range of materials due to difficulties in devising equipment suitable for accurate measurement of the film heat transfer coefficient, h_o.

Experimental work to date has been based on two methods of measuring the coefficient for organic vapors condensing on horizontal tubes; the embedded thermocouple method (15, 18, 20, 26); and the Wilson method (28).

The embedded thermocouple method measures the average condensing surface temperature to determine the film coefficient, relying upon an empirical equation for determining the cooling water resistance film. Rhodes and Younger (25) found that the use of fixed thermocouples to determine an average wall temperature involved certain assumptions of questionable validity. Rhodes and Younger also found discrepancies in the empirical calculation of the cooling water film resistance. Later work by Baker and Mueller (1) proved that there is no one position at which a thermocouple will indicate a representative tube wall surface temperature.

Wilson (28) proposed an indirect method of determining the film coefficient without recourse to obtaining an accurate tube surface temperature. Rhodes and Younger employed the use of the Wilson method to obtain values that were in closer agreement with the Nusselt equation than were previously obtained by the thermocouple approach.

Following this work, Chu, Flitcraft and Holeman (7) proposed a modification of the Wilson method using a rigorous theoretical analysis that gave values in closer agreement with the Nusselt equation.

The modified technique of Chu and associates was investigated further by Lipuma and Mirmaier (16) on several other organics.

This investigation was initiated to enlarge the number of homologous organic alcohols tested and to expand the range of operating conditions. Normal propyl, butyl and amyl alcohols have been tested for study. The predicted film coefficients will be calculated and compared with the observed values.

THEORY

For the case of a pure vapor condensing on a cold surface, the Nusselt equation (17, 19) is generally used to preduct the coefficients of heat transfer. As applied to the specific case of a single horizontal cylindrical tube, the equation is:

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

The equation is based on the assumption that streamline flow exists in the condensate film with liquid flow by gravity only. Any acceleration effects due to vapor velocity are neglected.

As previously noted, the major portion of the past work initiated to test the Nusselt equation relied upon the embedded thermocouple method (15, 18, 20, 26). The data obtained were was variable and the values of h_o did not agree well with the Nusselt-predicted values. Since the condensate film thickness will vary around the perifery of the cylindrical tube, it was thought that the film surface temperature would also vary. Baker and Mueller (1) proved that the temperature variation was significant and that there was no point on the surface of the tube that a thermocouple installation could be positioned to obtain a representative temperature.

Wilson (28) developed an indirect approach to circumvent the difficulties in obtaining representative temperature measurements based on the following theory. The vapor to water heat flow is across a total resistance composed of the vapor resistance R_v, ~~water~~ tube resistance R_w, and for simplicity a ~~tube~~ water resistance composed of a constant and the water velocity

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

This equation assumes R_v to be independent of the cooling water rate.

In later work Rhodes and Younger (25) proved that R_v was affected by the water rate and postulated that

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

Further work was undertaken by Beatty and Katz (3) using equation III in working with finned tubes, but maintained constant water temperatures to minimize its effect on the water film.

To other investigators in the field it appeared that the Wilson method and its modifications were empirical and fundamentally unsound. Chu, Flitcraft and Holeman (7) proposed a modification of the Wilson method based on a rigorous theoretical relationship. The Chu modification forms the basis for this investigation.

It was pointed out by Chu and associates that the group of terms

$$(k_f^3 \rho_f^2 g \lambda / \mu_f)^{0.25}$$

appears to remain constant for most organic solvents. The values of the group $(k_f^3 \rho_f^2 g \lambda / \mu_f)^{0.25}$ for various homologous alcohols have been listed in Table 1 for ranges of temperatures where data are available (11, 23).

For steady state heat transfer

$$q = h_o A \Delta t \qquad \text{IV}$$

and based on the Nusselt equation with substitution of a constant K for the grouping as noted above, then

$$h_o = \frac{K}{(\Delta t)^{.25}} \qquad \text{V}$$

and results in an equation for h_o as a function of the heat transferred.

$$q = K(h_o)^{1/3} \qquad \text{No!} \quad h_o = K q^{-\frac{1}{3}} \qquad \text{VI}$$

It can be seen that a log-log plot of h_o versus q should give a straight line of slope minus one third. Substituting equation VI in the usual expression of over-all thermal resistance from the condensing vapor to the cooling water, then

$$\frac{1}{U_oA_o} = \frac{1}{h_oA_o} + \frac{x}{K_wA_{av}} + \frac{(D)^{0.2}}{A_i 150\,(1 + 0.011t)V^{0.8}} \qquad \text{VII}$$

Inspection of equation VII for constant q shows K_w to be negligible, h_o constant and thus the only variables for a given tube are V, t and the value of $1/U_o$. Further, a plot of $1/U_oA_o$ versus $\frac{1 \times 10^3}{(1 + 0.011t)V^{0.8}}$ should yield a straight line at equal values of q.

The intercept of this line equals $1/h_oA_o + x/K_wA_{av}$ and can be used to calculate h_o since

$$\frac{1}{U_oA_o} = \frac{\Delta t}{q} = \frac{1}{h_oA_o} + \frac{x}{K_wA_{av}} \qquad \text{VIII}$$

and

$$\frac{1}{h_o} = \frac{1}{U_o} - \frac{xA_o}{K_wA_{av}} \qquad \text{IX}$$

Thus by obtaining several sets of experimental data such that each set maintained a constant over-all vapor to water temperature difference at varying water flows, and plotting q versus water flow $\frac{1 \times 10^3}{(1 + 0.011t)V^{0.8}}$, it is possible to obtain two or more sets of conditions where q is equal. The over-all temperature difference is varied by altering the absolute pressure in the system. When q is equal, the h_o value would be equal and a plot of $1/U_oA_o$ versus the water flow provides the intercept value equal to $\frac{1}{h_oA_o} + \frac{x}{K_wA_{av}}$, with h_o determined by equation IX.

TABLE I

Ratio of $(k_f^3 \rho_f^2 g \lambda / \mu_f)^{0.25}$ at Different Temperatures

Compound:	Upper Temp. °F	Lower Temp. °F	Ratio
Methyl Alcohol	72	63	1.02
i - Propyl Alcohol	80	69	1.13
n - Propyl Alcohol	95	60	1.11
n - Butyl Alcohol	98	86	1.09
n - Amyl Alcohol	105	75	1.07
n - Hexyl Alcohol	100	50	1.07

DESCRIPTION OF APPARATUS

The equipment used in this work was constructed by Lipuma and Nirmaier (16) for a previous thesis and modified to extend the range of operating conditions. The major portions of the unit as shown in Figures 1 and 2 included a kettle, horizontal tube condenser, a cold water circulating system and a vacuum pump.

The vapor kettle was of five gallon capacity, 316 stainless steel throughout and jacketed for a maximum of 90 P.S.I.G. Steam flow to the kettle was controlled at 1 to 10 P.S.I.G. with a spring operated cash valve.

The horizontal tube condenser consisted of an 0.375 inch O.D. brass tube with a wall thickness of 0.035 inches and a heat transfer length of 24 inches, providing a surface area of 0.196 sq. ft. The metal conductivity was 60 Btu/(hr.) (sq. ft.) (°F/ft.). The annular vapor space was a 2.5 inch, Schedule 40, 316 stainless steel pipe flanged at both ends.

Vapors passed to the condenser annulus from the kettle through three 0.5 inch diameter tubes. Condensate returned to the kettle through two 0.5 inch tubes. The return lines were provided with three inch liquid seal traps.

Excess vapors passed to a final glass condenser for return to the kettle through a 15 inch liquid seal trap.

The pot temperature was measured with a 0-150°C thermometer while excess vapor from the test condenser was measured with a -1 to 101°C or 99 to 201°C thermometer as required. The vapor temperatures were read in 0.1°C increments. A thermocouple was installed in the annulus to record the condensate film temperature.

The cooling water system consisted of a centrifical pump rated for 80 gallons at an 80 ft. head and 1.0 specific gravity. Constant head was provided by two fifty-five gallon drums equipped for heating or cooling. Water flow to the system was controlled and measured through alternate Fischer-Porter flowrators of 13.6 and 0.91 gallons per minute.

The condenser inlet and outlet water temperatures were measured with a 0 to 50°C thermometer graduated in 0.1°C increments and a 0 to 5°C Beckmann thermometer that could be read to .01°C.

The desired system vacuum was obtained with a Cenco-Hypervac 4 pump rated at 1.44 cubic feet per minute of air. Vacuum control was maintained with a Cartesian manostat and measured with a mercury manometer.

All hot surfaces on the vapor side were heavily insulated. Cooling water lines were insulated adjacent to the measuring thermometers. The entire condenser was located in a plywood box and packed with Perlite to reduce heat losses in the shell.

The alcohols used were reagent grade with boiling ranges of less than 1°C.

SCHEMATIC FLOW SHEET OF APPARATUS

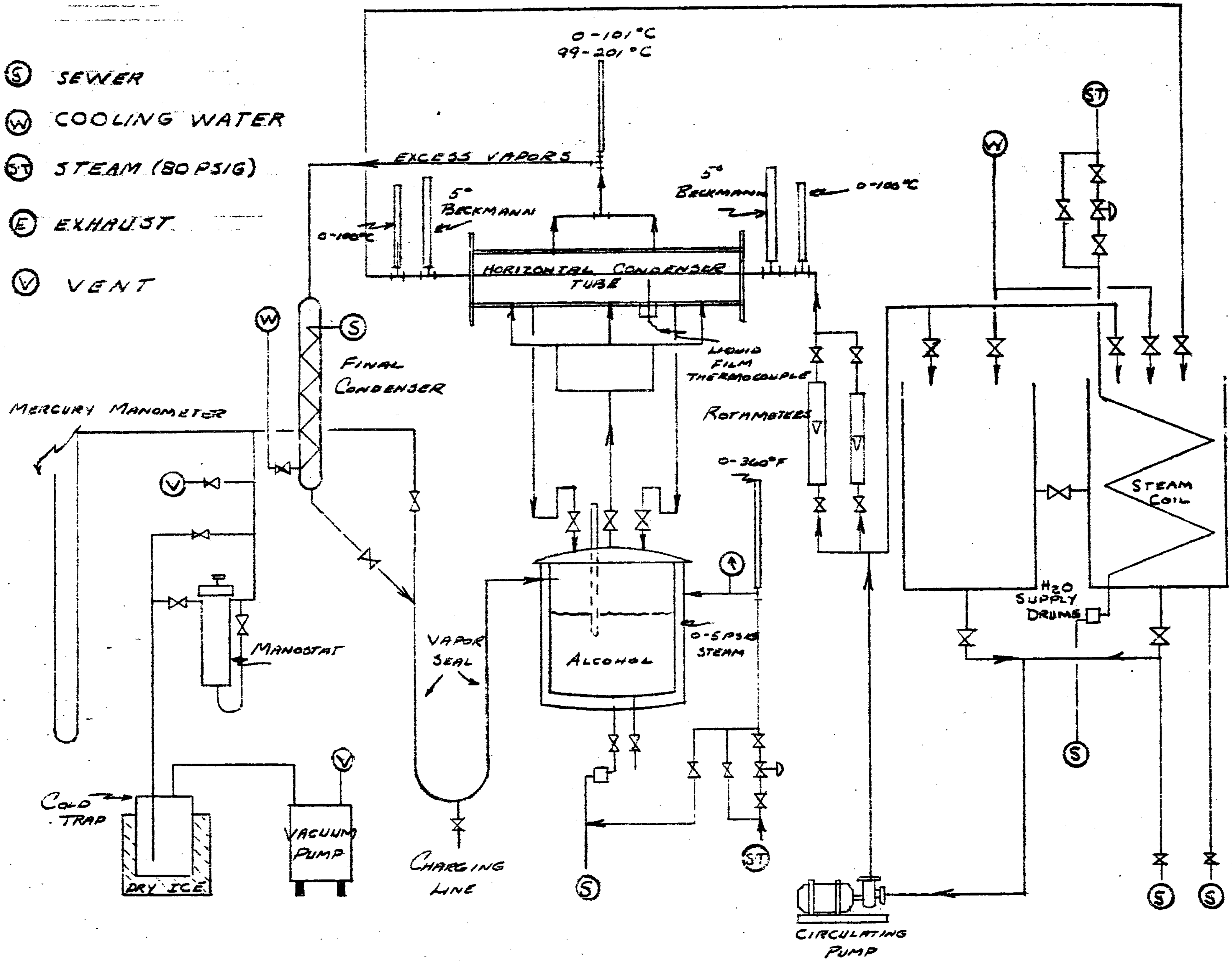
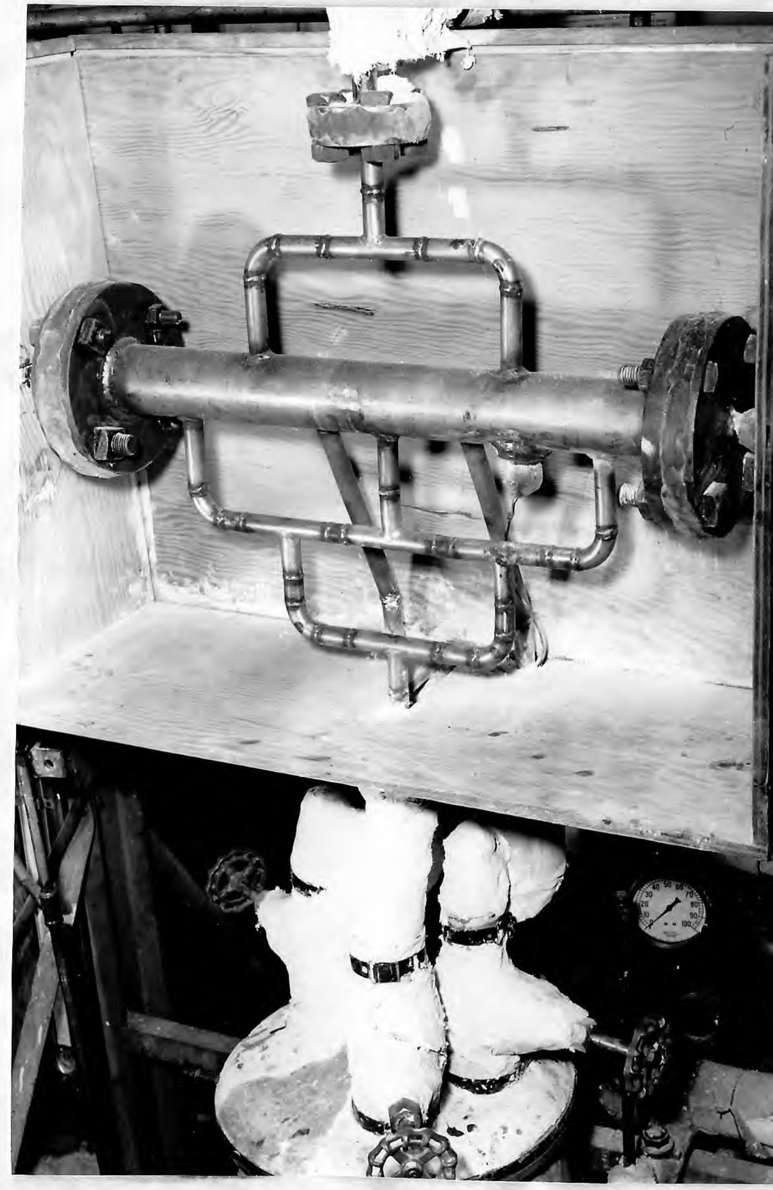


