COEFFICIENTS OF HEAT TRANSFER BETWEEN CONDENSING ALCOHOL VAPORS AND A VERTICAL COPPER TUBE

by

Bennett Douglas Buckles

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Approved:

In charge of Major work

Head of Major Department

Dean of Engineering Division

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I. INTRODUCTION

Joule[25] probably was the first one to understand clearly that the major resistance to heat transfer from a fluid to a solid surface is a film of nearly stagnant fluid at the interface. Both he and Lord Kelvin[26] realized that the thickness of the film was indeterminant, since in general heat flows both by convection and conduction through the film. McAdams and Frost[33] elaborated on the film conception theory and came to the conclusion that each film and the metal wall has to be treated separately in calculating the heat flow.

In the past twenty years many experiments have been performed measuring the actual metal temperature when steam was condensed on tubes. In this way the heat transfer coefficients of the condensing vapor could be determined. Other experiments have been made using organic vapors such as diphenyl compounds, benzene, toluene, and carbon tetrachloride vapors.

In the condensation of vapors the resistances encountered are those of the water, tube wall, and condensing vapor. Since the resistance of the film is the reciprocal of the film coefficient, it can easily be seen that the vapor film coefficient is indispensible in the calculations of heat flow. Since there has been intensive investigation on the calculation of water film coefficients and tube wall resistances, only the film coefficients of the condensing vapor has to be known in order to calculate the heat flow. This fact shows the importance of determining the film coefficients of condensing vapors as is done in this experiment.

The purpose of this investigation is:

(1) To compare actual experimental film coefficients obtained for alcohol vapors with the theoretical film coefficients obtained by the Nusselt equation.

(2) To correlate the values of the vapor film coefficients in a series of alcohols, methyl, ethyl, isopropyl, n-butyl, and n-amyl, with their physical properties.

II. REVIEW OF LITERATURE

According to Walker, Lewis, and McAdams[50] heat may flow by one or more of three basic mechanisms: conduction, convection, and radiation. This investigation deals principally with convection and conduction. Convection is the transfer of heat from one point to another within a fluid, gas or liquid, by the mixing of one portion of the fluid with another. Conduction is the transfer of heat from one part of a body to another part of the same body, or from one body to another in physical contact with it, without appreciable displacement of the particles of the body. In the condensation of vapors the heat flow is across the vapor film, the tube wall, and the water film.

Probably Joule[25] was the first one to understand clearly the fact that the major resistance to heat flow from a fluid to a solid surface is a film of nearly stagnant fluid at the interface. Both he and Lord Kelvin realized that the thickness of this film was indeterminant, since in general heat flows both by convection and conduction through the film. Kelvin[26] suggested the term "heat transfer coefficient" be used for such cases. The coefficient was defined as the amount of heat passing through unit surface in unit time with unit temperature difference. Peclet is also given credit for having a conception of the water film in 1844.

In 1873 Reynolds[44] studied the effect of air on the over all coefficient of heat transfer from steam to water. He concluded that there is no limit to the rate at which heat will flow from pure condensing steam to metal surface except the power of the surface to carry away the heat.

From the time of Reynolds until about 1910 no significant experiments were made. A large number of investigators worked on the overall coefficient of heat transfer from steam to water in condensers and evaporators, but these were largely tests on specific apparatus.

Since 1910 rather a large number of experiments have been made measuring the actual metal temperature when steam was condensed on tubes. In this way the heat transfer coefficient of the condensing vapor could be determined.

Webster[52], Clement and Garland,[11] McAdams and Frost,[33] Morris and Whitman,[38] and Othmer[41] have investigated the condensation of steam on the outside of a horizontal tube. McAdams and Frost[34] also reported experiments on benzene and carbon tetrachloride. Jakob, Erk and Eck[22] have studied steam condensation inside a horizontal tube.

Jordan,[23] Collendar and Nicholson,[9] Philipp,[42] and Jacob and Erk[21] have studied steam condensation on vertical tubes. Badger and Monrad[4] have reported results obtained with diphenyl vapor condensing at high temperature differences on a long vertical tube.

Othmer,[41] Merkel,[37] Josse,[24] Arzcomanian and Alpert,[2] Kerr,[27] Robinson,[47] Chambers and Eskew,[10] and Colburn and Hougen[12] have studied the effect of air on the condensation of steam.

The effects of vapor velocity have been studied experimentally by several of the above investigators, but no very definite conclusions were reached. The effect of superheat of the vapor has been studied by Jacob and Erk[21] and shown to have a very small effect on the transfer of heat.

In 1916 Nusselt[39] in an excellent mathematical paper studied the effects of vapor and liquid properties, shape of the surface, and the purity and superheat of the vapor on the condensation of any vapor on a solid surface.

The formulas developed for the case of the vertical tube are probably accurate for short tubes and low temperature differences, but are in general inaccurate for industrial operations, owing probably to the effect of turbulence and possibly to the formation of drops.

In 1915 Wilson[53] employed a valuable graphical analysis of the over-all coefficient of heat transfer which has not received the attention the method deserves. The method was first developed by Professor C. E. Lucke[53]. An article by McAdams, Sherwood and Turner,[36a] shows plots of data for a number of condensers and feed heaters employing this same method.

McAdams and Frost[33] in 1922 elaborated on the film conception theory and came to the conclusion that each film and metal wall has to be treated separately in calculating the heat flow, instead of all these factors being treated in one lump as had been done before this time. Another experiment by McAdams and Frost[35] in 1923 developed an equation for heat transfer coefficients from a metal tube to a liquid inside a pipe. It is:

$$H = (22.6\,\frac{K}{D})(\frac{DV}{Z})^{0.8} \qquad (1)$$

In 1924 McAdams and Frost[36] developed another equation for the water film coefficient. It is:

$$H = 5.06\,[D(1 + \frac{50}{r})]\,[(\frac{V}{Z})^{0.8}] \qquad (2)$$

Two experiments, one in 1925 and one in 1927 evaluated overall coefficients of materials of construction and found their variation with formation of scales and oxide films.

In 1928, Morris and Whitman[38] experimented with the basic equation

$$\frac{hD}{k} = \phi\left(\frac{Dv}{Z}\right)\psi\left(\frac{CZ}{k}\right) \qquad (3)$$

For heating, $\left(\frac{CZ}{k}\right)$ was found to be $\left(\frac{CZ}{k}\right)^{0.37}$ and approximately the same value was found for cooling. The equation developed by these investigations is:

$$\frac{\frac{hD}{k}}{\left(\frac{CZ}{k}\right)^{0.37}} = \psi\left(\frac{DV}{Z}\right) \qquad (4)$$

Kirkbridge and McCabe[29] in 1931 formulated an equation for the point film coefficient for viscous flow,

$$\frac{hD}{k} = \psi\left(\frac{kL}{D^2VC}\right) \qquad (5)$$

and for the average film coefficient

$$h_{av.} = \frac{q}{\pi DL(\Delta T)_{av.}} \qquad (6)$$

In 1932 Sherwood and Petric[48] found heat transfer coefficients for various organic liquids in turbulent flow and found close agreement with the Dittus and Boelter[14] equation for heating

$$\frac{hD}{k} = 0.29\left(\frac{DV}{Z}\right)^{0.8}\left(\frac{CZ}{k}\right)^{0.4} \qquad (7)$$

For cooling $\left(\frac{CZ}{k}\right)^{0.3}$ is used.

McAdams[31] points out that the film coefficients in case of condensing vapors are largely determined by the conductivity, viscosity, and density of the condensate and the latent heat of condensation of the vapor. He also states that the recommended relation for the condensation of a pure saturated vapor in the absence of non-condensable gas, outside the tube of a horizontal multitubular condenser is given by the equation

$$h = \frac{0.725}{n^{.25}} \left(\frac{rd^2k^3g}{ZD(\Delta T)}\right)^{0.25} \qquad (8)$$

There have been few experiments pertaining to the condensation of organic vapors. Most of these experiments have been with benzene, dowtherim diphenyl compounds and mercury. Rhodes and Younger[46], in 1935, measured the thermal conductances between several condensing vapors and a horizontal copper tube. In general, the experimentally determined values agreed satisfactorily with the values computed from the Nusselt equation. In this investigation a series of alcohols was condensed and the decrease in the coefficient within this series of alcohols was calculated.

Badger and McCabe[3] give the Nusselt equation for condensing vapors on a horizontal tube as:

$$h = 0.943 \left[\frac{k^3d^2gQ_v}{LZ(\Delta T)}\right]^{0.25} \qquad (9)$$

In 1937, Baker and Mueller[6] found film coefficients of condensing vapors on horizontal tubes and formulated an empirical equation for the film coefficient.

Also, in 1937, Bays and McAdams[8] made a study of heat transfer in falling film heaters using streamline flow and formulated numerous equations for calculating the vapor heat transfer coefficient.

In 1938 Wallace and Davidson[51] gave results for variation of the film coefficient with velocity of the cooling water and with the composition of the mixed vapor, ethanol and water. Differences between actual and apparent film coefficients were demonstrated. For pure benzene and toluene the coefficient deviated but slightly from the Nusselt value.

During the same year, Quigg, Mayer, and Huntington[43] determined the effect of tube position for steam condensation. They concluded that at slow flow rates the effect of tube position was negligible, but at the higher Reynolds number the overall coefficient for the 45° and horizontal tube positions were about 25 to 50 per cent higher, respectively, than the corresponding ones for the vertical position.

In 1939, Stroebe, Baker, and Badger[49] found film heat transfer coefficients for water, sugar, and "Duponal" solutions, boiling in a long-tube vertical evaporator, equipped with a single 20-foot tube under a wide range of conditions. From the data obtained, an empirical correlation of the coefficients was derived.

Morrison,[38a] in 1939, determined heat transfer coefficients for condensing organic vapors. The vapors used were methyl, ethyl, and butyl alcohols and methyl, ethyl, and butyl acetates. The actual vapor film coefficients were much lower than the vapor film coefficients calculated by the Nusselt equation.

Also in 1939, Baker, Kazmark, and Stroebe[5] correlated steam film coefficients for a 2 in. o.d., 20-foot long vertical tube. Other data for tubes 8 feet and 12 feet long were also correlated on the same basis and were found to deviate from those for the 20-foot tube. Fitzpatrick, Baum, and McAdams[15] found that the use of benzyl mercaptan as a drop-wise-condensation promotor gave a substantial increase in the steam side coefficients for vertical tubes of admiralty metal and of copper.

In 1940, McAdams[31] reviewed and summarized the developments in heat transfer by conduction and convection. Several papers on the film type condensation of steam on vertical tubes reported film coefficients ranging from 15 to 50 per cent higher than predicted from the theoretical equation in the range of viscous flow of condensate. When condensing vapors of certain high boiling organic substances on vertical tubes, turbulence flow of condensate was obtained, and the film coefficient agreed approximately with predictions from several sources.

The method used in this investigation of incorporating thermocouple junctions into a copper tube was taken from an investigation of mixed vapors carried out by Wallace and Davidson[51]. Also the general set-up of apparatus in their experiment is similar to the set-up used in this investigation.

III. EXPERIMENTAL

A. Purpose of Study

The purpose of this investigation is:

1. To compare actual experimental film coefficients obtained for condensing alcohol vapors with the theoretical film coefficients obtained by the Nusselt equation.

2. To correlate the values of the vapor film coefficients in a series of alcohols, methyl, ethyl, isopropyl, n-butyl, and n-amyl, with their physical properties.

B. Plan of Investigation

The plan of investigation will be as follows:

1. Supply alcohol vapors.
2. Condense these vapors on the outside of a vertical copper tube with cooling water inside the tube.
3. Observe the type of condensation on this tube.
4. Measure the temperatures of the vapor and cooling water in and out of the condenser, and the temperature of the tube wall.
5. Measure the rate of flow of the condensate and the cooling water.
6. Calculate the film coefficients of these vapors.
7. Correlate these coefficients with the physical properties of the series of alcohols.

C. Materials

Methyl Alcohol. The methyl alcohol used in this investigation was purchased from Phipps and Byrd Company, Richmond, Virginia. This solvent was 99 per cent pure.

Ethyl Alcohol. The ethyl alcohol used was secured from the laboratory and by testing was found to be 90 per cent pure.

Isopropyl Alcohol. The isopropyl alcohol used in this experiment was purchased from the Carbide and Carbon Chemicals Corporation, Charleston, West Virginia. Their specifications are:

Specific Gravity at 20° C	- 0.786
Boiling Range	- 1.5° C
Purity	- 99%

No water, water soluble or non volatile material.

n-Butyl Alcohol. The butyl alcohol used in this investigation was purchased from the Carbide and Carbon Chemicals Corporation, Charleston, West Virginia. Their specifications are:

Specific Gravity at 20° C	- 0.811
Boiling Range	- 1.5° C
Purity	- 99%

No water, water soluble or non volatile materials.

n-Amyl Alcohol. The amyl alcohol used in this investigation was purchased from the Sharples Solvents Corporation, Wyandotte, Michigan. This alcohol was 99 per cent pure.

D. Apparatus

Still. The still (Plate I) consisted of a 38-inch section of standard 10-inch flanged cast iron pipe. Two 1½ by 16-inch cast iron flanges served as the top and bottom of the still. Standard ½-inch copper tubing was made into a heating unit by coiling it into the shape of a spiral. The tubing was 19-feet long and had a wall thickness of 1/32-inch. Steam lines were connected to the tubing with standard connections. The still was well lagged with ¾ of an inch of asbestos cement completely covering the still.

Heat Exchanger. The heat exchanger (Plate I) was made by enclosing, within a 3-foot section of standard 4-inch Pyrex glass pipe, and a condensing tube consisting of a 38-inch section of 18 B.W.G. 7/8-inch copper tube. Six thermo-couples placed six inches apart were made by slotting the tube at right angles to the axis of the tube and covering the constantan-copper couple with solder at the junction, the copper pipe serving as one metal of the couple. The constantan wire was led around the slot for a quarter of an inch and from the slot into the vapor space. The wire in the vapor space was enclosed in small glass tubing to prevent the wires from making contact with each other and the copper tube. The heat exchanger was lagged with a three foot section of Philip Carey Air Cell insulation. A 150-watt bulb placed in a reflector was used to light the exchanger. This bulb was turned on only when observations were being made.

Secondary Condenser. A Liebig glass condenser was used to further cool the condensate from the heat exchanger. This further cooling did not effect the heat balance since the temperature of the condensate was taken before it reached this condenser.

Resistance Thermometer. Resistance thermometers were used for taking all temperatures other than those of the tube wall. This apparatus (Plate II) consisted of a Brown Instrument Company 9003 indicator, with a range of from 0° to 300° F, a twelve point selector switch and a standardizing panel for the indicator. An Eveready Compensated Air Cell battery was used as a source of current.

Millivoltmeter. The millivoltmeter used was a type 8657-B potentiometer indicator manufactured by the Leeds and Northrup

Company. An Eveready No. 6 dry cell was used as a source of current for the potentiometer circuit. The thermocouple leads were brought into the instrument as shown in Plate II.

Wiring. The constantan wire used was No. 28 B.W.G. and was purchased from the Central Scientific Company, Chicago, Illinois. The copper wire used was No. 18 B.W.G. copper bell wire. It was purchased locally.

Cold Junction. A one gallon glass jar covered with one quarter of an inch of asbestos cement was used for the cold junction. A resistance thermometer was immersed in the ice and water to take the temperature of the mixture. The thermocouple leads were immersed in the jar as shown in Plate II.

Balances. A set of O. Haus balances, accurate to within one gram, sold by the Central Scientific Company were used in making all weighings.

Timer. A Luxor Photographic Timer manufactured by Burke and James Company, Chicago, Illinois, was used for timing readings.

Piping. Standard pipe, fittings and valves, were used in all cases. Steam and vapor lines were lagged with Philip Carey Air Cell insulation and Philip Carey A.S.I. covering was used on cold water lines after the temperature of the incoming water was taken.

E. Methods of Procedure

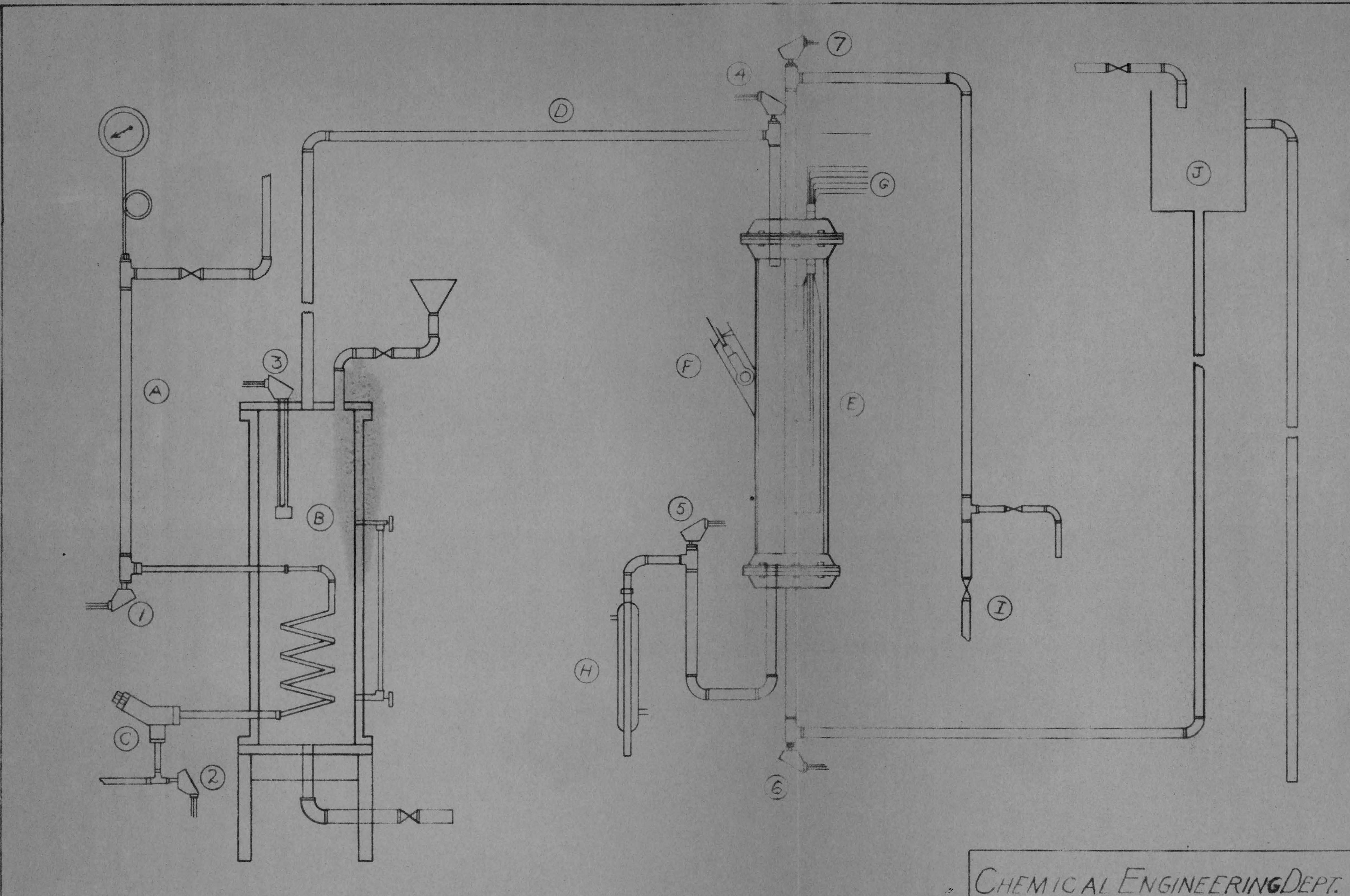
Starting a Run. When a run was made the following procedure was followed:

1. Set the desired water rate.
2. Lower the temperature of the cold junction.
3. Turn on the steam.

4. Turn on the water to the secondary condenser
5. Adjust the steam condensate valve to give a suitable rate.

When the vapors began to come over, the steam condensate valve was readjusted to obtain the desired rate of flow of the condensate of the material being investigated. It was desired to vary the condensate rate on the different runs, but to keep this rate constant during each individual run. This was done by varying the steam condensate rate by means of the valve on the steam condensate outlet.

<u>Recording Data</u>. When the condensate was observed to be flowing steadily and the vapor in the still was equal in temperature to the vapor coming into the heat exchanger, the system was said to be in equilibrium. The timer was set to zero and a run started. Readings of all indicating thermometers and millivoltmeter readings were taken at zero and at five minute intervals during the length of the run. The water rate was kept constant. The condensate from the heat exchanger and the steam condensate were weighed over the entire length of the run.



LEGEND

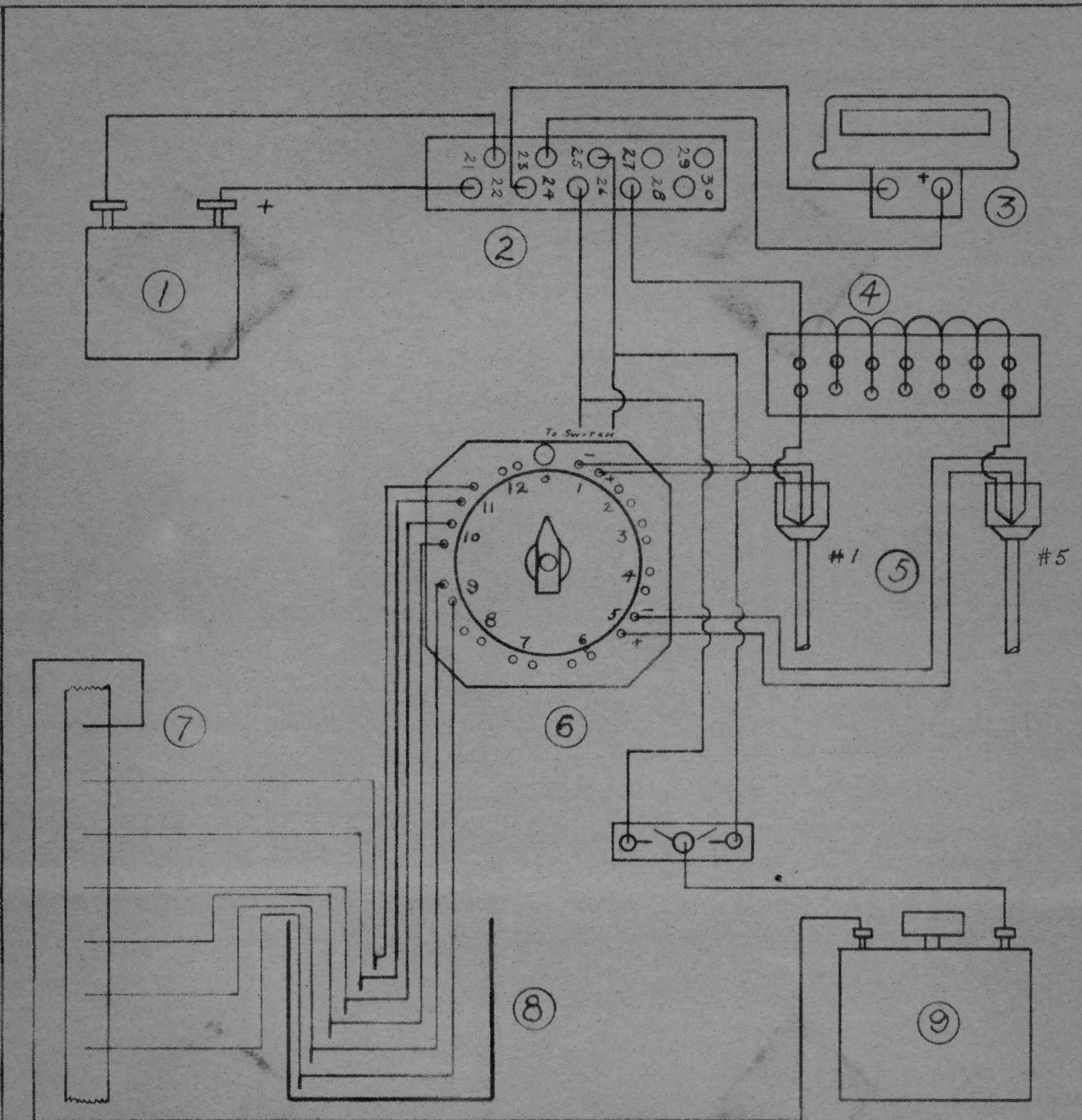
A INLET STEAM LINE
B KETTLE
C STEAM TRAP
D VAPOR LINE
E PRINCIPAL CONDENSER
F ELECTRIC LIGHT BULB
G THERMOCOUPLE LEADS
H SECONDARY CONDENSER
I COOLING WATER RETURN
J CONSTANT LEVEL TANK
2. ETC. THERMOMETERS

CHEMICAL ENGINEERING DEPT.
VIRGINIA POLYTECHNIC INSTITUTE
BLACKSBURG, VIRGINIA

HEAT TRANSFER APPARATUS

DRAWN BY - R.H.M.
CHECKED BY - DR. A.H.C.
TRACED BY - [illegible] E.H.