FIGURE 1

FIGURE 2



EXPERIMENTAL APPARATUS

EXPERIMENTAL PROCEDURE

The system was evacuated to 29.5 inches of mercury vacuum and tested for leaks. The pump was stopped and the unit considered air-tight if no noticeable change in absolute pressure occurred in twenty minutes. The test alcohol was charged to the kettle and vacuum maintained in the system equivalent to the alcohol vapor pressure in order to minimize non-condensables.

The Beckmann readings on the cooling water line were taken to determine the difference in readings between the two Beckmann columns at zero heat flow. Except where new absolute levels were required, these readings were used consistently.

In starting up the system it was customary to by-pass the manostat for faster evacuation. Then the pump was stopped until the application of heat on the kettle had raised the vapor pressure in the system to the desired level. The manostat was set, the pump started and an air bleed introduced to maintain the desired vacuum. It was deemed necessary to use this approach to reduce the possibility of introducing air into the condenser annulus.

The heat to the kettle was raised gradually until an excess of vapors was passing into the final condenser.

The system required fifteen to thirty minutes to reach steady-state conditions. At this point four sets of readings were taken and averaged to obtain one run. The readings included the rotameter setting, system vacuum, pot temperature, vapor temperature, condensate film temperature and the absolute and Beckmann temperature readings.

Due to the wide range of water flows investigated, it was often necessary to change the feed water temperature to the condenser in order to maintain a consistent vapor to average coolant temperature difference.

EXPERIMENTAL RESULTS AND TREATMENT OF DATA

The experimental results for butyl, amyl and propyl alcohol are tabulated in Tables 2, 3 and 4. The Tables also include the calculated values of the Wilson factor $\frac{1 \times 10^3}{(1 \neq .011t)V^{0.8}}$. Plots of the Wilson factor versus the heat transferred, q, are shown in Figures 3, 5 and 7.

The heat transfer coefficients h_o were obtained by drawing a series of parallel lines at constant heat loads through the vapor to water temperature difference curves of Figures 3, 5 and 7. For each intersection the Δt at constant heat load q and a value of $(1 \times 10^3)/(1 \neq .011t)V^{0.8}$ was read. The $(1 \times 10^3)/(1 \neq .011t)V^{0.8}$ value was then plotted against the corresponding $\Delta t/q$. The results are straight lines which were extrapolated to the ordinates at $\left(\frac{1 \times 10^3}{(1 \neq .011t)V^{0.8}}\right) = 0$. The intercepts represent the value of $\Delta t/q$ or $1/U_oA_o$ at infinite water flow. At infinite water flow the water film resistance is negligible and the value of h_o can be calculated from Equation IX.

TABLE 2
TABULATED RESULTS - n-BUTYL ALCOHOL

RUN NO.	INLET WATER TEMP. °C	WATER TEMP. RISE °C	VAPOR TEMP. °C	OVERALL WATER-VAPOR T, °C	WATER FLOW W LB/HR	HEAT DUTY Q BTU/HR	$\frac{1 \times 10^3 V^{-0.8}}{1 + 0.011t}$
1	11.15	1.03	93.00	81.33	3300	6110	0.970
2	10.90	1.26	93.00	81.47	2640	5980	1.16
3	11.20	1.67	92.85	80.81	1980	5940	1.44
4	11.50	2.45	92.80	80.07	1320	5830	1.95
5	11.00	3.10	92.80	80.25	980	5480	2.55
6	10.65	4.40	92.85	80.00	650	5150	3.38
7	9.70	6.27	92.85	80.01	425	4800	4.90
8	8.90	7.50	93.00	80.35	335	4530	6.12
9	7.90	9.60	93.00	80.30	250	4330	7.50
10	10.90	8.80	80.80	65.50	250	3960	7.30
11	11.80	6.80	80.80	65.60	335	4090	5.93
12	12.50	5.35	80.80	65.62	425	4080	4.76
13	13.10	3.93	80.70	65.63	650	4600	3.40
14	13.75	2.74	81.00	65.88	980	4830	2.45
15	13.95	2.10	81.00	66.00	1320	4980	1.935
16	13.95	1.45	81.10	66.43	1980	5160	1.405
17	13.80	1.10	81.20	66.85	2640	5230	1.124
18	14.00	0.91	81.15	66.70	3300	5410	0.935
19	11.20	1.14	105.00	93.23	3300	6770	1.04
20	11.10	1.40	105.05	93.25	2640	6650	1.16
21	11.00	1.88	105.10	93.16	1980	6690	1.45
22	10.80	2.60	105.20	93.10	1320	6170	2.01
23	10.40	3.50	105.05	92.90	980	6180	2.54
24	9.60	5.05	104.95	92.83	650	5910	3.55
25	8.55	7.02	104.95	92.89	425	5370	4.98
26	7.80	8.30	104.90	92.95	335	5000	6.05
27	6.60	10.50	105.00	93.15	250	4720	7.62
28	12.20	1.05	93.40	80.68	3300	6230	0.97
29	12.15	1.31	93.25	80.44	2640	6220	1.13
30	11.70	1.60	93.20	80.70	1980	5700	1.47
31	11.40	2.52	93.05	80.39	1320	6000	1.92
32	11.10	3.04	93.10	80.48	980	5360	2.57
33	10.80	4.32	93.00	80.04	650	5040	3.41
34	9.75	6.39	92.95	80.00	425	4880	4.84
35	8.80	7.62	92.80	80.10	335	4600	6.06

TABLE 2 (CON'T)

TABULATED RESULTS - n-BUTYL ALCOHOL

RUN NO.	INLET WATER TEMP. °C	WATER TEMP. RISE °C	VAPOR TEMP. °C	OVERALL WATER-VAPOR T, °C	WATER FLOW W LB/HR	HEAT DUTY Q BTU/HR	$\frac{1 \times 10^3 v^{-0.8}}{1 + 0.011t}$
36	8.05	9.45	92.90	80.13	250	4250	7.61
37	14.40	0.98	81.35	66.36	3300	5820	0.930
38	14.35	1.13	81.42	66.50	2640	5370	1.12
29	14.20	1.50	81.45	66.50	1980	5330	1.38
40	14.00	2.00	81.30	66.30	1320	4750	1.95
41	13.75	2.80	81.06	65.91	980	4930	2.39
42	13.10	3.85	80.95	65.93	650	4500	3.48
43	12.30	5.45	80.87	65.85	425	4170	4.70
44	11.70	6.97	80.92	65.73	335	4200	5.81
45	10.95	9.01	80.90	65.45	250	4050	7.20
46	11.50	1.10	105.30	93.25	3300	6540	1.06
47	11.40	1.45	105.25	93.13	2640	6880	1.12
48	11.35	1.80	105.05	92.80	1980	6410	1.51
49	10.85	2.72	105.00	92.79	1320	6470	1.96
50	10.60	3.41	104.90	92.60	980	6000	2.61
51	9.90	4.95	104.85	92.47	650	5790	3.63
52	8.70	6.86	104.80	92.67	425	5230	5.10
53	7.95	8.45	104.70	92.53	335	5100	5.97
54	6.80	10.70	104.75	92.60	250	4810	7.60

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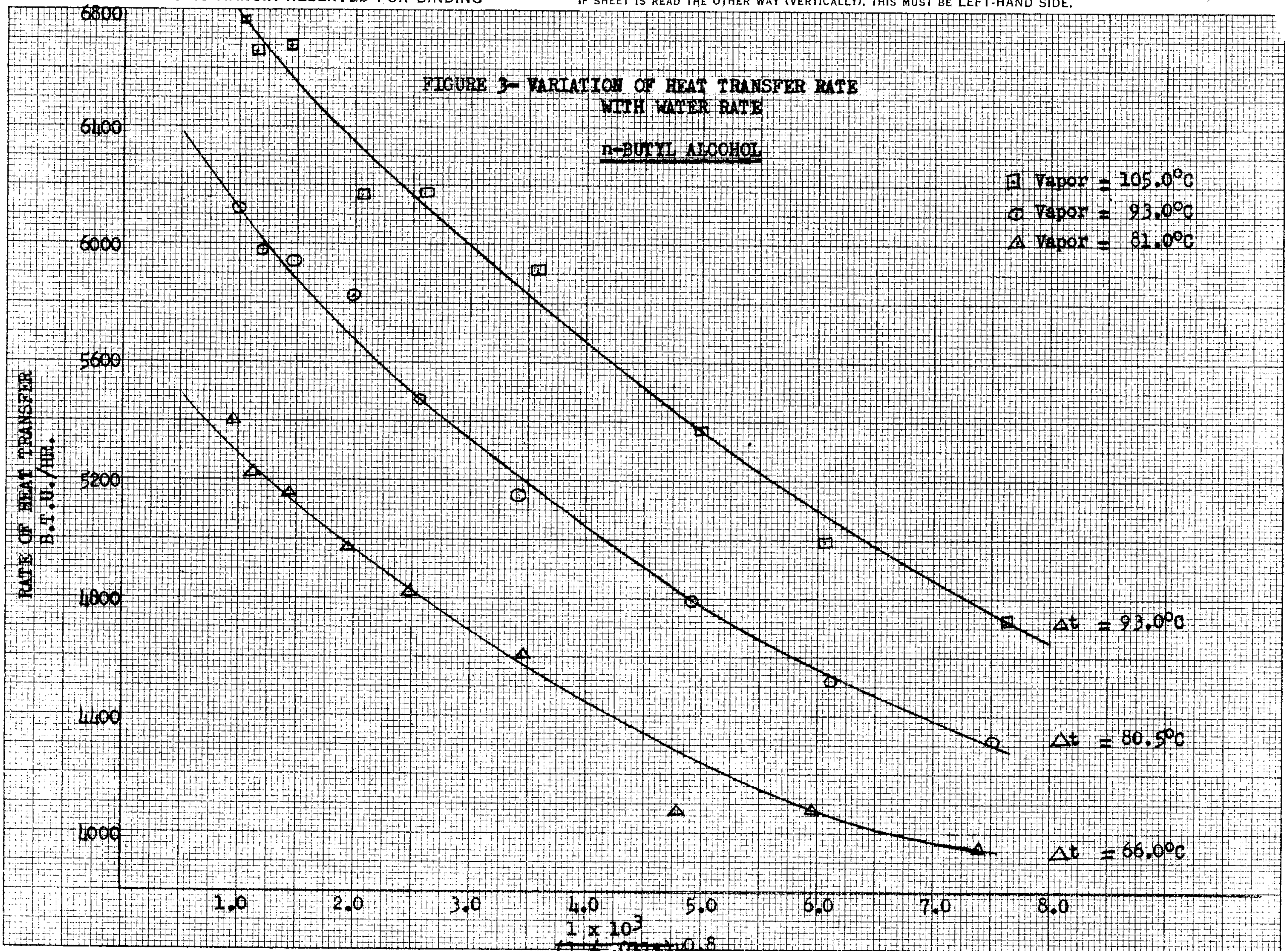

FIGURE 3- VARIATION OF HEAT TRANSFER RATE WITH WATER RATE

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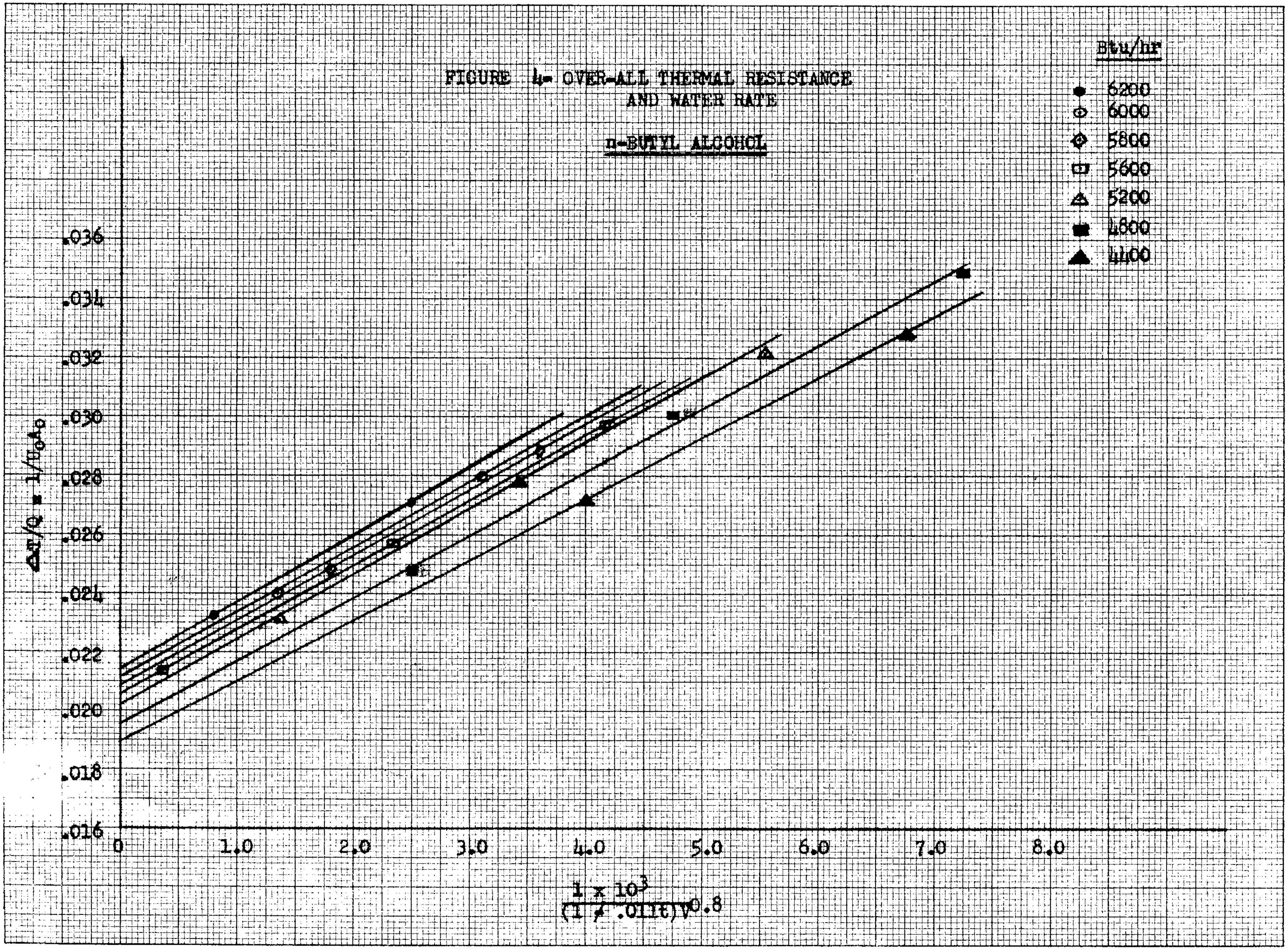

FIGURE 4- OVER-ALL THERMAL RESISTANCE AND WATER RATE

n-BUTYL ALCOHOL

29/64 Inch Divisions

TABLE 3

TABULATED RESULTS - n-AMYL ALCOHOL

RUN NO.	INLET WATER TEMP. °C	WATER TEMP. RISE °C	VAPOR TEMP. °C	OVERALL WATER-VAPOR T, °C	WATER FLOW W LB/HR	HEAT DUTY Q BTU/HR	$\frac{1 \times 10^3 v^{-0.8}}{1 + 0.011t}$
55	12.45	0.87	82.50	69.61	3300	5170	0.951
56	12.40	1.03	82.35	69.43	2640	4900	1.14
57	12.35	1.37	82.10	69.06	1980	4880	1.43
58	12.20	2.05	82.15	68.93	1320	4870	1.97
59	11.95	2.49	82.00	68.80	980	4400	2.52
60	11.40	3.59	81.95	68.75	650	4200	3.49
61	10.60	5.22	81.80	68.55	425	4000	4.88
62	10.05	6.41	81.75	68.50	335	3860	5.92
63	8.80	8.30	81.60	68.65	250	3730	7.51
64	11.00	0.97	93.50	82.01	3300	5760	
65	11.10	1.18	93.50	81.81	2640	5600	1.16
66	10.95	1.52	93.45	81.74	1980	5410	1.45
67	10.70	2.24	93.35	81.53	1320	5320	1.99
68	10.55	2.86	93.20	81.22	980	5040	2.54
69	10.40	4.10	93.20	80.75	650	4790	3.51
70	9.75	5.81	93.15	80.50	425	4430	4.93
71	9.20	6.83	93.15	80.53	335	4120	5.95
72	8.15	8.75	93.10	80.57	250	3940	7.53
73	11.25	1.05	100.60	88.83	3300	6230	0.97
74	11.15	1.29	100.60	88.80	2640	6130	1.16
75	10.90	1.66	100.65	88.92	1980	5920	1.44
76	10.50	2.36	100.70	89.02	1320	5610	2.00
77	10.20	3.13	100.75	88.88	980	5520	2.53
78	9.65	4.35	100.90	89.07	650	5090	3.51
79	8.80	6.10	101.00	89.15	425	4670	4.90
80	8.15	7.44	100.90	89.03	335	4480	5.94
81	7.30	9.23	100.95	89.03	250	4160	7.61
82	12.60	0.84	82.20	69.18	3300	4980	0.97
83	12.50	1.05	82.35	69.32	2640	4980	1.12
84	12.35	1.32	82.20	69.19	1980	4700	1.47
85	12.10	1.91	82.10	69.04	1320	4530	2.20
86	11.85	2.55	82.05	68.93	980	4500	4.28
87	11.40	3.61	81.90	68.70	650	4220	3.47
88	10.80	5.16	81.75	68.37	425	3960	4.91
89	10.15	6.27	81.70	68.41	335	3780	6.00

TABLE 3 (CON'T)
TABULATED RESULTS - n-AMYL ALCOHOL

RUN NO.	INLET WATER TEMP. °C	WATER TEMP. RISE °C	VAPOR TEMP. °C	OVERALL WATER-VAPOR T, °C	WATER FLOW W LB/HR	HEAT DUTY Q BTU/HR	$\frac{1 \times 10^3 V^{-0.8}}{1 + 0.011t}$
90	9.05	8.06	81.80	68.72	250	3640	7.62
91	11.05	1.03	100.70	89.13	3300	6120	0.98
92	11.00	1.27	100.70	89.07	2640	6030	1.20
93	10.80	1.69	100.60	88.94	1980	5960	1.41
94	10.40	2.40	100.50	88.90	1320	5690	1.98
95	10.15	3.09	100.55	88.86	980	5440	2.57
96	9.50	4.52	100.65	88.89	650	5280	3.45
97	8.85	6.27	100.70	88.71	425	4800	4.98
98	8.20	7.23	100.75	88.93	335	4370	6.01
99	7.50	9.16	100.70	88.62	250	4120	7.67
100	11.35	0.94	93.05	81.23	3300	5590	1.00
101	11.25	1.19	93.10	81.25	2640	5650	1.16
102	11.05	1.54	93.20	81.38	1980	5480	1.42
103	10.60	2.19	93.25	81.55	1320	5200	2.02
104	10.50	2.91	93.15	81.19	980	5120	2.50
105	10.10	4.02	93.00	80.89	650	4700	3.55
106	9.05	6.01	92.80	80.75	425	4600	4.85
107	8.50	6.95	92.70	80.72	335	4180	5.89
108	7.40	8.80	92.75	80.95	250	4010	7.51