FIG. NO. 1



LEGEND

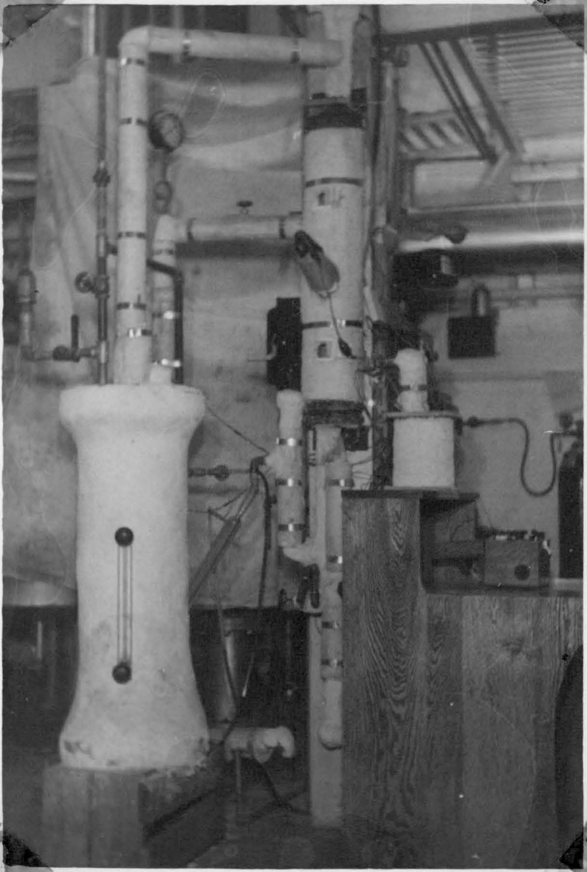
1. AIR CELL BATTERY
2. STANDARDIZING PANEL
3. TYPE 9001 INDICATOR
4. CONNECTION BLOCK
5. THERMOMETER BULBS
6. 12-POINT SWITCH
7. HOT JUNCTION THERMOCOUPLE
8. COLD JUNCTION THERMOCOUPLE
9. L AND N MILLIVOLTMETER

CHEM. ENG. DEPT.
VIRGINIA POLYTECHNIC INST.
BLACKSBURG, VIRGINIA

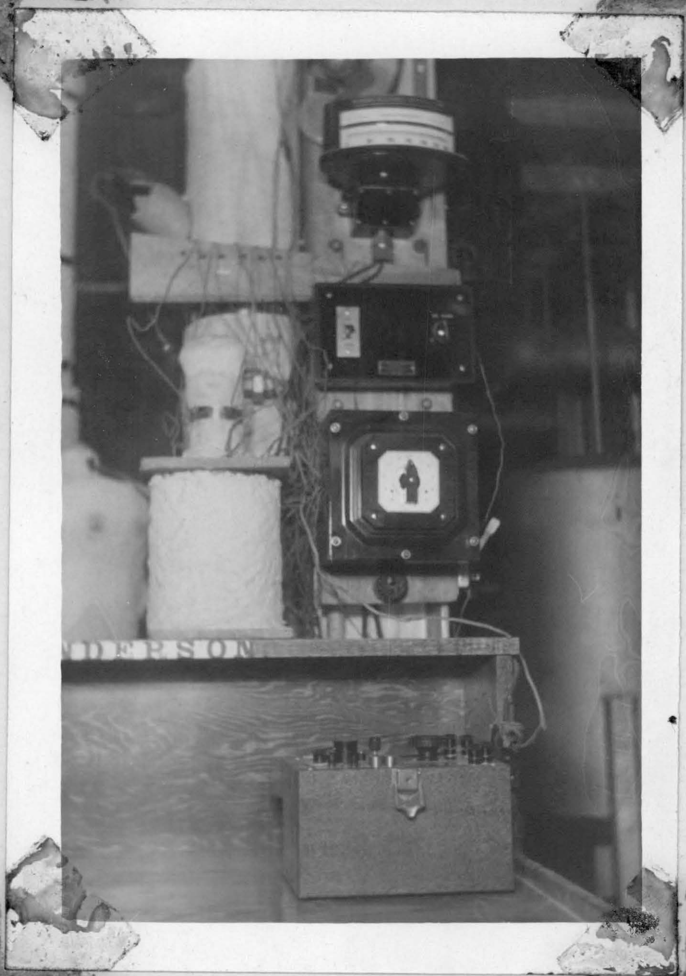
WIRING DIAGRAM
FOR HT. TRANSFER EQPT.

DRAWN BY H.E.H.
CHECKED BY A.H.C.
TRACED BY H.E.H.

FIG. No. 2



SET-UP OF APPARATUS



FRONT VIEW OF RESISTANCE

THERMOMETER

F. Experimental Data

The data is presented in sequence with data on each material on one page or section of pages. The runs are numbered in the following order: Steam; methyl, ethyl, isopropyl, n-butyl and n-amyl alcohols.

Thermometer Readings. The resistance thermometers are given a number. The key to these numbers is,

1. Temperature of steam to still.
2. Temperature of condensate from still.
3. Temperature of vapor in top of still.
4. Temperature of vapor in top of condenser.
5. Temperature of vapor out of condenser.
6. Temperature of cooling-water into condenser.
7. Temperature of cooling-water out of condenser.
8. Temperature of cold junction.

Thermocouple Readings. The thermocouples are numbered 1 to 6 from the top of the tube to the bottom.

TABLE NO. 1

Data for steam

Run no.	Steam press p.s.i.	Resistance thermometers - deg. F 1	2	3	4	5	6	7	8
1	10	232	226	210	210	76	50	85	35
2	10	230	206	210	210	84	50	66	35
3	10	231	204	210	210	71	50	57	35
4	10	231	203	209	209	70	50	55	35
A	10	231	210	210	210	75	50	66	35
5	15	237	220	210	210	96	50	95	36
6	15	240	211	210	210	97	50	89	36
7	15	242	211	210	210	96	50	96	36
8	15	240	209	210	210	78	50	87	37
B	15	240	213	210	210	92	50	92	36
9	15	240	233	210	210	200	51	88	37
10	15	238	225	210	210	150	51	81	37
11	15	240	224	210	210	202	51	85	37
12	15	240	222	210	210	192	51	76	38
C	15	240	226	210	210	186	51	83	37
13	15	238	235	210	210	162	52	94	39
14	15	240	215	210	210	168	51	58	39
15	15	240	228	210	210	184	52	87	39
16	15	241	207	210	210	108	51	70	39
D	15	240	221	210	210	156	51	77	39

TABLE NO. 2

Data for steam (continued)

Run No.	Time min.	Steam rate lb./hr.	Cond. rate lb./hr.	Thermocouples - m.v. 1	2	3	4	5	6
1	0			4.01	4.01	3.62	3.80	3.12	2.05
2	10			3.11	3.20	2.91	2.40	1.10	0.68
3	20			2.08	1.92	0.98	0.70	0.60	0.60
4	30			2.10	2.01	1.05	0.70	0.66	0.65
A	-	20.7	6.0	2.83	2.79	2.14	1.90	1.37	1.00
5	0			4.20	4.18	3.82	4.00	3.60	2.95
6	10			4.10	4.10	3.78	4.00	3.60	3.40
7	20			3.95	4.05	3.70	3.82	3.00	1.90
8	30			4.00	3.90	3.30	3.10	1.90	0.92
B	-	32.8	16.3	4.06	4.06	3.68	3.73	3.63	2.29
9	0			4.30	4.12	3.82	3.82	2.55	1.20
10	10			4.28	4.20	4.05	4.20	3.80	3.70
11	20			4.28	4.21	4.06	4.14	3.66	2.80
12	30			3.85	4.00	3.50	3.40	1.90	1.00
C	-	26.2	15.3	4.18	4.13	3.86	3.89	2.98	2.18
13	0			4.48	4.40	4.18	4.30	4.04	3.90
14	10			2.08	2.04	1.20	0.90	0.88	0.75
15	20			4.48	4.38	4.15	4.22	3.80	2.60
16	30			3.65	3.61	3.10	2.70	1.20	0.80
D	-	19.2	11.8	3.67	3.61	3.16	3.03	2.48	2.01

TABLE NO.3

Data for methyl alcohol

Run no.	Steam press p.s.i.	Resistance thermometers - deg. F 1	2	3	4	5	6	7	8
17	1.5	211	137	147	147	142	58.0	70.0	34
18	1.5	212	140	148	148	147	58.5	70.5	34
19	1.5	212	142	148	148	147	58.5	70.0	34
20	1.5	212	142	148	148	147	58.0	70.0	34
E	1.5	212	140	148	148	146	58.6	70.0	34
21	1.0	211	140	148	148	143	58.5	68.0	34
22	1.0	210	138	148	148	110	58.0	68.5	34
23	1.0	210	138	147	147	92	58.0	68.0	34
24	1.0	210	138	147	147	86	58.0	67.5	34
F	1.0	210	139	148	148	108	58.0	68.0	34
25	0.75	210	136	147	147	82	58.0	63.5	34
26	0.75	210	135	147	147	78	58.0	63.0	34
27	0.75	210	134	147	147	75	58.0	63.0	34
28	0.75	210	134	147	147	74	58.0	62.5	34
G	0.75	210	135	147	147	77	58.0	63.0	34
29	2.0	213	140	147	147	122	59.0	70.0	36
30	2.0	214	142	148	148	146	60.0	72.0	36
H	2.0	214	141	148	148	134	60.0	71.0	36

TABLE NO. 4

Data for methyl alcohol (continued)

Run No.	Time min.	Steam rate lbs./hr.	Cond. rate lbs./hr.	Thermocouples - m.v. 1	2	3	4	5	6
17	0			2.50	2.65	2.35	2.55	2.08	1.92
18	5			2.50	2.60	2.38	2.52	2.10	1.98
19	10			2.50	2.60	2.32	2.52	2.10	1.98
20	15			2.50	2.68	2.32	2.52	2.10	1.97
E	-	13.7	17.0	2.50	2.64	2.36	2.53	2.09	1.96
21	0			2.45	2.55	2.22	2.42	1.81	1.30
22	5			2.42	2.60	2.30	2.48	1.90	1.42
23	10			2.48	2.60	2.25	2.45	1.85	1.30
24	15			2.40	2.56	2.22	2.35	1.68	1.22
F	-	7.1	9.5	2.44	2.58	2.26	2.43	1.81	1.31
25	0			1.77	2.01	1.60	1.70	1.05	0.75
26	5			1.78	2.02	1.60	1.68	0.95	0.65
27	10			1.75	1.95	1.58	1.68	0.95	0.60
28	15			1.80	1.95	1.58	1.58	1.00	0.55
G	-	4.9	5.2	1.78	2.00	1.59	1.66	0.99	0.64
29	0			2.55	2.70	2.30	2.58	2.10	1.85
30	5			2.65	2.72	2.40	2.62	2.20	1.90
H	-	--	--	2.60	2.71	2.35	2.60	2.15	1.88

TABLE NO.5

Data for ethyl alcohol

Run No.	Steam press. p.s.i.	Resistance thermometers - deg. F 1	2	3	4	5	6	7	8
31	1.5	209	159	172	172	80	56.0	60.0	33
32	1.5	210	160	174	173	78	56.0	60.5	33
33	1.5	210	160	174	174	76	56.5	61.5	33
34	1.5	210	160	174	174	74	57.0	61.5	33
I	1.5	210	160	174	173	77	56.5	61.0	33
35	2.0	210	164	174	174	79	57.0	70.0	34
36	2.0	210	166	175	175	96	58.0	71.5	34
37	2.0	212	169	176	176	152	58.0	72.0	34
38	2.0	212	169	176	176	169	58.0	72.5	34
J	2.0	211	167	175	175	124	58.0	72.0	34
39	2.5	212	170	176	176	170	58.0	72.5	34
40	2.5	212	170	176	176	174	58.0	73.5	34
41	2.5	213	176	176	176	174	58.0	74.0	34
42	2.5	214	178	176	176	174	57.5	74.0	34
K	2.5	213	174	176	176	173	58.0	73.5	34
43	2.0	211	174	177	176	156	57.5	73.0	34
44	2.0	211	173	178	178	178	58.0	73.5	34
45	2.0	211	174	178	178	170	57.5	73.5	34
46	2.0	211	180	178	178	167	57.0	74.0	34
L	2.0	211	175	178	178	168	57.5	73.5	34
47	1.5	210	174	174	174	108	56.5	68.0	34
48	1.5	210	170	174	174	99	56.5	69.0	34
49	1.5	210	168	174	174	100	57.0	69.5	34
50	1.5	210	168	174	174	102	57.0	69.5	34
M	1.5	210	170	174	174	102	57.0	69.0	34
51	1.25	209	164	174	174	102	57.0	65.5	34
52	1.25	209	162	174	174	94	57.0	62.0	34
53	1.25	209	161	174	174	87	57.0	62.0	34
54	1.25	209	160	174	174	82	57.0	61.5	34
N	1.25	209	162	174	174	91	57.0	63.0	34

TABLE NO. 6

Data for ethyl alcohol (continued)

Run No.	Time min	Steam rate lb./hr.	Cond. rate lb./hr/	Thermocouples - m.v. 1	2	3	4	5	6
31	0			1.40	1.50	1.22	1.20	0.76	0.38
32	5			1.45	1.60	1.30	1.40	0.77	0.35
33	10			1.65	1.80	1.45	1.45	0.83	0.40
34	15			1.70	1.90	1.50	1.50	0.85	0.38
I	--	6.1	5.0	1.55	1.70	1.37	1.39	0.80	0.38
35	0			2.90	3.10	2.68	2.88	2.10	1.45
36	5			3.00	3.15	2.72	2.92	2.25	1.90
37	10			3.08	3.28	2.80	3.00	2.40	1.92
38	15			3.15	3.28	2.85	3.05	2.48	2.05
J	--	11.2	16.7	3.04	3.20	2.76	2.96	2.31	1.83
39	0			3.15	3.29	3.00	3.02	2.50	2.10
40	5			3.25	3.30	2.90	3.05	2.55	2.05
41	10			3.22	3.22	3.00	3.20	2.65	2.10
42	15			3.22	3.30	3.08	3.12	2.70	2.15
K	--	19.5	17.2	3.21	3.28	3.00	3.10	2.60	2.10
43	0			3.22	3.28	3.02	3.08	2.60	2.10
44	5			3.20	3.32	3.05	2.99	2.58	2.10
45	10			3.25	3.35	3.10	3.20	2.68	2.12
46	15			3.22	3.32	3.08	3.18	2.62	2.10
L	--	12.7	17.6	3.22	3.32	3.06	3.00	2.62	2.11
47	0			2.88	3.10	2.60	2.90	2.05	1.12
48	5			2.98	3.15	2.65	2.92	2.00	1.30
49	10			2.99	3.13	2.68	2.88	2.20	1.28
50	15			2.98	3.12	2.65	2.90	2.10	1.20
M	--	8.7	12.2	2.96	3.13	2.65	2.90	2.14	1.23
51	0			1.85	1.92	1.58	1.70	1.10	0.58
52	5			1.81	2.08	1.60	1.55	1.02	0.55
53	10			1.81	1.95	1.60	1.60	1.05	0.50
54	15			1.78	1.95	1.50	1.63	0.98	0.52
N	--	4.8	5.6	1.81	1.99	1.57	1.63	1.04	0.54

TABLE NO. 7

Data for propyl alcohol

Run No.	Steam press p.s.i.	Resistance thermometers - deg. F 1	2	3	4	5	6	7	8
55	2.5	212	177	178	176	172	58.0	71.0	32
56	2.5	212	176	178	178	177	56.0	69.0	32
57	2.5	212	178	178	178	177	55.0	67.0	32
58	2.5	214	210	178	178	177	56.0	70.0	32
O	2.5	213	185	178	178	176	56.5	69.5	32
59	2.5	210	172	177	176	162	55.5	68.0	32
60	2.5	212	178	178	178	176	56.0	69.0	32
61	2.5	212	179	178	178	177	56.0	69.0	32
62	2.5	212	210	178	178	176	56.0	68.0	32
P	2.5	212	185	178	178	173	56.0	68.5	32
63	2.0	210	175	177	177	153	56.0	68.0	32
64	2.0	210	174	178	177	176	56.0	68.5	32
65	2.0	210	175	178	178	177	56.0	69.0	32
66	2.0	210	206	178	178	174	56.0	67.0	32
Q	2.0	210	182	178	178	170	56.0	68.0	32
67	2.0	210	209	178	177	142	56.0	63.0	32
68	2.0	210	209	178	177	118	56.0	60.0	32
69	2.0	210	209	178	177	106	56.0	59.0	32
70	2.0	210	209	178	177	100	56.0	57.0	32
R	2.0	210	209	178	177	117	56.0	60.0	32
71	2.0	210	170	178	176	102	58.0	68.5	32
72	2.0	210	170	178	178	130	58.0	70.5	32
73	2.0	211	173	178	178	160	59.0	72.0	32
74	2.0	210	202	178	178	168	58.0	70.0	32
S	2.0	210	179	178	178	140	58.0	70.0	32
75	1.5	210	208	178	178	134	58.0	61.0	32
76	1.5	210	204	178	178	118	58.0	60.0	32
77	1.5	209	208	178	178	108	58.0	60.0	32
78	1.5	209	208	178	178	102	57.5	59.0	32
T	1.5	210	207	178	178	116	58.0	60.5	32

TABLE NO. 8

Data for propyl alcohol (continued)

Run No.	Time min.	Steam rate lb./hr.	Cond. rate lb./hr.	Thermocouples - m.v. 1	2	3	4	5	6
55	0			2.80	3.00	2.28	2.80	1.85	1.70
56	5			2.70	3.00	2.30	2.75	1.85	1.70
57	10			2.70	3.00	2.30	2.75	1.90	1.70
58	15			2.70	3.10	2.30	2.82	1.90	1.70
O	--	21.2	32.1	2.73	3.03	2.30	2.78	1.88	1.70
59	0			2.78	3.02	2.32	2.80	1.90	1.70
60	5			2.75	3.00	2.35	2.80	1.88	1.70
61	10			2.80	3.00	2.30	2.80	1.90	1.70
62	15			2.65	2.90	2.10	2.55	1.53	1.20
P	--	17.0	29.6	2.73	2.98	2.27	2.74	1.81	1.57
63	0			2.70	3.00	2.30	2.75	1.90	1.70
64	5			2.75	3.00	2.30	2.75	1.92	1.70
65	10			2.75	3.00	2.32	2.82	1.95	1.75
66	15			2.50	2.70	2.00	2.35	1.40	1.00
Q	--	11.3	27.4	2.68	2.93	2.23	2.67	1.79	1.54
67	0			1.75	1.95	1.40	1.70	1.00	0.85
68	5			1.38	1.50	1.18	1.35	0.90	0.70
69	10			1.05	1.10	0.95	1.10	0.78	0.62
70	15			0.81	0.90	0.76	0.88	0.62	0.57
R	--	6.5	5.2	1.25	1.36	1.07	1.26	0.83	0.69
71	0			2.75	3.00	2.30	2.80	1.90	1.50
72	5			2.95	3.08	2.30	2.85	2.00	1.78
73	10			2.88	3.10	2.30	2.90	2.05	1.80
74	15			2.65	2.85	2.00	2.50	1.50	1.20
S	--	11.4	20.5	2.81	3.01	2.23	2.76	1.86	1.57
75	0			1.60	1.65	1.18	1.43	1.00	0.80
76	5			1.25	1.30	0.90	1.25	0.90	0.70
77	10			1.10	1.15	0.90	1.15	0.90	0.70
78	15			0.95	0.98	0.78	0.95	0.76	0.62
T	--	4.3	4.9	1.23	1.27	0.94	1.20	0.89	0.71

TABLE NO. 9

Data for butyl alcohol

Run No.	Steam press p.s.i.	Resistance thermometers - deg. F. 1	2	3	4	5	6	7	8
79	20	250	249	214	208	112	57.0	68.0	32.0
80	20	252	251	220	215	104	57.0	68.0	32.0
81	20	252	251	225	220	106	57.0	66.0	32.0
82	20	256	255	230	228	108	57.5	68.5	32.0
U	20	253	252	222	218	108	57.0	67.5	32.0
83	24	254	253	234	232	112	57.5	66.0	32.0
84	24	258	257	236	235	111	57.5	68.0	32.0
85	24	258	257	238	237	116	58.0	68.0	32.0
86	24	256	255	239	238	116	57.5	63.5	32.0
V	24	257	256	237	236	114	57.5	66.5	32.0
87	26	255	254	226	212	188	57.0	72.5	32.0
88	26	260	259	226	221	200	57.0	73.0	32.0
89	26	262	261	228	226	196	57.0	72.5	32.0
90	26	266	262	234	234	202	57.0	64.0	32.0
W	26	261	260	229	226	197	57.0	70.5	32.0
91	18	248	247	222	210	74	58.0	61.0	33.0
92	18	248	247	226	214	78	58.0	60.5	33.0
93	18	249	248	228	218	80	58.0	60.0	33.0
94	18	249	248	230	220	81	58.0	60.0	33.0
X	18	249	248	227	216	78	58.0	60.5	33.0
95	20	251	250	232	224	84	58.0	61.5	33.0
96	20	253	251	234	230	89	58.0	62.0	33.0
97	20	252	251	236	232	94	57.0	60.5	33.0
98	20	252	251	237	235	98	57.5	50.5	33.0
Y	20	252	251	235	230	91	57.5	61.0	33.0
99	25	260	259	240	239	111	57.0	68.0	33.0
100	25	262	261	241	240	123	57.5	67.0	33.0
101	25	261	260	241	240	118	57.5	65.0	33.0
102	25	260	259	241	240	112	57.0	59.5	33.0
Z	25	261	260	241	240	116	57.5	65.0	33.0

TABLE NO. 10

Data for butyl alcohol (continued)