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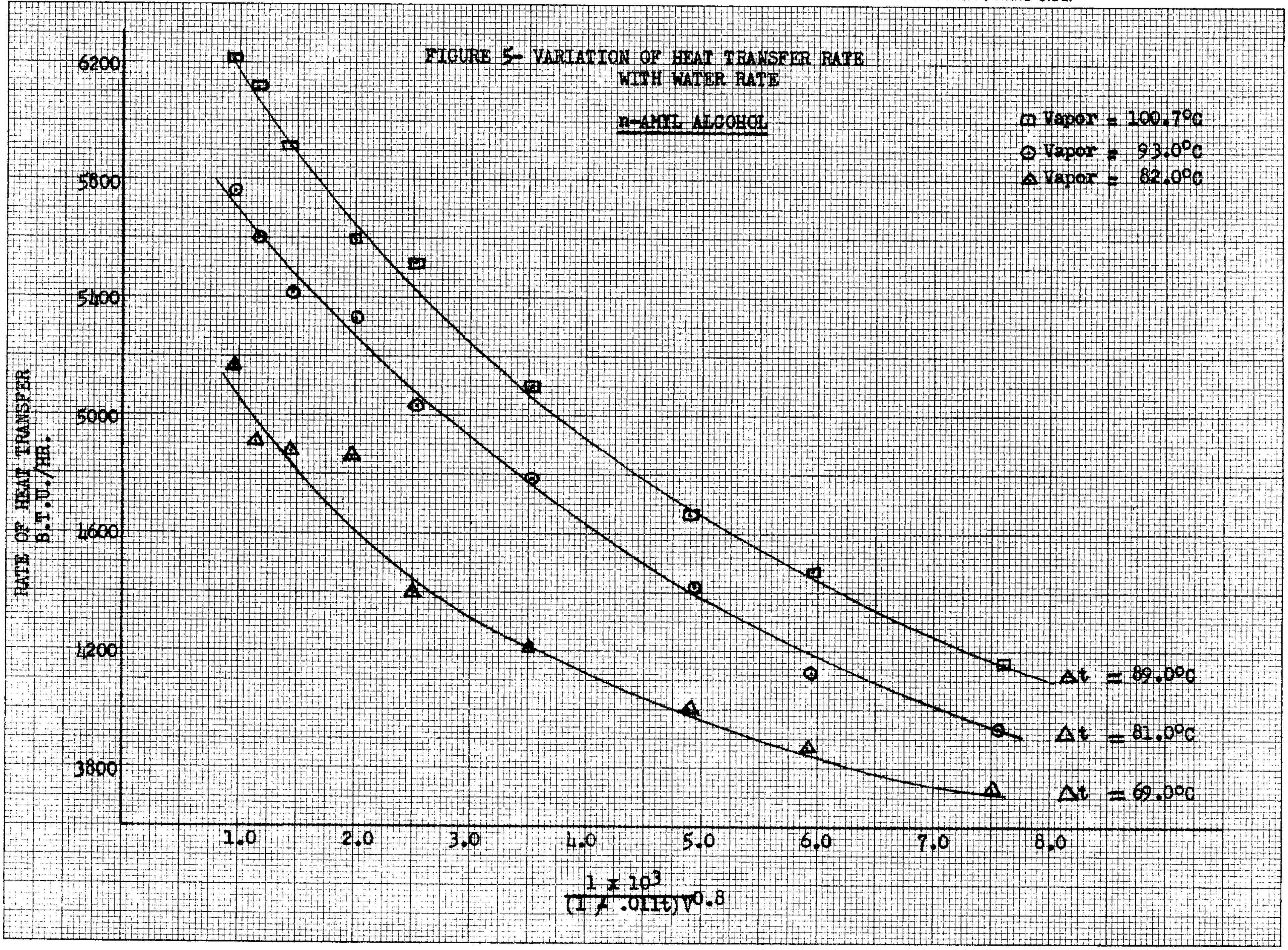

FIGURE 5- VARIATION OF HEAT TRANSFER RATE WITH WATER RATE

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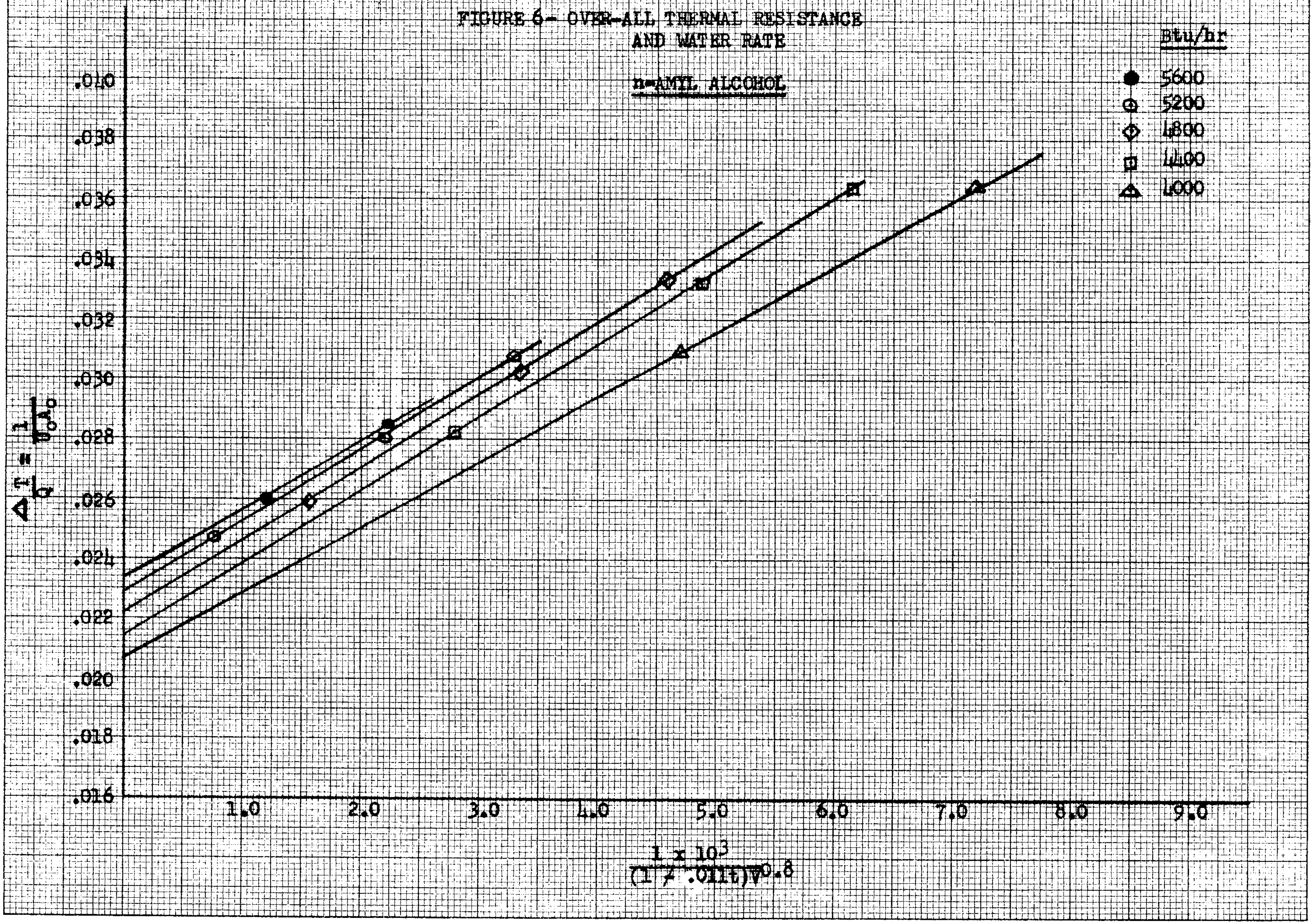

FIGURE 6- OVER-ALL THERMAL RESISTANCE AND WATER RATE

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TABLE 4

TABULATED RESULTS - n-PROPYL ALCOHOL

RUN NO.	INLET WATER TEMP. °C	WATER TEMP. RISE °C	VAPOR TEMP. °C	OVERALL WATER-VAPOR T, °C	WATER FLOW W LB/HR	HEAT DUTY Q BTU/HR	$\frac{1 \times 10^3 V^{-0.8}}{1 + 0.011t}$
109	9.75	1.02	92.90	82.64	3300	6060	0.985
110	9.90	1.25	93.10	82.57	2640	5930	1.185
111	10.15	1.62	93.20	82.24	1980	5770	1.47
112	10.20	2.40	93.40	82.00	1320	5690	2.03
113	10.00	3.13	93.45	81.89	980	5520	2.59
114	9.55	4.43	93.40	81.63	650	5200	3.56
115	8.40	6.32	93.20	81.64	425	4920	5.00
116	7.55	7.80	93.20	81.75	335	4700	6.03
117	6.85	10.10	93.15	81.25	250	4550	7.63
118	11.60	0.92	83.40	71.34	3300	5470	0.97
119	11.55	1.11	83.50	71.40	2640	5270	1.16
120	11.40	1.49	83.65	71.50	1980	5310	1.46
121	11.25	2.17	83.55	71.21	1320	5150	2.01
122	11.05	2.83	83.50	71.03	980	4990	2.54
123	10.30	4.10	83.35	71.00	650	4800	3.54
124	9.45	6.06	83.20	70.72	425	4630	4.95
125	8.80	7.31	83.15	70.69	335	4400	5.95
126	7.55	9.68	83.40	71.01	250	4360	7.57
127	11.00	0.86	74.50	63.07	3300	5120	0.970
128	10.65	1.05	74.50	63.32	2640	4980	1.172
129	10.40	1.37	74.40	63.31	1980	4880	1.468
130	9.95	2.03	74.45	63.48	1320	4830	2.03
131	9.60	2.61	74.50	63.58	980	4610	2.58
132	9.05	3.84	74.55	63.58	650	4490	3.58
133	8.10	5.77	74.50	63.51	425	4410	5.02
134	7.35	7.01	74.50	63.65	335	4230	6.07
135	6.80	9.20	74.50	63.10	250	4130	7.68
136	10.55	1.04	93.15	82.08	3300	6180	0.973
137	10.25	1.31	93.20	82.29	2640	6220	1.170
138	10.10	1.70	93.35	82.40	1980	6040	1.463
139	9.95	2.44	93.50	82.33	1320	5790	2.03
140	9.70	3.16	93.40	82.12	980	5570	2.57
141	9.20	4.37	93.20	81.81	650	5130	3.57
142	8.05	6.26	93.05	81.87	425	4790	4.99
143	7.20	7.93	93.00	81.84	335	4780	6.02

TABLE 4 (CON'T.)

TABULATED RESULTS - n-PROPYL ALCOHOL

RUN NO.	INLET WATER TEMP. ° C.	WATER TEMP. RISE °C	VAPOR TEMP. °C	OVERALL WATER-VAPOR T, °C	WATER FLOW W LB/HR	HEAT DUTY Q BTU/HR	$\frac{1 \times 10^3 V^{-0.8}}{1 + 0.011t}$
144	6.60	10.20	92.95	81.25	250	4580	7.63
145	11.75	0.95	83.25	71.02	3300	5640	0.972
146	11.60	1.16	83.35	71.17	2640	5510	1.16
147	11.50	1.57	83.50	71.22	1980	5600	1.45
148	11.05	2.37	83.50	71.26	1320	5580	2.01
149	10.90	2.95	83.55	71.17	980	5210	2.54
150	10.60	4.32	83.60	70.84	650	5050	3.51
151	10.05	6.15	83.50	70.37	425	4700	4.90
152	9.20	7.48	83.50	70.56	335	4520	5.92
153	8.05	9.80	83.45	70.50	250	4420	7.52
154	10.90	0.85	74.65	63.32	3300	5040	0.972
155	10.80	1.06	74.55	63.22	2640	5030	1.167
156	10.55	1.40	74.50	63.25	1980	4980	1.465
157	10.30	2.00	74.50	63.20	1320	4750	2.01
158	9.90	2.67	74.50	63.26	980	4710	2.55
159	9.15	3.89	74.45	63.35	650	4550	3.56
160	8.30	5.62	74.40	63.29	425	4300	4.99
161	7.75	6.95	74.50	63.27	335	4180	6.02
162	6.80	9.30	74.50	63.05	250	4180	7.66
163	11.80	0.91	83.80	71.55	3300	5420	0.960
164	11.45	1.14	83.65	71.63	2640	5420	1.155
165	11.30	1.48	83.60	71.56	1980	5270	1.45
166	11.20	2.14	83.50	71.23	1320	5080	2.00
167	10.75	2.87	83.50	71.31	980	5070	2.55
168	10.30	4.18	83.50	71.11	650	4900	3.52
169	9.45	5.97	83.50	71.06	425	4570	4.94
170	8.80	7.48	83.45	70.91	335	4500	5.96
171	7.35	9.61	83.50	71.35	250	4330	7.58
172	10.05	0.99	92.90	82.35	3300	5880	0.989
173	10.00	1.27	92.95	82.31	2640	6030	1.18
174	9.90	1.64	93.15	82.43	1980	5830	1.47
175	9.75	2.35	93.20	82.27	1320	5580	2.05
176	9.60	3.07	93.20	82.06	980	5420	2.63
177	8.95	4.55	93.20	81.97	650	5330	3.48
178	8.00	6.57	93.25	81.96	425	5030	4.95
179	7.45	7.90	93.30	81.90	335	4770	5.97
180	6.75	10.15	93.25	81.42	250	4580	7.57