Run No.	Time min.	Steam rate lb./hr.	Cond. rate lb./hr.	Thermocouples - m.V. 1	2	3	4	5	6
79	0			2.70	3.00	2.20	2.70	1.68	1.02
80	5			2.70	2.90	2.00	2.60	1.50	1.00
81	10			2.50	2.68	2.02	2.32	1.45	0.90
82	15			2.82	3.00	2.00	2.60	1.30	0.90
U	--	14.7	13.6	2.68	2.90	2.06	2.56	1.48	0.95
83	0			2.40	2.65	1.95	2.30	1.35	0.85
84	5			2.50	2.80	2.00	2.45	1.45	0.92
85	10			2.60	2.95	2.08	2.40	1.40	0.88
86	15			1.22	1.25	0.92	1.28	0.88	0.60
V	--	12.0	14.6	2.18	2.41	1.74	2.11	1.27	0.81
87	0			3.40	3.60	2.75	3.40	2.40	1.95
88	5			3.42	3.62	2.78	3.45	2.42	1.98
89	10			3.55	3.72	2.75	3.52	2.40	1.90
90	15			1.40	1.55	1.20	1.55	1.02	0.68
W	--	20.2	28.6	2.94	3.12	2.37	2.98	2.06	1.63
91	0			1.30	1.50	1.28	1.30	0.70	0.58
92	5			1.18	1.40	1.12	1.20	0.65	0.52
93	10			1.10	1.25	1.10	1.10	0.60	0.60
94	15			1.05	1.15	0.98	1.08	0.55	0.60
X	--	11.4	4.5	1.16	1.33	1.12	1.17	0.63	0.58
95	0			1.30	1.56	1.20	1.40	0.75	0.70
96	5			1.40	1.58	1.25	1.50	0.78	0.75
97	10			1.28	1.50	1.20	1.50	0.80	0.70
98	15			1.32	1.55	1.25	1.48	0.80	0.70
Y	--	11.4	7.2	1.33	1.55	1.23	1.47	0.78	0.71
99	0			3.00	3.40	2.34	2.90	1.50	1.10
100	5			2.35	2.80	1.95	2.45	1.15	0.80
101	10			1.90	2.10	1.45	1.92	1.05	0.75
102	15			1.15	1.32	1.10	1.38	0.90	0.65
Z	--	12.0	13.4	2.10	2.41	1.74	2.16	1.15	0.83

TABLE NO. 11

Data for amyl alcohol

Run No.	Steam press p.s.i.	Resistance thermometers - deg. F. 1	2	3	4	5	6	7	8
103	50	290	270	249	245	175	56.0	73.0	34
104	50	294	275	254	254	242	55.0	74.0	34
105	50	294	284	258	257	246	56.0	74.0	34
106	50	292	290	258	258	206	57.0	68.0	34
a	50	293	280	255	254	217	56.0	72.0	34
107	40	283	281	252	250	150	58.0	73.0	34
108	40	282	278	254	253	212	55.0	72.0	34
109	40	282	274	256	254	202	52.5	70.0	34
110	40	282	270	256	256	178	54.5	69.0	34
b	40	282	276	255	253	188	55.0	71.0	34
111	30	270	269	250	248	180	56.0	62.0	34
112	30	266	265	250	250	140	56.0	61.0	34
113	30	268	267	253	252	120	56.0	60.0	34
c	30	268	267	251	250	150	56.0	61.0	34
114	32	271	270	249	247	96	56.0	58.0	32
115	32	271	270	250	250	100	56.0	60.0	32
116	32	271	270	251	250	104	56.0	61.5	32
117	32	271	270	252	251	110	56.0	62.0	32
d	32	271	270	250	250	103	56.0	60.5	32
118	34	273	272	252	252	112	56.0	64.0	32
119	34	274	273	254	253	123	56.0	66.0	32
120	34	273	272	254	253	128	55.5	64.0	32
121	34	274	273	255	254	123	55.5	63.0	32
e	34	274	273	254	253	122	56.0	64.5	32
122	37	276	275	256	255	120	55.5	65.5	32
123	37	278	277	256	255	129	55.5	64.0	32
124	37	278	277	257	256	122	55.5	63.5	32
125	37	277	276	257	256	120	55.5	60.5	32
f	37	277	276	257	256	123	55.5	63.0	32

TABLE NO. 12

Data for amyl alcohol (continued)

Run No.	Time min.	Steam rate lb./hr.	Cond. rate lb./hr.	Thermocouples - m.v. 1	2	3	4	5	6
103	0			4.20	4.55	3.35	4.35	2.70	2.35
104	5			4.30	4.60	3.40	4.40	2.80	2.35
105	10			4.22	4.60	3.30	4.40	2.70	2.35
106	15			2.30	2.70	1.90	2.40	1.30	0.95
a	--	24.1	52.8	3.76	4.11	2.99	3.89	2.38	2.00
107	0			4.20	4.70	3.50	4.35	2.75	2.40
108	5			4.10	4.50	3.30	4.20	2.60	2.30
109	10			4.10	4.20	3.20	4.10	2.40	1.85
110	15			3.60	4.00	2.80	3.60	1.95	1.49
b	--	13.2	39.2	4.00	4.35	3.20	4.06	2.43	2.01
111	0			1.90	2.20	1.60	2.20	1.10	0.90
112	5			1.55	1.90	1.70	1.95	1.10	0.86
113	10			1.20	1.30	1.10	1.40	0.90	0.70
c	--	8.8	10.8	1.55	1.80	1.47	1.75	1.03	0.82
114	0			1.15	1.22	1.00	1.30	0.90	0.70
115	5			1.65	1.85	1.30	1.60	1.02	0.70
116	10			2.00	2.15	1.60	1.95	1.05	0.80
117	15			1.75	1.80	1.25	1.70	1.00	0.75
d	--	11.0	10.9	1.65	1.76	1.29	1.64	0.99	0.74
118	0			2.78	3.15	2.20	2.75	1.50	1.05
119	5			2.90	3.20	2.25	2.70	1.50	1.10
120	10			2.50	2.70	1.90	2.47	1.32	0.90
121	15			2.08	2.20	1.47	2.00	1.10	0.80
e	--	11.2	18.5	2.57	2.81	1.96	2.48	1.36	0.96
122	0			3.00	3.35	2.30	2.90	1.60	1.15
123	5			2.40	2.55	1.72	2.25	1.30	0.90
124	10			2.22	2.40	1.65	2.15	1.20	0.85
125	15			1.62	1.75	1.25	1.60	0.98	0.70
f	--	10.3	15.5	2.31	2.51	1.73	2.23	1.27	0.90

Experimental Results

The results are presented in sequence. The calculated results and graphical data for each material are found in the same group of pages. The runs are numbered in the same order as found in the data.

Curve I is a plot of the vapor film coefficient of steam against the temperature drop across the steam film. Both actual and theoretical (Nusselt) valves of the steam film coefficient are plotted on this curve. Curves II, III, IV, V, and VI contain this same plot for methyl, ethyl, isopropyl, n-butyl, and n-amyl alcohols.

TABLE NO. 1

Calculated results for steam

Run No.	Reynolds no.	Prandtl no.	hw	U	hv actual	hv Nusselt	t	$\frac{K^3\ {}^2 g}{N\ z\ t}$ x10^{-10}
1	4110	7.01	1840	324	281	1000	26	127.0
2	3580	8.22	1800	123	93	700	79	30.4
3	3380	8.78	1785	62	45	605	126	17.0
4	3320	8.96	1790	44	32	600	122	16.4
A	3580	8.22	1800	137	104	670	88	25.5
5	4410	6.50	1880	348	306	1230	11	290.0
6	4240	6.79	1860	291	246	1240	10	299.0
7	4410	6.50	1880	357	315	890	35	79.4
8	4190	6.80	1840	336	394	800	52	51.9
B	4270	6.72	1855	331	288	990	25	122.0
9	4240	6.79	1860	159	122	900	32	83.0
10	4020	7.23	1830	153	118	2300	1	3540.0
11	4110	7.01	1840	146	112	1230	9	290.0
12	3900	7.45	1810	101	76	800	48	51.9
C	4060	7.13	1830	128	97	1000	22	127.0
13	4410	6.50	1880	198	157	1790	3	1060.0
14	3440	8.64	1815	305	262	605	119	17.0
15	4190	6.80	1840	159	123	1420	5	515.0
16	3740	7.82	1820	120	91	710	67	32.2
D	3900	7.45	1810	130	98	800	46	51.9

TABLE NO. 2

Calculated results for methyl alcohol

Run No.	Reynolds no.	Prandtl no.	hw	U	hv actual	hv Nusselt	t	$\frac{K^3\ {}^2 g}{N\ z\ t} \times 10^{-6}$
17	3900	7.45	1810	87	65	350	11	19000
18	3980	7.29	1805	85	63	340	12	16900
19	3900	7.45	1810	80	58	340	12	16900
20	3900	7.45	1810	84	62	340	12	16900
E	3900	7.45	1810	81	60	340	12	16900
21	3830	7.60	1810	67	49	290	21	8960
22	3830	7.60	1810	95	61	310	18	18700
23	3830	7.60	1810	109	82	300	19	10300
24	3830	7.60	1810	112	84	290	22	8960
F	3830	7.60	1810	91	58	290	21	8960
25	3740	7.82	1820	67	42	250	47	4950
26	3740	7.82	1820	65	48	230	49	3540
27	3740	7.82	1820	69	51	225	50	3250
28	3690	7.95	1820	64	46	220	51	2970
G	3740	7.82	1820	67	49	230	49	3540
29	3980	7.29	1805	92	68	350	11	19000
30	4020	7.23	1830	87	64	380	8	26400
H	4020	7.23	1830	86	63	360	10	21300

TABLE NO. 3

Calculated results for ethyl alcohol

Run No.	Reynolds no.	Prandtl no.	hw	U	hv actual	hv Nusselt	t	$\frac{K^{3}\rho^{2}g}{N\,z\,t}$ x10^{-6}
31	3580	8.22	1800	41	29	150	90	641
32	3580	8.22	1800	47	34	151	88	658
33	3640	8.08	1810	56	40	154	84	711
34	3640	8.08	1810	52	38	158	82	789
I	3640	8.08	1810	49	35	157	86	769
35	3900	7.45	1810	143	110	200	31	2030
36	3980	7.29	1805	121	91	225	26	3250
37	3980	7.29	1805	85	63	230	23	3540
38	3980	7.29	1805	81	60	240	20	4021
J	3980	7.29	1805	98	73	230	24	3540
39	3980	7.29	1805	80	59	235	20	3860
40	4020	7.23	1830	84	62	240	19	4021
41	4020	7.23	1830	87	64	250	16	4950
42	4020	7.23	1830	90	66	255	15	5350
K	4020	7.23	1830	85	63	250	17	4950
43	4020	7.23	1830	88	65	248	18	4790
44	4020	7.23	1830	79	58	240	19	4021
45	4020	7.23	1830	90	66	250	16	4950
46	4020	7.23	1830	96	71	248	18	4790
L	4020	7.23	1830	91	67	248	18	4790
47	3830	7.60	1810	89	66	208	34	2370
48	3830	7.60	1810	106	79	210	30	2460
49	3830	7.60	1810	106	79	210	30	2460
50	3830	7.60	1810	103	77	210	32	2460
M	3830	7.60	1810	99	73	210	31	2460
51	3740	7.82	1820	69	50	164	76	916
52	3690	7.95	1820	43	31	164	76	916
53	3690	7.95	1820	47	34	160	78	829
54	3640	8.08	1810	45	33	160	78	829
N	3690	7.95	1820	54	39	162	77	905

TABLE NO. 4

Calculated results for propyl alcohol

Run No.	Reynolds no.	Prandtl no.	hw	U	hv actual	hv Nusselt	t	$\frac{K^3 \ {}^2 g}{N \ z \ t} \times 10^{-6}$
55	3980	7.29	1805	73	53	161	30	831
56	3830	7.60	1810	66	48	150	40	641
57	3740	7.82	1820	61	44	150	40	641
58	3830	7.60	1810	71	52	149	39	624
O	3830	7.60	1810	66	48	150	38	641
59	3780	7.70	1815	72	53	151	37	658
60	3830	7.60	1810	66	48	150	40	641
61	3830	7.60	1810	65	48	149	39	624
62	3780	7.70	1815	60	44	140	50	488
P	3830	7.60	1810	62	45	147	42	591
63	3780	7.70	1815	70	51	149	39	624
64	3780	7.70	1815	63	46	149	39	624
65	3830	7.60	1810	66	48	149	39	624
66	3740	7.82	1820	53	38	134	57	408
Q	3780	7.70	1815	69	50	144	44	545
67	3690	7.95	1820	42	30	119	80	254
68	3580	8.22	1800	27	19	112	91	199
69	3580	8.22	1800	22	16	110	101	185
70	3530	8.35	1805	8	5	105	109	154
R	3580	8.22	1800	27	19	111	95	192
71	3830	7.60	1810	86	64	150	38	641
72	3900	7.45	1810	83	61	153	36	694
73	4020	7.23	1830	74	54	155	35	731
74	3900	7.45	1810	69	51	139	52	473
S	3900	7.45	1810	75	55	150	40	641
75	3580	8.22	1800	36	26	112	87	199
76	3640	8.08	1810	14	10	111	97	192
77	3640	8.08	1810	15	10	111	100	189
78	3640	8.08	1810	8	5	108	106	172
T	3640	8.08	1810	21	15	111	98	189

TABLE NO. 5

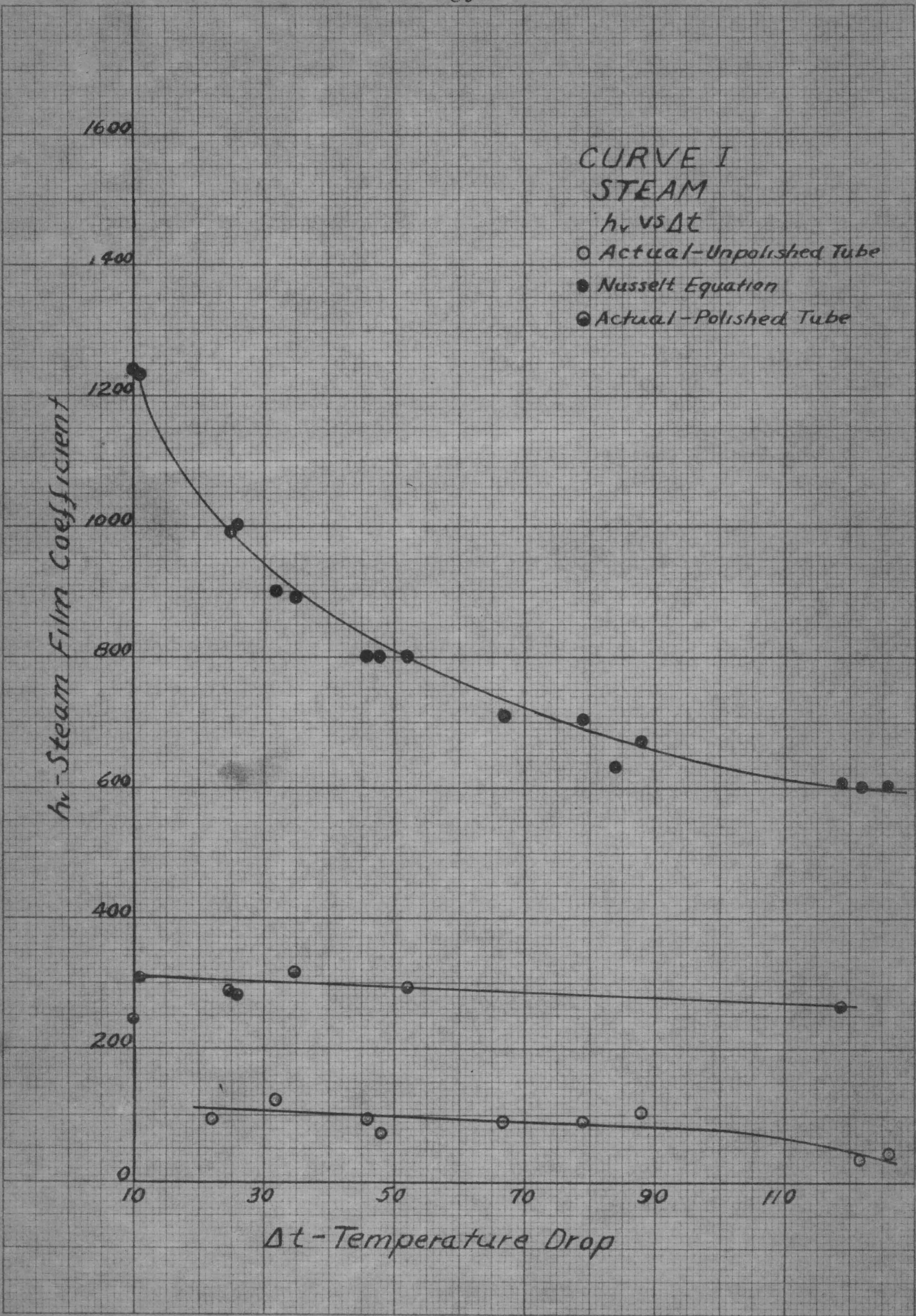
Calculated results for Butyl alcohol

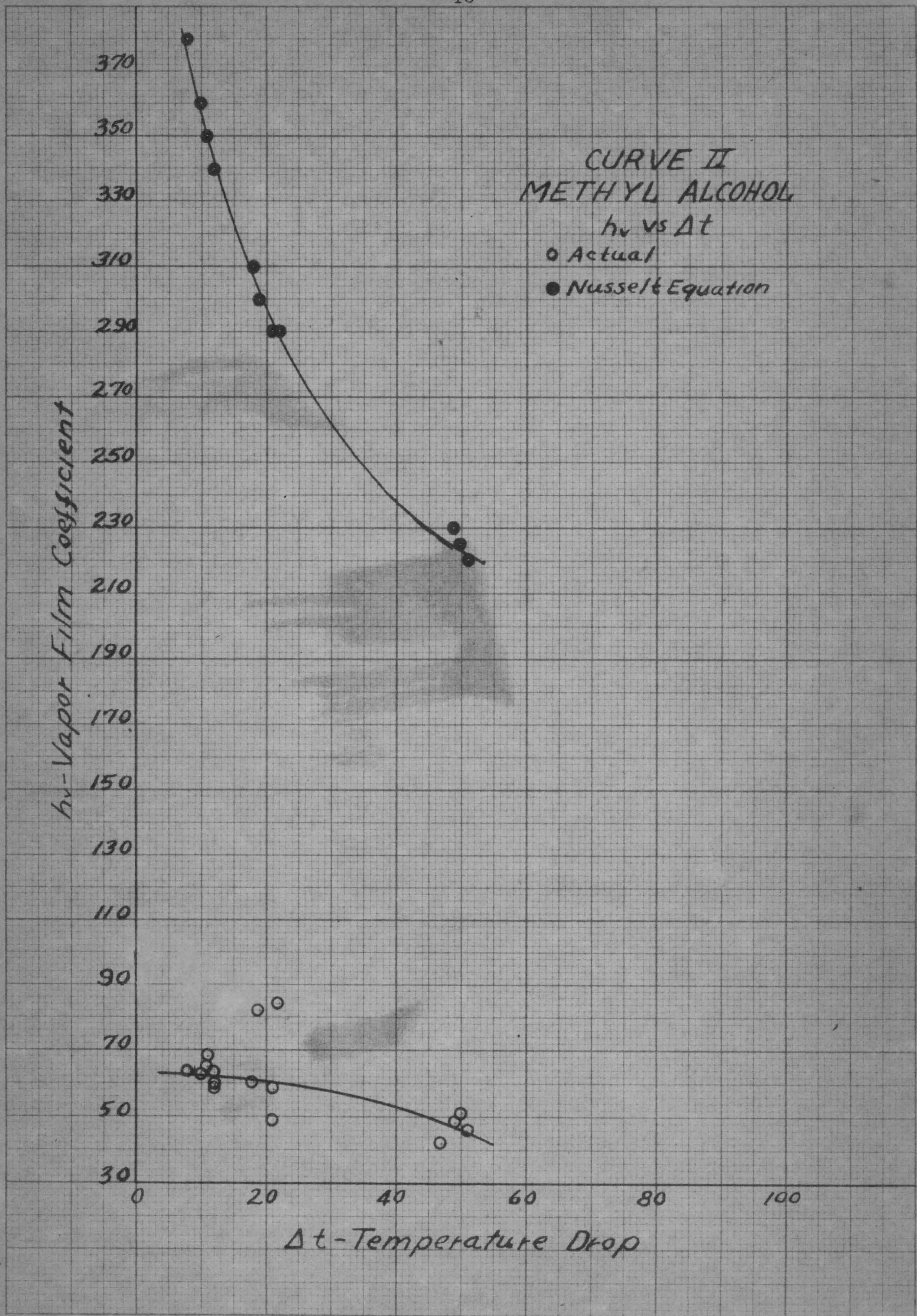
Run No.	Reynolds no.	Prandtl no.	hw	U	hv actual	hv Nusselt	t	$\frac{K^3 \rho^2 g}{N z t} \times 10^{-6}$
79	3780	7.70	1815	70	51	118	78	246
80	3780	7.70	1815	73	53	113	89	206
81	3780	7.70	1815	57	41	110	100	185
82	3830	7.60	1810	68	50	115	103	221
U	3780	7.70	1815	67	49	112	92	199
83	3740	7.83	1820	50	36	109	114	179
84	3780	7.70	1815	61	44	111	113	192
85	3830	7.60	1810	56	41	111	112	192
86	3690	7.95	1820	33	24	91	158	87
V	3780	7.70	1815	51	37	108	125	172
87	3980	7.29	1805	66	48	145	52	560
88	3980	7.29	1805	73	54	151	59	658
89	3980	7.29	1805	61	45	150	63	641
90	3740	7.82	1820	26	18	97	145	112
W	3900	7.45	1810	55	40	130	82	361
91	3690	7.95	1820	29	21	92	127	91
92	3640	8.08	1810	22	16	91	135	87
93	3640	8.08	1810	17	12	91	141	87
94	3640	8.08	1810	17	12	91	146	87
X	3640	8.08	1810	22	16	91	138	87
95	3690	7.95	1820	28	20	93	139	95
96	3690	7.95	1820	29	21	91	142	87
97	3650	8.08	1810	23	17	93	147	95
98	3640	8.08	1810	19	14	95	149	103
Y	3640	8.08	1810	28	20	95	144	103
99	3780	7.70	1815	63	46	126	101	319
100	3780	7.70	1815	50	36	110	122	186
101	3740	7.82	1820	41	29	102	139	137
102	3640	8.08	1810	14	10	92	158	91
Z	3740	7.82	1820	41	30	109	130	179