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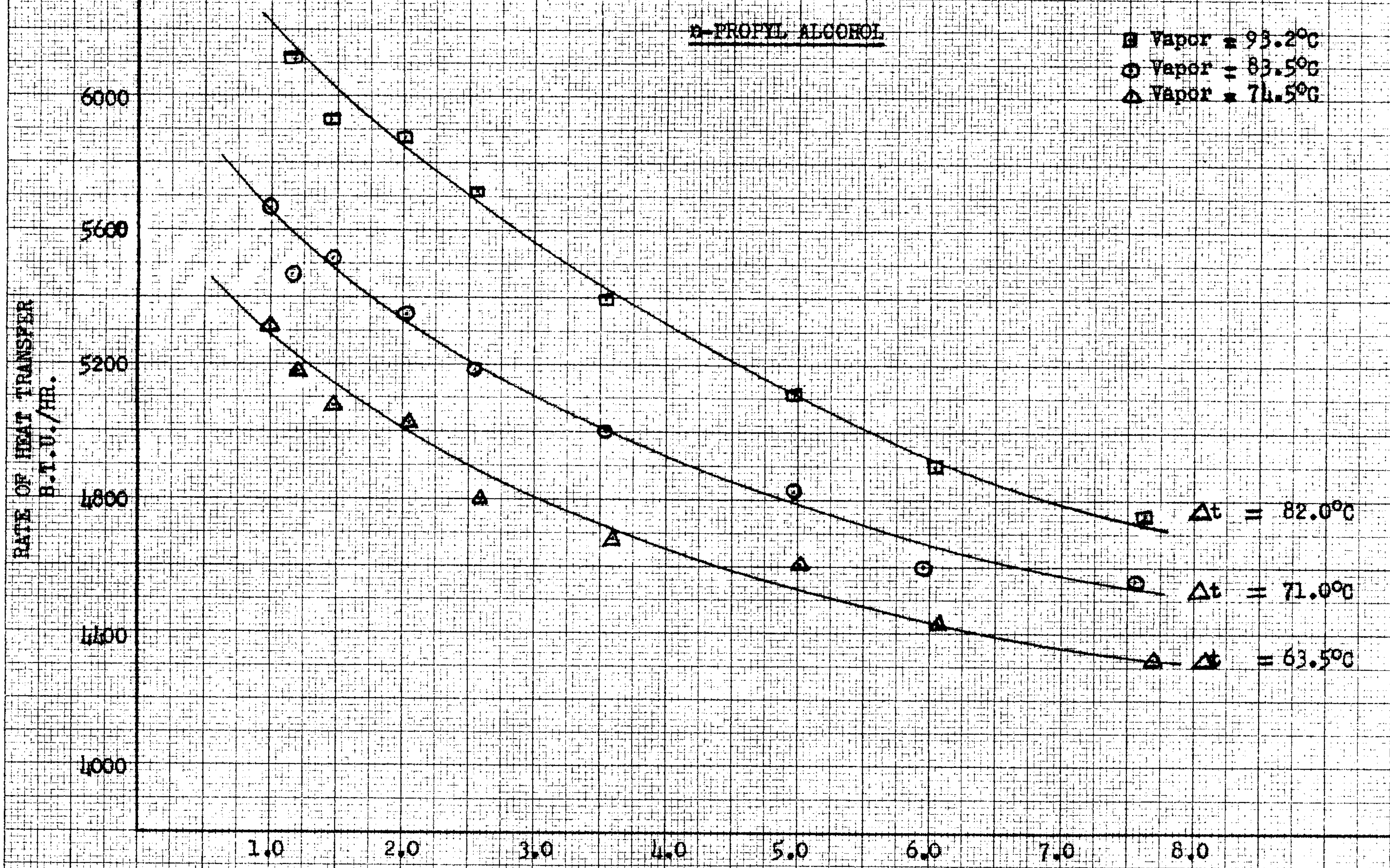
FIGURE 7- VARIATION OF HEAT TRANSFER RATE WITH WATER RATE

n-PROPYL ALCOHOL



$$\frac{1 \times 10^3}{(1 + .011t)V^{0.8}}$$

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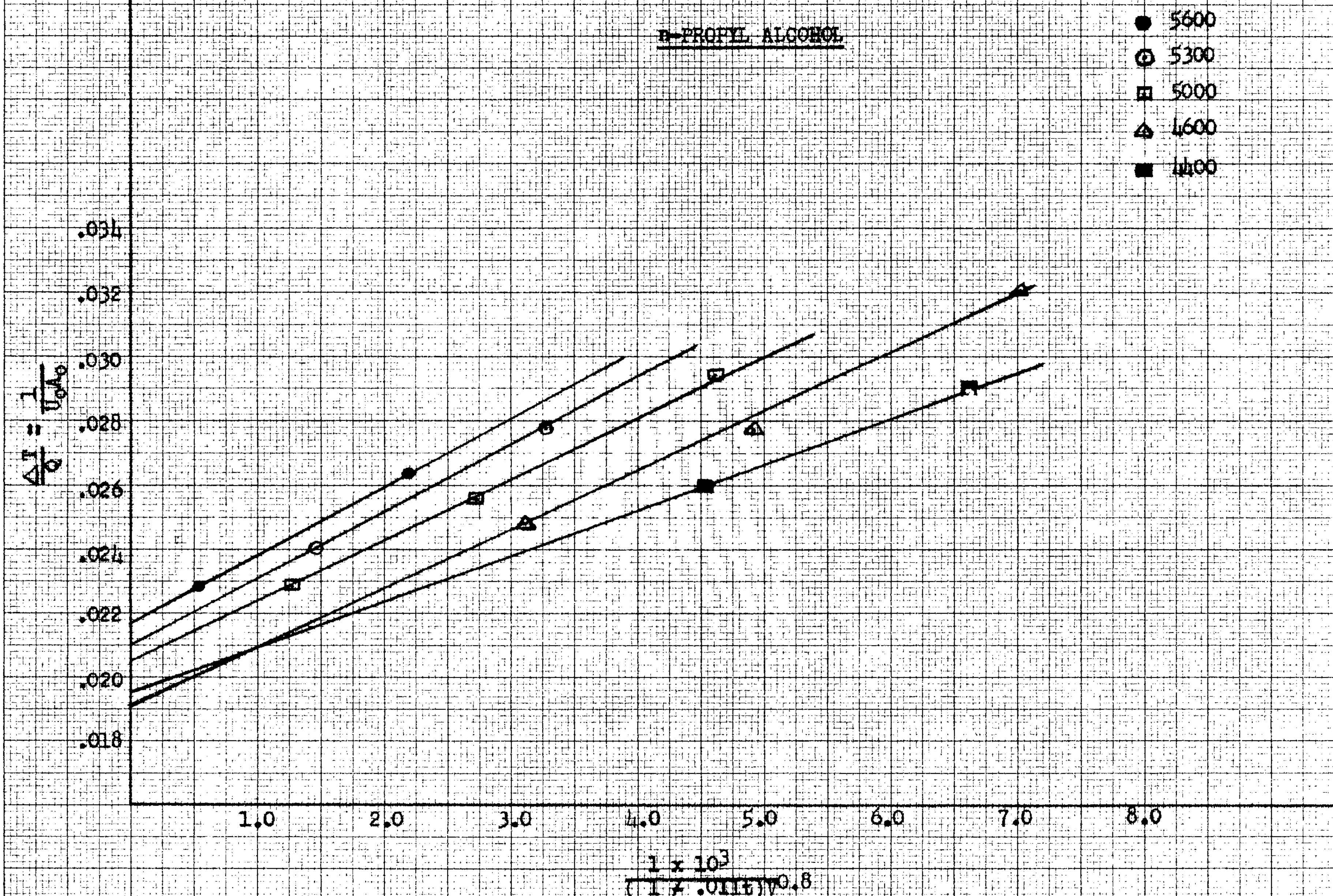


FIGURE 8- OVER-ALL THERMAL RESISTANCE AND WATER RATE

n-PROPYL ALCOHOL

DISCUSSION OF RESULTS

The results of this investigation have shown that the film heat transfer coefficient, h_o, varies inversely with q for n-propyl, n-butyl and n-amyl alcohol. For n-propyl alcohol, h_o varies from 238 to 264 at heat flows of 5600 to 4400 Btu/hr. The values for n-butyl are 241 to 272 with q varying between 6200 and 4400, while n-amyl varies from 220 to 250 at q values of 5600 to 4000.

The values were obtained from two or three points as shown on Figures 4, 6 and 8. The number of points is determined by the slope of the curves in Figures 3, 5 and 7, and a decrease in the over-all temperature difference would require a large number of experiments with a tendency for overlapping of the data. The enlargement of the temperature difference curves is a variable determined by equipment limitations.

The accuracy of the film coefficient values obtained is estimated to be accurate to ± 10%, based on the accuracy of the graphical method and the experimental error analysis. The cooling water temperature rise was read to 0.01°C. The error at the lowest temperature rise corresponding to high water flows was less than ± 2%. The deviations of the points in Figures 3, 5 and 7 were ± 2% or less. The water flow was accurate to within ± 3%. At low flows a larger deviation was possible due to the limited flow in the rotameters. For these conditions it was customary to check weigh the warm water return to provide an accurate water balance. Based on the above, it is believed that the value of the observed coefficient is accurate within ± 10%.

The relation of h_o to q as determined by Chu plotted on log-log paper should give a straight line of slope equal to minus one-third. The slopes for the three alcohols are plotted in Figure 9. The slopes for n-propyl, n-butyl and n-amyl are -0.437, -0.344 and -0.385, respectively. In the main, the previous data of Chu (7) with values of -0.374 and -0.307 for ethyl acetate and benzene, and Lipuma and Nirmaier (16) with values of -0.278 and -0.405 for methyl alcohol and i-propyl alcohol agrees with the above values in the variation from the predicted slope of -0.333. It is believed that this variation is a result of the limited number of points available for plotting Figures 4, 6 and 8. A small displacement of the curve effects a large change in the value of $\Delta t/Q$ at zero Wilson factor and results in a change in the slopes of Figure 9. Accordingly, it is felt that the variation is an experimental error and not the result of an unknown parameter.

Chu, Fliteraft and Holeman found the slope of toluene to be positive. It would be expected that further work on toluene and other homologous organics over an extended operating range would define more clearly the true slope.

Lipuma and Nirmaier substantiated the work of Chu with the exception of n-butyl alcohol where a variation with q was not noticed. N-butyl alcohol was investigated in this work and a variation with q was found. The earlier data for n-butyl has been rechecked and except for the temperature correction for fluid friction, as noted in the Appendix section, is in agreement with the current work. The exclusion of the temperature correction and the extended water flows used in this work increases the slopes of the curves in Figures 3, 5 and 7, and accounts for the increased slope of h_o in Figure 9.

The comparison of the observed values of h_o with the calculated values of h_o by the Nusselt equation are listed in Table 5. The agreement between the two values is considered to be good for all three alcohols tested, although the maximum variation is 11%. In all cases the predicted values are higher than the observed values. This is in agreement with all previous work. Unfortunately, the physical data available for the three alcohols is meagre and where available from sources (2, 9, 10, 11) is not in good agreement. Because of the variability of physical data for the three alcohols, it is felt that study of the relationship between $h_{obs.}/h_{calc.}$ to molecular weight or other parameters is not warranted.

The effect of sub-cooling has often been investigated in similar work, but it is felt to be of negligible effect for this investigation due to the small temperature difference between the saturated vapor and the condensate temperature as checked by the annular thermocouple.

The effect of condenser tube fouling appears to be negligible since the tube was dismantled and checked periodically for scale or dirt build-up. The presence of non-condensable fouling was minimized by the method of operation, as noted in a previous section.