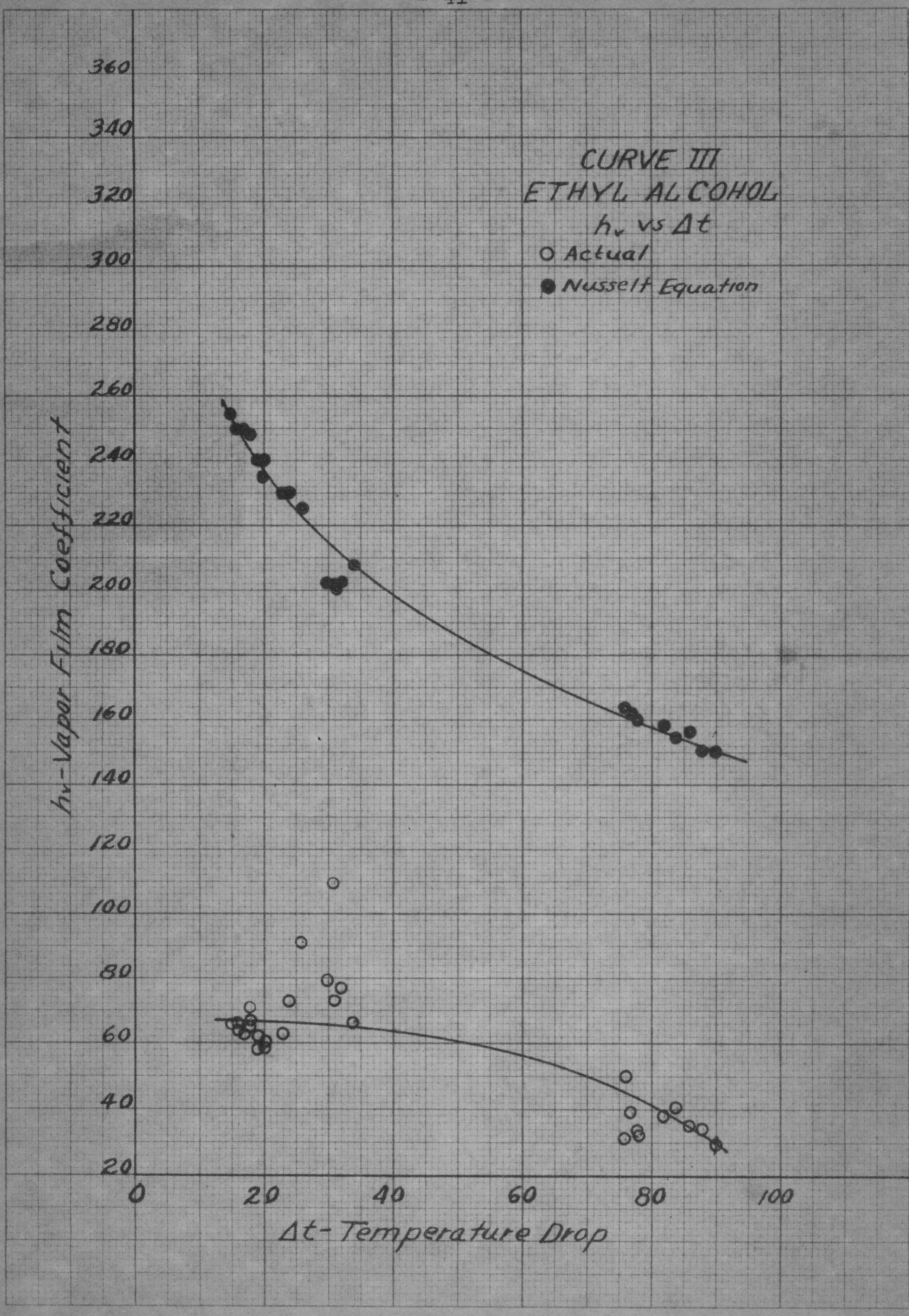
TABLE NO. 6

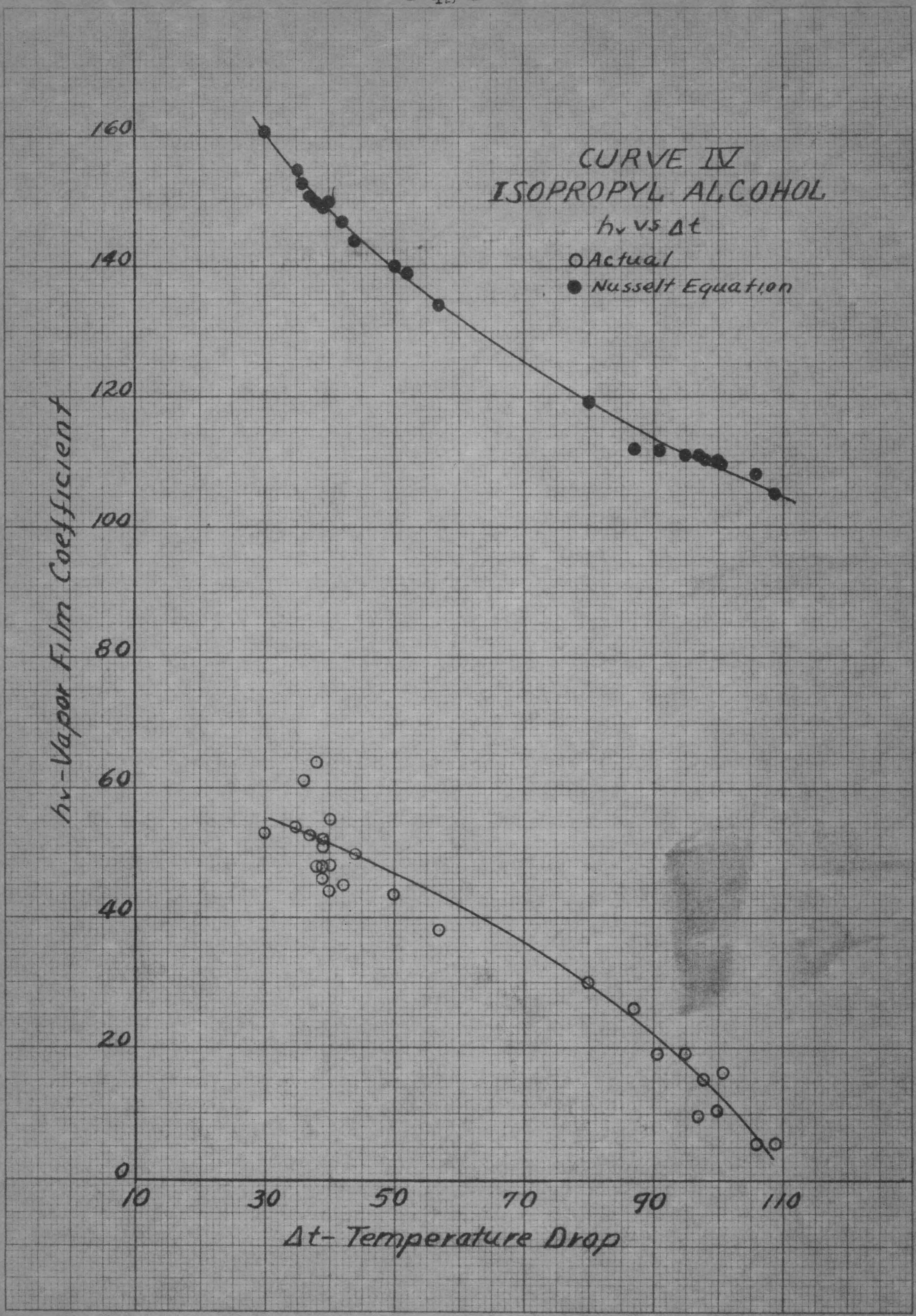
Calculated results for amyl alcohol

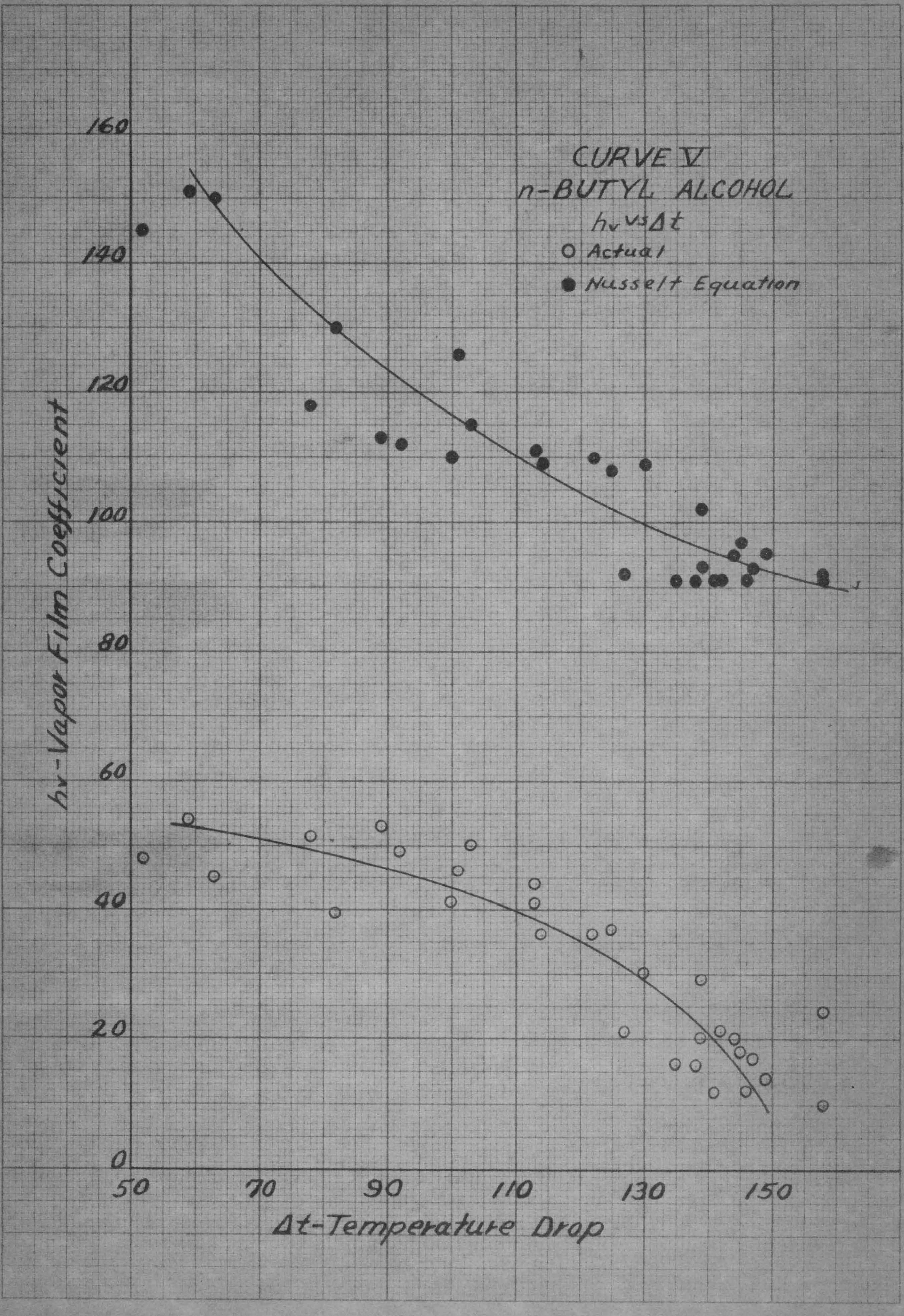
Run No.	Reynolds no.	Prandtl no.	hw	U	hv actual	hv Nusselt	t	$\frac{K^3 \; ^2g}{N \; z \; t} \times 10^{-6}$
103	3980	729	1805	70	51	130	57	361
104	3980	729	1805	62	45	128	64	340
105	3980	729	1805	59	43	125	69	309
106	3780	7.70	1815	39	28	88	140	76
a	3900	7.45	1810	53	38	112	87	199
107	4020	7.23	1830	65	47	130	59	361
108	3900	7.45	1810	58	42	121	69	271
109	3740	7.82	1820	63	46	113	78	206
110	3740	7.82	1820	55	40	109	95	179
b	3830	7.60	1810	60	43	117	75	237
111	3640	8.08	1810	23	16	82	142	57
112	3640	8.08	1810	23	16	81	150	55
113	3580	8.22	1800	20	14	77	170	45
c	3640	8.08	1810	21	15	80	153	52
114	3530	8.35	1805	12	9	77	167	45
115	3580	8.22	1800	23	17	80	156	52
116	3640	8.08	1810	31	22	81	146	55
117	3640	8.08	1810	32	23	81	156	55
d	3580	8.22	1800	26	18	81	156	55
118	3690	7.95	1820	43	31	91	120	87
119	3740	7.82	1820	50	36	91	120	87
120	3690	7.95	1820	41	29	89	133	79
121	3640	8.08	1810	37	26	83	149	60
e	3690	7.95	1820	43	31	90	130	83
122	3690	7.95	1820	45	33	93	118	95
123	3690	7.95	1820	40	29	88	140	76
124	3640	8.08	1810	39	28	85	146	66
125	3580	8.22	1800	25	18	81	163	55
f	3640	8.08	1810	37	26	85	142	66