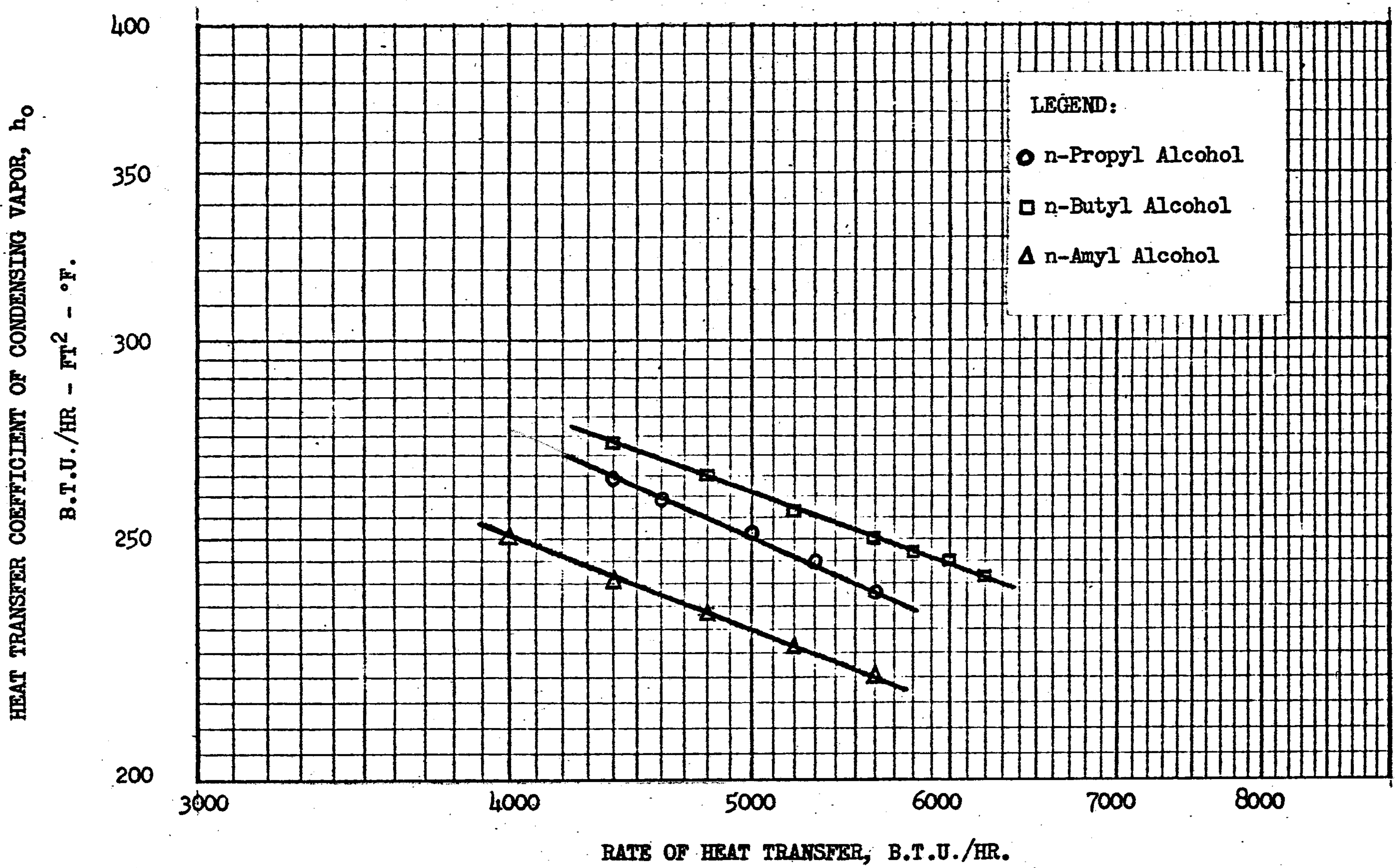
In comparing the $h_{obs.}$ versus the $h_{calc.}$ from the Nusselt equation, the most serious source of error available appeared to be the possibility that excessive vapor flow in the test condenser would affect the condensing film thickness. As previously noted, the Nusselt equation assumes gravity flow without acceleration affects from the vapor velocity. For the alcohols used in this investigation excessive vapor velocity was noted at points of high vacuum with the high boilers and during excessive vaporization of low boilers at low vacuum. This was evidenced by "blowing" of the seal legs. The problem was minimized by manual throttling of the steam to the jacket, but could better be controlled through use of tempered water for low boiling materials coupled with installation of a larger vapor space for the high vacuum work.

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

q	h_o		Ratio of Observed to Theoretical h_o
Btu/hr	Observed	Theoretical Nusselt	
	n-Propyl Alcohol		
5600	238	244	0.975
5300	245	252	0.972
5000	252	268	0.940
4600	259	279	0.928
4400	264	280	0.916
	n-Butyl Alcohol		
6200	242	269	0.900
6000	245	274	0.895
5800	247	287	0.860
5600	250	288	0.868
5200	256	289	0.885
4800	265	298	0.890
4400	272	300	0.906
	n-Amyl Alcohol		
5600	220	270	0.815
5200	227	289	0.785
4800	234	290	0.807
4400	240	297	0.808
4000	250	330	0.758

FIGURE 9

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



CONCLUSIONS

The film coefficients of heat transfer, h_o, have been obtained for the three aliphatic alcohols, n-propyl, n-butyl and n-amyl. The theory of Chu, Flitcraft and Holeman that h_o is a function of the heat transferred, q, has been substantiated.

The organics and flow rates tested in this work have extended considerably the range of operating conditions investigated for checking the validity of the Wilson method as modified by Chu and associates. The range of the Wilson numbers investigated has been increased by sixty per cent with water flows tested at Reynolds numbers of 4000 to 55,000.

Good agreement was found between the observed coefficients and the coefficients calculated by the Nusselt equation. For the aliphatic alcohols tested at vapor pressures up to one atmosphere, it can be concluded that the Nusselt equation satisfactorily predicts the condensing film coefficients. The effect of heat capacity at positive pressures is unknown.

It is further concluded that the method of Chu and associates offers a satisfactory method of obtaining accurate film coefficients for condensing organics, particularly where physical properties are unknown or variable, and application of the Nusselt equation is questionable.

RECOMMENDATIONS

The following recommendations are made:

1. Conduct investigations of the aliphatic alcohols at high water rates with Wilson numbers of less than 1.0, and at low water rates of Wilson numbers above 8.0. Determine the variation from the Nusselt value, if any.

2. Investigate the values of h_o for the aliphatic alcohols at positive pressures.

3. Initiate studies of another series of homologous organics.

4. Further investigations should include modification of the existing equipment to include:

   (a) tempered water system for vaporization of low boiling point organics;

   (b) enlarged vapor annulus to reduce the effect of vapor velocity on the condensate film;

   (c) provide weighed water holding tanks for more accurate determination of the water flows;

   (d) provide a positive displacement water circulating pump to allow investigation of higher water flows than possible in the existing equipment due to centrifugal pump head limitations.

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.).
K	=	a constant.
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 (= $1/U_o$).
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.).

A P P E N D I X

APPENDIX CONTENTS

Page

FIGURE 10

LARGE ROTAMETER CALIBRATION CURVE

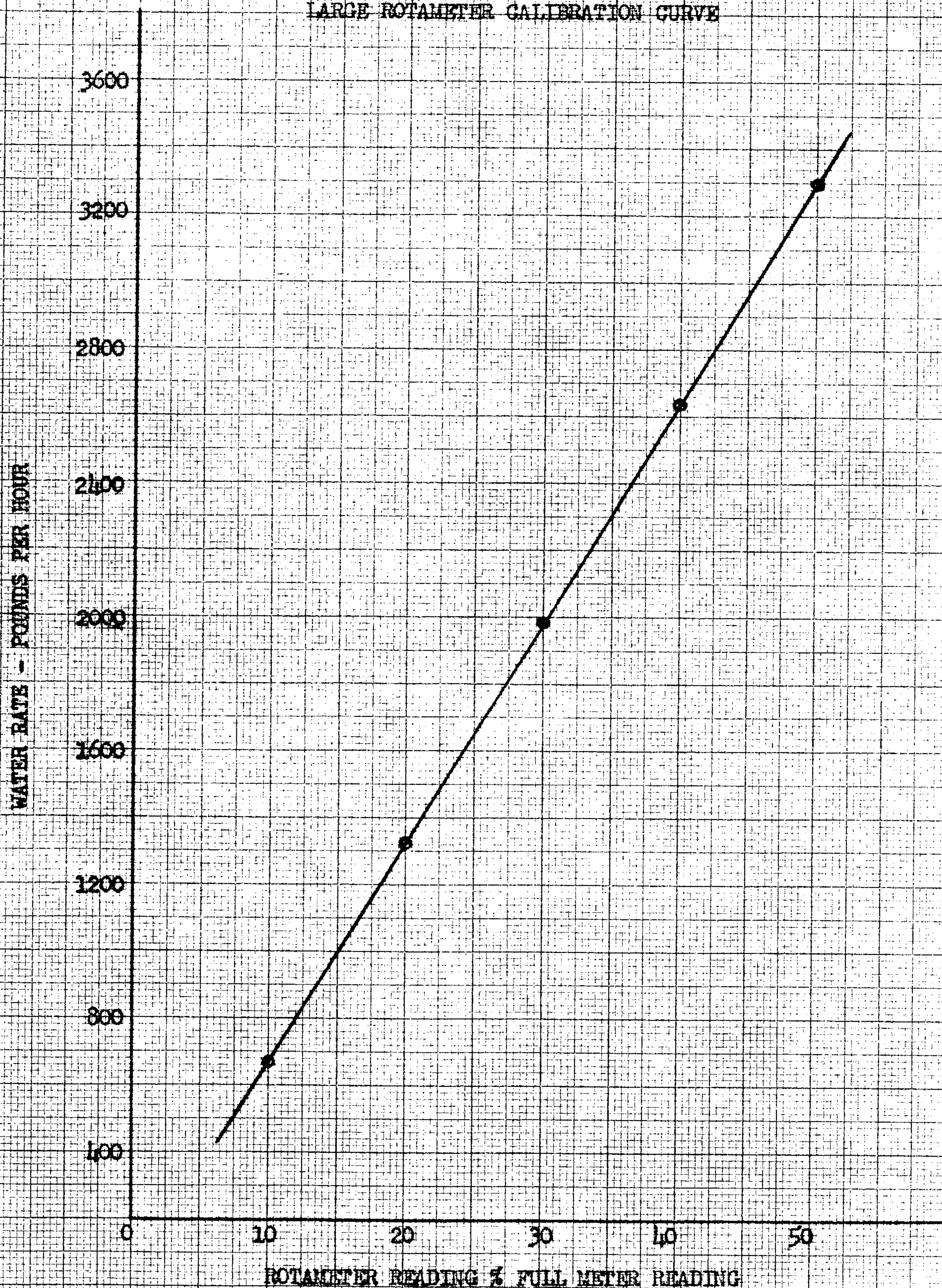


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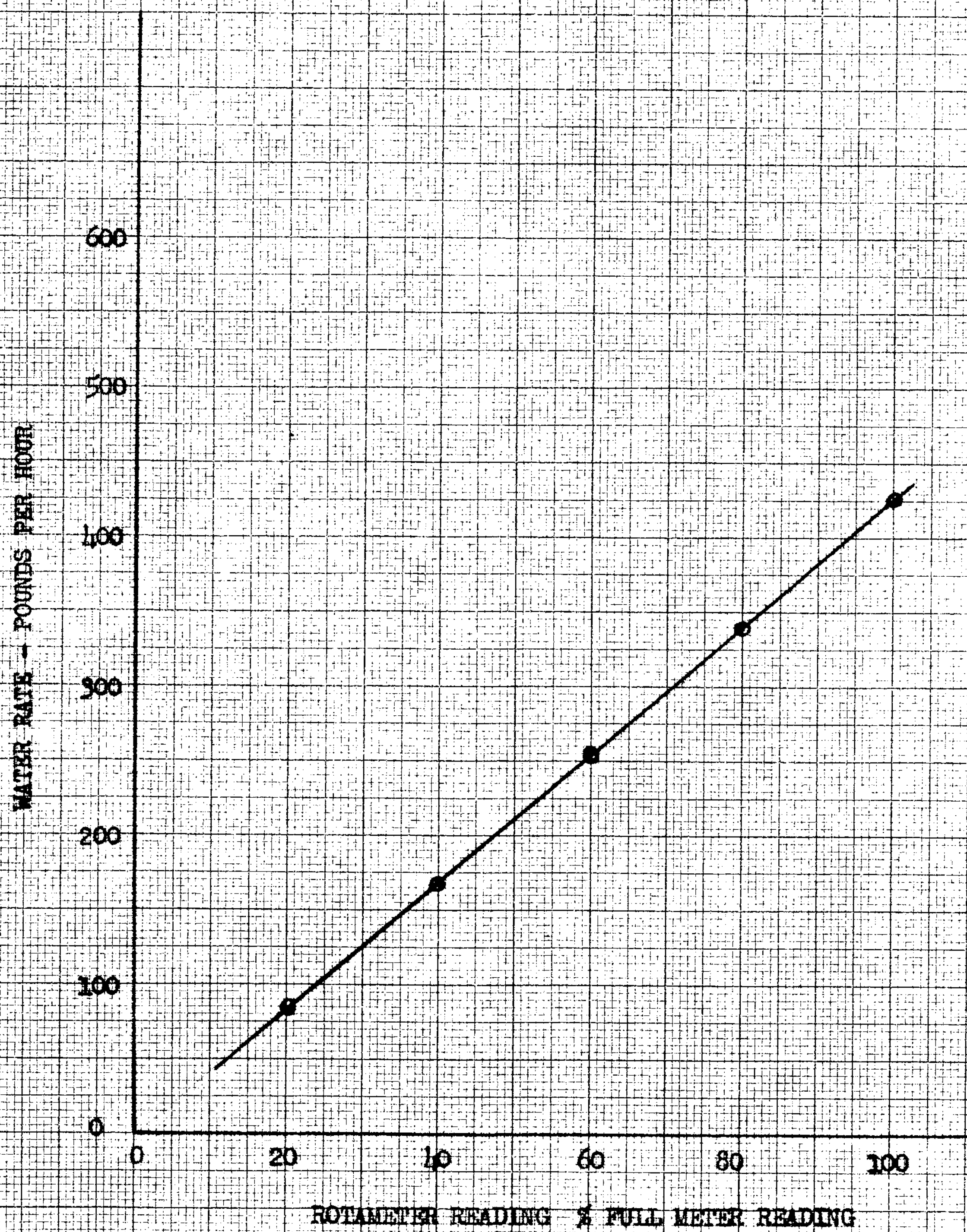
FIGURE 11

SMALL ROTAMETER CALIBRATION CURVE



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REFERENCE CORRECTION OF BECKMANN THERMOMETERS

Three 5°C Beckmann thermometers were used to measure the cooling water rise through the condenser tube. One of the instruments was positioned at the cold inlet permanently. The other two instruments were rotated as required to cover the maximum temperature rise of 10°C.

No attempt was made to adjust the mercury columns to the same scale readings due to the wide temperature range and the difficulty in adjusting the absolute temperature level through alternate heating and cooling of the bulb.

At the outset of the investigation, the temperature difference readings were obtained at zero heat flow and all three units calibrated with respect to each other.

The 0-100°C thermometers were used as check points for the calibrations. The temperature rise due to fluid friction noted by Lipuma and Nirmaier (16) was not found. The amount of temperature rise expected from fluid friction was calculated and found to be negligible except at full flow where the maximum temperature rise was 5 per cent of the temperature rise due to vapor condensation.

TABLE 6
ORIGINAL DATA - n-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	°C	°C	°C	MV	°C
B	50.0	11.05	1.04	11.25	1.08			
1	50.0	11.15	1.13	12.20	2.20	93.00	3.63	85.5
2	40.0	10.90	0.88	12.20	2.18	93.00	3.60	85.4
3	30.0	11.20	1.23	12.90	2.94	92.85	3.60	85.4
4	20.0	11.50	1.46	13.95	3.95	92.80	3.60	85.4
5	15.0	11.00	0.95	14.10	4.09	92.80	3.60	85.4
6	10.0	10.65	0.62	15.10	5.06	92.85	3.60	85.4
B	100.0 s	8.40	2.34	14.70	1.54			
7	100.0 s	9.70	3.60	16.00	2.77	92.85	3.75	89.0
8	80.0 s	8.90	2.82	16.45	3.22	93.00	3.70	87.5
9	60.0 s	7.90	1.87	17.50	4.37	93.00	3.70	87.5
B	60.0 s	10.85	0.65	19.25	3.07			
10	60.0 s	10.90	0.72	19.65	3.54	80.80	3.10	74.4
11	80.0 s	11.80	0.61	18.60	1.43	80.80	3.10	74.4
12	100.0 s	12.50	1.35	17.90	0.72	80.80	3.10	74.4
13	10.0	13.10	2.06	17.00	0.01	80.70	3.15	75.3
B	10.0	13.80	3.62	16.08	2.82			
14	15.0	13.75	3.60	16.50	3.26	81.00	3.20	76.3
15	20.0	13.95	3.81	16.00	2.83	81.00	3.20	76.3
16	30.0	13.95	3.83	15.45	2.20	81.10	3.20	76.3
17	40.0	13.80	3.60	14.90	1.62	81.20	3.20	76.3
18	50.0	14.00	3.84	14.95	1.67	81.15	3.20	76.3
B	50.0	11.30	2.45	12.20	2.78			
19	50.0	11.20	2.37	12.35	2.94	105.00	4.10	96.3
20	40.0	11.10	2.25	12.55	3.08	105.05	4.10	96.3
21	30.0	11.00	2.13	12.90	3.44	105.10	4.15	97.3
22	20.0	10.80	1.95	13.50	3.98	105.20	4.15	97.3
23	15.0	10.40	1.57	13.95	4.50	105.05	4.15	97.3
B	10.0	9.80	3.62	14.40	1.34			
24	10.0	9.60	3.45	14.75	1.62	104.95	4.20	98.7
25	100.0 s	8.55	2.33	15.50	2.47	104.95	4.20	98.7
26	80.0 s	7.80	1.60	16.05	3.02	104.90	4.20	98.7
27	60.0 s	6.60	0.38	17.15	4.00	105.00	4.15	97.3
B	50.0	12.30	3.43	12.50	2.95			
28	50.0	12.20	3.32	13.20	3.69	93.40	3.80	89.8

TABLE 6 (CON'T.)
ORIGINAL DATA - n-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	°C	°C	°C	MV	°C
29	40.0	12.15	3.29	13.40	3.92	93.25	3.76	89.0
30	30.0	11.70	2.85	13.35	3.77	93.20	3.70	87.6
31	20.0	11.40	2.60	13.95	3.44	93.05	3.70	87.6
32	15.0	11.10	2.25	14.10	3.61	93.10	3.68	86.9
B	10.0	10.95	4.12	15.00	1.74			
33	10.0	10.80	3.97	15.10	1.86	93.00	3.72	88.9
34	100.0 s	9.75	2.90	16.10	2.86	92.95	3.65	85.5
35	80.0 s	8.80	1.93	16.35	3.12	92.80	3.63	87.7
36	60.0 s	8.05	1.11	17.55	4.13	92.90	3.70	87.6
B	50.0	14.45	4.72	14.60	2.12			
37	50.0	14.40	4.61	15.35	2.84	81.35	3.30	78.6
38	40.0	14.35	4.58	15.50	2.96	81.42	3.34	79.6
39	30.0	14.20	4.39	15.65	3.14	81.42	3.38	80.6
40	20.0	14.00	4.21	16.05	3.46	81.30	3.28	78.2
41	15.0	13.75	3.97	16.45	4.02	81.06	3.15	75.3
B	10.0	13.40	3.68	16.80	1.14			
42	10.0	13.10	3.41	17.00	1.32	80.95	3.00	72.1
43	100.0 s	12.30	2.58	17.80	2.09	80.87	2.96	71.6
44	80.0 s	11.70	1.94	18.65	2.97	80.92	2.90	69.9
45	60.0 s	10.95	1.27	19.90	4.34	80.90	2.92	70.4
B	50.0	11.70	1.95	12.60	2.76			
46	50.0	11.50	1.72	12.65	2.73	105.30	4.30	100.0
47	40.0	11.40	1.60	12.95	2.96	105.25	4.27	99.6
48	30.0	11.35	1.53	14.10	3.24	105.05	4.22	98.7
49	20.0	10.85	1.01	13.60	3.64	105.00	4.18	98.4
50	15.0	10.60	0.75	14.10	4.07	104.90	4.10	96.3
B	10.0	10.00	4.43	14.65	1.47			
51	10.0	9.90	4.31	14.80	1.65	104.85	4.13	97.1
52	100.0 s	8.70	3.17	15.55	2.42	104.80	4.08	95.8
53	80.0 s	7.95	2.30	16.45	3.14	104.70	4.10	96.3
54	60.0 s	6.80	1.26	17.40	4.35	104.75	4.12	96.8

TABLE 7
ORIGINAL DATA – n-AMYL ALCOHOL

RUN NO.	ROTA-METER RDG	INLET WATER TEMPERATURE		OUTLET WATER TEMPERATURE		VAPOR TEMP.	FILM TEMP.	
		ABSOLUTE	BECKMANN	ABSOLUTE	BECKMANN			
	%	°C	°C	°C	°C	°C	MV	°C
B	50.0	12.50	4.73	12.60	2.42			
55	50.0	12.45	4.70	13.40	3.16	82.50	3.20	76.3
56	40.0	12.40	4.66	13.50	3.28	82.35	3.15	75.3
57	30.0	12.35	4.59	13.75	3.55	82.10	3.20	76.3
58	20.0	12.20	4.36	14.30	4.02	82.15	3.10	74.4
59	15.0	11.95	4.20	14.40	4.28	82.00	3.10	74.4
B	10.0	12.50	4.73	14.80	1.03			
60	10.0	11.40	3.61	15.05	1.20	81.95	3.00	72.1
61	100.0 s	10.60	2.84	15.75	2.06	81.80	2.90	69.9
62	80.0 s	10.05	2.23	16.50	2.64	81.75	2.95	71.0
63	60.0 s	8.80	1.05	17.05	3.35	81.60	3.05	73.6
B	50.0	11.05	3.34	12.00	1.88			
64	50.0	11.00	3.30	11.95	1.86	93.50	3.50	84.2
65	40.0	11.10	3.39	12.25	2.16	93.50	3.50	84.2
66	30.0	10.95	3.20	12.45	2.31	93.45	3.47	83.5
67	20.0	10.70	2.97	13.00	2.80	93.35	3.40	81.6
68	15.0	10.55	2.82	13.35	3.27	93.20	3.26	78.4
B	10.0	10.50	2.79	14.45	0.68			
69	10.0	10.40	2.67	14.55	0.71	93.20	3.25	78.0
70	100.0 s	9.75	2.00	15.60	1.75	93.15	3.20	76.3
71	80.0 s	9.20	1.47	16.05	2.24	93.15	3.18	75.8
72	60.0 s	8.15	0.41	16.85	3.10	93.10	3.15	75.3
B	50.0	11.20	3.82	11.30	1.63			
73	50.0	11.25	3.86	12.30	2.62	100.60	4.00	94.0
74	40.0	11.15	3.75	12.40	2.75	100.60	3.95	93.0
75	30.0	10.90	3.52	12.55	2.89	100.65	3.95	93.0
76	20.0	10.50	3.13	12.85	3.20	100.70	3.95	93.0
77	15.0	10.20	2.80	13.40	3.64	100.75	4.00	94.0
B	10.0	9.90	2.52	13.90	0.13			
78	10.0	9.65	2.26	14.05	0.22	100.90	4.00	94.0
79	100.0 s	8.80	1.42	15.05	1.13	101.00	3.95	93.0
80	80.0 s	8.15	0.87	15.60	1.92	100.90	4.00	94.0
81	60.0 s	7.30	0.02	16.15	2.86	100.95	4.05	95.1
B	50.0	12.60	5.16	12.70	3.01			
82	50.0	12.60	5.17	13.25	3.76	82.20	3.15	75.3