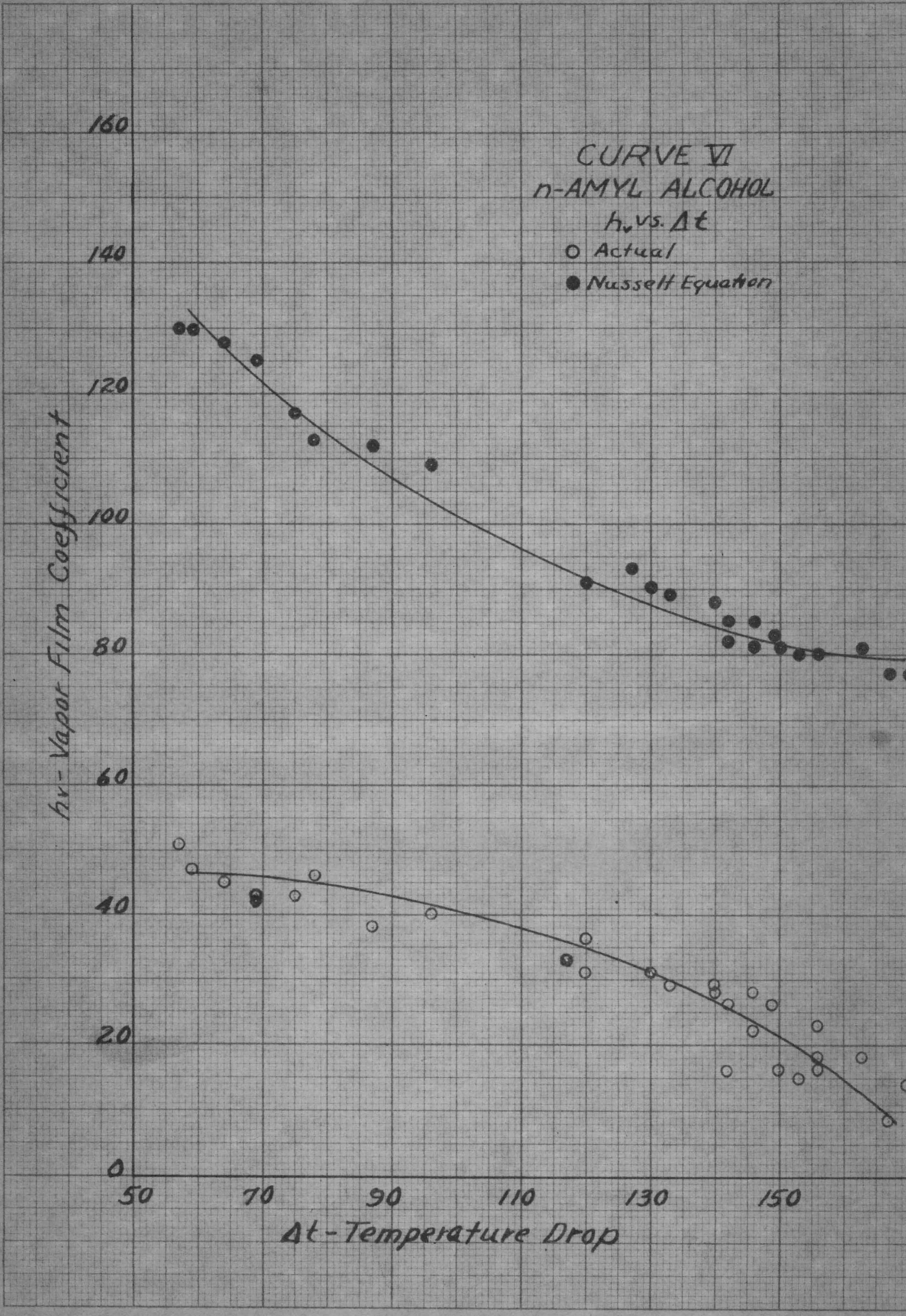

CURVE I
STEAM
h_v vs Δt
○ Actual-Unpolished Tube
● Nusselt Equation
● Actual-Polished Tube
h_v - Steam Film Coefficient
1600
1400
1200
1000
800
600
400
200
0
10
30
50
70
90
110
Δt - Temperature Drop


CURVE II
METHYL ALCOHOL
h_v vs Δt
o Actual
● Nusselt Equation
h_v-Vapor Film Coefficient
370
350
330
310
290
270
250
230
210
190
170
150
130
110
90
70
50
30
0
20
40
60
80
100
Δt-Temperature Drop


CURVE III
ETHYL ALCOHOL
h_v vs Δt
O Actual
● Nusselt Equation
h_v-Vapor Film Coefficient
Δt-Temperature Drop
360
340
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
20
40
60
80
100


CURVE IV
ISOPROPYL ALCOHOL
h_v vs Δt
○ Actual
● Nusselt Equation
h_v-Vapor Film Coefficient
Δt- Temperature Drop
160
140
120
100
80
60
40
20
0
10
30
50
70
90
110


CURVE V
n-BUTYL ALCOHOL
h_v vs Δt
○ Actual
● Nusselt Equation
hv-Vapor Film Coefficient
160
140
120
100
80
60
40
20
0
50
70
90
110
130
150
Δt-Temperature Drop


CURVE VI
n-AMYL ALCOHOL
h_v vs. Δt
○ Actual
● Nusselt Equation
hv - Vapor Film Coefficient
0
20
40
60
80
100
120
140
160
50
70
90
110
130
150
Δt - Temperature Drop

IV. DISCUSSION

<u>Discussion of Results</u>. Henderson[19] in 1939 did some work of the same nature as this investigation using methyl, ethyl and n-butyl alcohols. As shown in his results of the investigation the vapor film coefficient calculated by the Nusselt equation was in all cases over 75 per cent higher than the actual vapor film coefficient. This compares favorably with the results of this experiment in which the film coefficients calculated by the Nusselt equation for methyl, ethyl, isopropyl, n-butyl and n-amyl alcohols range from 70 to 80 per cent higher than the actual vapor film coefficient.

In the experiment performed by Henderson the actual coefficients of the alcohols plotted against the temperature difference across the vapor film gave a curve with almost the identical shape of the same values of temperature difference plotted against the values of the film coefficient calculated from the Nusselt equation. In this experiment, as can be seen from curves II, III, IV, V, and VI, the curves are not of the same shape, but, instead the curve obtained by using results calculated by the Nusselt equation has a concave shape while the curve obtained by using the actual vapor film coefficient and the same temperature difference across the vapor film has a convex shape. From these curves it can be seen that the Nusselt vapor film coefficient decreases faster than the actual vapor film coefficient as the temperature difference across the vapor film increases. Since the curves do not have a similar shape, a constant can not be incorporated in the Nusselt equation to shift the theoretical curve down so that it would fall on the actual curve.

The points plotted for the curves were scattered considerably. This is probably due to variation in the rate of condensation of the vapor on the copper tube. When the rate is fairly slow, air is given a better chance to come in contact with the tube, thus causing a variation in the temperature of the tube and vapor. Since the feed did not have a constant head, the vapor velocity and rate of condensation of the vapor changes, thus causing a change in the vapor film coefficient. Another cause for the scattered points could be unknown defects in the apparatus.

A possible explanation as to why the vapor film coefficient decreases as the temperature difference across the vapor film increases is that due to a high temperature difference the vapor velocity is lower giving air a chance to make better contact with the tube wall thus decreasing the temperature and, of course, the vapor film coefficient.

It can easily be seen from this investigation that the vapor film is the controling factor in every case.

Recommendations. If further work is to be done on this subject, three suggestions may be made: first, construct a reflux line from the condenser to the still in order to obtain a constant head for the feed and also give continuous operation. Second, have a larger secondary condenser to take care of the condensate at higher vapor velocities. Third, use rates of flow for cooling water which will carry from the viscous region through the critical region and into the turbulent region in order to investigate the effect of the type of flow on heat transfer.

Limitations. In this investigation it wasn't possible to obtain high enough vapor velocity. At a high velocity the material was vaporized before the run could be completed. This was also unfavorable because of the marked change in head of feed. Due to the fact that there was no reflux line from the condenser to the still, it wasn't possible to make our runs for a longer period of time. These factors have a direct effect on the results obtained.

V. CONCLUSIONS

The conclusions which may be drawn from this investigation are:

1. The type of condensation of methyl, ethyl, isopropyl, n-butyl, and n-amyl alcohol is filmwise condensation.

2. The vapor film coefficients of these alcohols at ordinary temperature differences across the vapor film at atmospheric pressure are:

(a) methyl - 60 average ΔT - 22
(b) ethyl - 50 average ΔT - 70
(c) isopropyl - 30 average ΔT - 80
(d) n-butyl - 25 average ΔT - 135
(e) n-amyl - 20 average ΔT - 152

3. The vapor film coefficient of these alcohols decrease as the temperature difference across the vapor film increases.

4. The vapor film coefficient of the alcohols studied calculated by the Nusselt equation give values greater than the actual vapor film coefficient.

5. The vapor film coefficients of these alcohols at ordinary temperature difference across the vapor film at atmospheric pressure as calculated by the Nusselt equation are:

(a) methyl - 288 average ΔT - 22
(b) ethyl - 166 average ΔT - 70
(c) isopropyl 119 average ΔT - 80
(d) n-butyl - 97.5 average ΔT - 135
(e) n-amyl - 81 average ΔT - 152

6. As the molecular weight increases in a series of alcohols, the vapor film coefficient decreases.

7. For a given value of a vapor film coefficient, a greater temperature difference across the vapor film is required as the molecular weight of the alcohols increase.

8. For a given temperature difference across the vapor film, the lower the alcohol is in a series the greater the difference between the actual film coefficient and the value calculated by the Nusselt equation.

9. For steam, the vapor film coefficient is higher on a polished surface than on an unpolished surface.

VI. SUMMARY

The purpose of this investigation is to compare actual experimental film coefficients for condensing alcohol vapors with the theoretical film coefficients obtained by the Nusselt equation. A secondary purpose is to correlate the values of the vapor film coefficients in a series of alcohols, methyl, ethyl, isopropyl, n-butyl, and n-amyl, with their physical properties.

The apparatus consists principally of a still and a condenser with equipment for measuring the temperatures and rates of flow at various points. An investigation was first made on steam and data taken on five runs. Data was then taken on methyl, ethyl, isopropyl, n-butyl, and n-amyl alcohols. Three runs were made on methyl alcohol and six runs on each of the remaining alcohols, making a total of twenty-seven runs. The actual vapor film coefficient of these materials were calculated and compared with the values obtained by the Nusselt equation. These coefficients were plotted against the temperature difference across the vapor film. The values of the film coefficients were correlated with the position of the alcohols in the series and the difference between the Nusselt values and the actual values for coefficients noted. As the molecular weight increased in this series of alcohols, the vapor film coefficient decreased. The vapor film coefficients for all of the alcohols ranged from 70 to 80 per cent higher than the actual values.

Symbols Used

k - thermal conductivity

Z - viscosity

h - film coefficient

D - diameter of pipe

r - radius of pipe

L - length of pipe

T - temperature difference

g - gravitational constant

C - specific heat

q - rate of heat flow

Q_v - latent heat

V - mass velocity

d - density

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