TABLE 7 (CON'T.)
ORIGINAL DATA - n-AMYL 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	°C	°C	°C	MV	°C
83	40.0	12.50	5.05	13.50	3.85	82.35	3.10	74.4
84	30.0	12.35	4.91	13.65	3.98	82.20	3.20	76.3
85	20.0	12.10	4.68	14.15	4.23	82.10	3.25	77.5
86	15.0	11.85	4.20	14.45	4.50	82.05	3.20	76.3
B	10.0	11.50	4.06	14.95	1.02			
87	10.0	11.40	3.97	15.05	1.10	81.90	3.10	74.4
88	100.0 s	10.80	3.40	15.90	2.08	81.75	3.05	73.6
89	80.0 s	10.15	2.78	16.70	2.57	81.70	3.10	74.4
90	60.0 s	9.05	1.57	17.15	3.15	81.80	3.10	74.4
B	50.0	11.20	3.80	11.30	1.61			
91	50.0	11.05	3.64	12.10	2.38	100.70	3.95	93.0
92	40.0	11.00	3.59	12.35	2.57	100.70	3.95	93.0
93	30.0	10.80	3.36	12.55	2.76	100.60	4.00	94.0
94	20.0	10.40	2.98	12.85	3.09	100.50	4.05	95.1
95	15.0	10.15	2.70	13.20	3.50	100.55	4.10	96.3
B	10.0	10.00	2.60	14.00	0.05			
96	10.0	9.50	2.12	14.05	0.09	100.65	4.05	95.1
97	100.0 s	8.85	1.43	15.15	1.15	100.70	4.00	94.0
98	80.0 s	8.20	0.81	15.50	1.49	100.75	4.00	94.0
99	60.0 s	7.50	0.09	16.75	2.70	100.70	3.95	94.0
B	50.0	11.30	3.90	11.40	1.71			
100	50.0	11.35	3.94	12.35	2.59	93.05	3.25	77.5
101	40.0	11.25	3.87	12.45	2.77	93.10	3.30	78.6
102	30.0	11.05	3.63	12.50	2.88	93.20	3.20	76.3
103	20.0	10.60	3.18	16.85	3.08	93.25	3.15	75.3
104	15.0	10.50	3.10	13.45	3.72	93.15	3.20	76.3
B	10.0	10.25	2.85	14.10	0.15			
105	10.0	10.10	2.72	14.15	0.17	93.00	3.15	75.3
106	100.0 s	9.05	1.66	15.15	1.12	92.80	3.10	74.4
107	80.0 s	8.50	1.14	15.50	1.54	92.70	3.10	74.4
108	60.0 s	7.40	0.03	16.25	2.28	92.75	3.15	75.3

TABLE 8

ORIGINAL DATA - n-PROPYL 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	°C	°C	°C	MV	°C
B	50.0	9.80	3.05	9.90	0.63			
109	50.0	9.75	3.01	10.80	1.51	92.90	3.70	87.5
110	40.0	9.90	3.13	11.10	1.86	93.10	3.75	89.0
111	30.0	10.15	3.42	11.75	2.52	93.20	3.75	89.0
112	20.0	10.20	3.44	12.65	3.32	93.40	3.75	89.0
113	15.0	10.00	3.23	13.25	3.84	93.45	3.75	89.0
114	10.0	9.55	2.80	14.05	4.71	93.40	3.75	89.0
B	10.0	8.60	1.85	14.50	1.63			
115	100.0 s	8.40	1.63	14.80	1.83	93.20	3.80	89.8
116	80.0 s	7.55	0.82	15.35	2.50	93.20	3.75	89.0
117	60.0 s	6.85	0.01	16.95	4.99	93.15	3.85	90.4
B	50.0	11.60	4.87	11.70	2.45			
118	50.0	11.60	4.86	12.55	3.26	83.40	3.20	76.3
119	40.0	11.55	4.81	12.70	3.40	83.50	3.20	76.3
120	30.0	11.40	4.69	12.90	3.66	83.65	3.35	79.8
121	20.0	11.25	4.60	13.55	4.25	83.55	3.35	79.8
122	15.0	11.05	4.38	14.00	4.69	83.50	3.35	79.8
123	10.0	10.30	3.55	14.60	5.13	83.35	3.25	78.0
B	10.0	9.60	2.87	15.00	2.13			
124	100.0 s	9.45	2.75	15.90	2.67	83.20	3.30	78.6
125	80.0 s	8.80	2.09	16.20	3.26	83.15	3.25	78.0
126	60.0 s	7.55	0.81	17.15	4.35	83.40	3.20	76.3
B	50.0	11.00	4.27	11.10	1.83			
127	50.0	11.00	4.28	11.85	2.60	74.50	2.90	69.9
128	40.0	10.65	3.98	11.80	2.49	74.50	2.90	69.9
129	30.0	10.40	3.67	11.75	2.50	74.40	2.95	71.0
130	20.0	9.95	3.21	12.05	2.70	74.45	2.90	69.9
131	15.0	9.60	2.92	12.25	2.99	74.50	2.95	71.0
132	10.0	9.05	2.30	12.90	3.60	74.55	2.90	69.9
B	10.0	8.30	1.57	13.60	0.73			
133	100.0 s	8.10	1.28	13.90	0.91	74.50	2.90	69.9
134	80.0 s	7.35	0.61	14.40	1.48	74.50	2.90	69.9
135	60.0 s	6.80	0.06	16.00	3.14	74.50	2.95	71.0
B	50.0	10.60	3.85	10.70	1.45			
136	50.0	10.55	3.81	11.60	2.35	93.15	3.75	89.0

TABLE 8 (CON'T.)

ORIGINAL DATA - n-PROPYL 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	°C	°C	°C	MV	°C
137	40.0	10.25	3.52	11.55	2.33	93.20	3.70	87.5
138	30.0	10.10	3.37	11.85	2.57	93.35	3.70	87.5
139	20.0	9.95	3.20	12.45	3.14	93.50	3.65	86.0
140	15.0	9.70	2.98	12.90	3.64	93.40	3.70	87.5
141	10.0	9.20	2.47	13.65	4.34	93.20	3.75	89.0
B	10.0	8.10	1.35	14.00	1.13			
142	100.0 *	8.05	1.32	14.30	1.46	93.05	3.80	89.8
143	80.0 *	7.20	0.56	15.15	2.37	93.00	3.85	90.4
144	60.0 *	6.60	0.01	16.75	4.09	93.95	3.80	89.8
B	50.0	11.70	4.95	11.75	2.50			
145	50.0	11.75	4.99	12.75	3.44	83.25	3.15	75.3
146	40.0	11.60	4.83	12.85	3.49	83.35	3.20	76.3
147	30.0	11.50	4.77	13.10	3.84	83.50	3.20	76.3
148	20.0	11.05	4.32	13.50	4.19	83.50	3.25	78.0
149	15.0	10.90	4.15	13.95	4.60	83.55	3.30	78.6
B	10.0	10.60	3.85	14.90	2.05			
150	10.0	10.60	3.85	14.95	2.07	83.60	3.30	78.6
151	100.0 *	10.05	3.34	16.25	3.39	83.50	3.25	78.0
152	80.0 *	9.20	2.40	16.75	3.86	83.50	3.25	78.0
153	60.0 *	8.05	1.35	17.85	5.05	83.45	3.25	78.0
B	50.0	11.00	4.25	11.10	1.85			
154	50.0	10.90	4.13	11.80	2.48	74.65	2.95	71.0
155	40.0	10.80	4.05	11.90	2.61	74.55	3.00	72.2
156	30.0	10.55	3.81	12.00	2.71	74.50	2.95	71.0
157	20.0	10.30	3.55	12.35	3.05	74.50	2.90	69.9
158	15.0	9.90	3.17	12.55	3.34	74.50	2.90	69.9
159	10.0	9.15	2.46	13.10	3.85	74.45	2.85	68.7
B	10.0	8.55	1.80	13.80	0.95			
160	100.0 *	8.30	1.63	13.95	1.15	74.40	2.90	69.9
161	80.0 *	7.75	1.02	14.70	1.87	74.50	2.90	69.9
162	60.0 *	6.80	0.04	16.05	3.24	74.50	2.90	69.9
B	50.0	11.80	5.05	11.90	2.65			
163	50.0	11.80	5.05	12.75	3.46	83.80	3.30	78.6
164	40.0	11.45	4.72	12.65	3.36	83.65	3.25	78.0
165	30.0	11.30	4.58	12.80	3.56	83.60	3.25	78.0

TABLE 8 (CON'T.)
ORIGINAL DATA - n-PROPYL 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	°C	°C	°C	MV	°C
166	20.0	11.20	4.45	13.35	4.09	83.50	3.25	78.0
167	15.0	10.75	4.03	13.65	4.40	83.50	3.25	78.0
B	10.0	10.60	3.85	14.30	1.45			
168	10.0	10.30	3.54	14.50	1.62	83.50	3.20	76.3
169	100.0 s	9.45	2.72	15.40	2.59	83.50	3.20	76.3
170	80.0 s	8.80	3.05	16.35	4.43	83.45	3.20	76.3
171	60.0 s	7.35	1.58	17.05	5.09	83.50	3.25	78.0
B	50.0	10.00	3.25	10.10	0.85			
172	50.0	10.05	3.28	11.05	1.77	92.90	3.60	85.4
173	40.0	10.00	3.24	11.30	2.01	92.95	3.70	87.6
174	30.0	9.90	3.15	11.45	2.29	93.15	3.70	87.6
175	20.0	9.75	3.02	12.15	2.87	93.20	3.75	88.7
176	15.0	9.60	2.87	12.70	3.44	93.20	3.75	88.7
177	10.0	8.95	2.20	13.50	4.25	93.20	3.75	88.7
B	10.0	8.10	1.35	14.35	1.40			
178	100.0 s	8.00	1.30	14.60	1.76	93.25	3.80	89.8
179	80.0 s	7.45	0.77	15.40	2.56	93.30	3.80	89.8
180	60.0 s	6.75	0.10	16.85	4.14	93.25	3.75	88.7

SAMPLE CALCULATIONS

I. RUN NO. 3 - BUTYL ALCOHOL

1. Rate of Heat Transfer, q

Water flow rate = 1980 lb./hr.

Water temperature rise = 1.67°C

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

q = (1980) (1.0) (1.26) (1.8) = 5940 Btu/hr.

2. Water Bulk Temperature, °F

Inlet water temperature = 11.20°C

Water temperature rise = 1.67°C

Bulk temperature °C $= 11.20 + \frac{1.67}{2} = 12.04$°C

Bulk temperature °F = (12.04) (1.8) + 32 = 53.7°F

3. Over-all Water to Vapor Temperature Difference, °C

Water bulk temperature = 12.04°C

Vapor temperature = 92.85°C

Over-all temperature difference = 92.85 - 12.04 = 80.81°C

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

Water bulk temperature = 53.7°F

$$V^{0.8} = 435$$

$$\frac{1 \times 10^3}{(1 + 0.011t)V^{0.8}} = \frac{1 \times 10^3}{(1 + .011(53.7)(435)} = 1.44$$

II. BUTYL ALCOHOL AT $q = 5600$ Btu/hr

1. **Observed Heat Transfer Coefficient, h_o**

From Figure at $q = 5600$ Btu/hr

T^oF	$\Delta T/q$	$\frac{1 \times 10^3}{(1 + 0.011t)V^{0.8}}$
167	.0298	4.15
144	.0257	2.30
119	.0213	0.35

From

$\Delta T/q$ versus $\frac{1 \times 10^3}{(1 + 0.011t)V^{0.8}}$ Plot Figure

at $\frac{1 \times 10^3}{(1 + 0.011t)V^{0.8}} = 0$, $\Delta T/q = 0.0206$

Tube wall thickness, $x = 0.00292$ ft.

Outside tube surface area $= 0.1962$ sq. ft.

Inside tube surface area $= 0.1596$ sq. ft.

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

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

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

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

$$h_o = \frac{1}{0.1962\ (0.0206 - 0.00027)} = 251 \text{ Btu/(hr) (sq. ft.) }^oF$$

2. **Theoretical Heat Transfer Coefficient, h_o**

Run #3 n-Butyl Alcohol

At infinite water rate:

Water temperature in = out 11.2°C

Saturated vapor t_{sv} = 92.85°C

Thermal resistance water film to vapor

$$\frac{\Delta t}{q} = 0.0206$$

Thermal resistance of tube wall = 0.00027

Saturated vapor to water temp. diff. = 92.85 - 11.20 = 81.65°C

Tube surface temp., $t_s = 11.20 + 81.65 \frac{.00027}{.0206} = 12.27°C$

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

$= 92.85 - 0.75 (92.85 - 12.27)$

$= 32.35°C$

Δt across condensate film = 92.85 - 12.27 = 80.58°C

at t_f = 32.35°C

Thermal conductivity, k_f = .088 Btu/(hr) (sq. ft.) (°F/ft.)

Density, ρ = 50.7 lb/cu. ft.

Latent heat, λ = 254 Btu/lb. ?

Viscosity, μ_f = 2.21 lb/(hr) (ft.) ?

Gravitational constant, g = 4.17×10^8 ft./hr^2

Outside tube diameter, D_o = 0.03125 ft.

Temperature drop across condensate film = 145°C

By the Nusselt equation

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

$$h_o = 0.725 \sqrt[4]{\frac{(.088)^3 \; (50.7)^2 \; (4.17 \times 10^8) \quad (254)}{(.03125) \; (2.21) \; (145)}}$$

= 268 ok Btu/(hr) (sq. ft.) (°F)

234.1

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