A STUDY OF DROP-WISE CONDENSATION
AS RELATED TO NORMAL ALKYL AMINES

Thesis for the Degree of M. S.

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Wayne Douglas Erickson

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This is to certify that the

thesis entitled

A STUDY OF DROP-WISE CONDENSATION AS

RELATED TO NORMAL ALKYL AMINES

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Wayne Douglas Erickson

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C. C. DeWitt

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A STUDY OF DROP-WISE CONDENSATION AS

RELATED TO NORMAL ALKYL AMINES

By

Wayne Douglas Erickson

A THESIS

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INTRODUCTION

Octadecylamine and its salts are presently being used in the industry as corrosion inhibitors (5, 28, 34). This inhibition is thought to be facilitated by the filming action of the amines. Field tests (34) made in paper mills and other industrial installations using octadecylamine for corrosion protection, indicates a simultaneous increase in plant efficiency. Screening tests with certain amine corrosion inhibitors indicated marked effect on the mode of steam condensation.

These tests showed that a copper surface coated with a normal alkyl amine containing eight to eighteen carbon atoms presented a non-wettable surface. This property of non-wettability is a requisite for drop-wise condensation. It was, therefore, the purpose of this study to determine the influence of the carbon-chain length of the various normal alkyl amines on the overall heat transfer coefficient of steam condensing on such prepared surfaces.

It was observed by Spoelstra (32) in 1931, that pipes coated with a small amount of oil permitted higher heat transfer coefficients than the same pipes when clean. Upon removal of the oil film by cleaning with benzene, a lower coefficient was observed. Spoelstra concluded that the oil on the surface upon which condensation took place caused the steam to condensate in droplets. These observations were made in a Javanese sugar plant.

Two years later, Nagle and Drew (26) made a qualitative study of drop-wise condensation. They studied the effect of various oils and fatty materials in combination with different metal surfaces. Some of the compounds used were fuel oil, kerosene, mutton tallow, beeswax, olive oil, and stearic acid. The metal surfaces studied were copper, brass, steel, chrome-nickel steel, chromium-plated copper and brass, monel metal and nickel. For the combinations which produced drop-wise condensation, the overall coefficients varied from 600 to 1300 Btu./Hr./Sq.Ft./°F. They also reported varying degrees of drop-wise condensation ranging from pure drop-wise to film type. A correlation between surface tension and a condition necessary for drop-wise condensation was also presented.

Wulfinghoff (36) reported that the high heat transfer coefficients caused by drop condensation are less likely to be observed in commercial condensers than in the laboratory. He states that the production of drop-wise condensation requires very low steam currents or velocities and an exceedingly smooth surface.

Jeffrey and Moynihan (17) made observations contrary to those reported by Wulfinghoff. They reported that drop-wise condensation was predominate on condenser tubes when the tubes were commercially clean, i.e., as received from manufacturer, this phenomenon being attributed to the presence of a thin film of oil. They say further, that drop-wise condensation was observed on a commercially clean tube at any steam or water velocity studied. It was suggested that film type condensation was an unstable condition and a slight degree of contamination on the condensing surface causes drop-wise condensation to occur. Overall coefficients observed, ranged from 249 to 1552 Btu./Hr./Sq.Ft./°F. for water velocities of 1.77 and 8.51 ft./sec. respectively.

In 1935 Nagle (24) disclosed the conditions necessary for promoting drop-wise condensation. The condensing surface must be modified so that the condensate does not wet the surface. The condensing surface, if treated with a suitable agent, forms a non-wetting film. This film must be adsorbed upon the condensing surface and not be washed off with the condensate. Nagle states that agents having a non-polar part attached to an active polar group causes this desired effect. The active polar group is adsorbed on the metal surface while the non-polar part causes the surface to be non-wettable to the condensate. Oleic and stearic acids fulfill these specifications and were observed to promote drop-wise condensation. By treating a nickel tube with oleic acid, upon which saturated steam was condensing, drop-wise condensation was observed with a corresponding overall coefficient of 950 Btu./Hr./Sq.Ft./°F. This same tube had previously rendered a coefficient of 446 Btu./Hr./Sq.Ft./°F. when clean.

Nagle and Associates (25) reported steam-side coefficients of the order of 14,000 Btu./Hr./Sq.Ft./°F. for drop-wise condensation. The apparatus used to obtain these results was a 2.875" O.D. x 24" long copper pipe set vertically inside a steam jacket.

Water flowed down the inside of the copper pipe. The steam side surface temperature of the copper pipe was measured with two copper-constantan thermocouples attached to the pipe at five different levels. The wires lay in horizontal grooves cut around the pipe and the tip of each thermocouple soldered in place. The method used for measuring the surface temperature was similar to that developed by Hubbard and Badger (13). The thermocouple readings indicated an erratic variation in the temperature of the pipe from point to point. This apparatus did not allow for observation of the mode of condensation.

Drew, Nagle, and Smith (6) made a study of the conditions necessary for drop-wise condensation of steam. They suggested that the presence of rubber in the system may have caused, in part, the discrepancies of former investigators. The basis of this statement being that rubber tubing that had been treated with caustic, contained drop-wise promoters. Some conditions related to drop-wise condensation were presented. Clean steam always condenses with a film formation on a clean surface. The cooling surface must be contaminated in some way if drop-wise condensation is to occur. Only agents which are firmly held on the condensing surface are significant as drop-wise promoters. A smooth surface is more conducive to drop-wise condensation than a rough surface.

Fitzpatrick, Baum, and McAdams (11) studied the effect of benzyl mercaptan on various metal surfaces. In their tests it was not possible to obtain film type condensation because of the presence of a fatty-acid promoter which entered the steam system through a boiler feed pump in the power plant. These investigators, no doubt, had an experience similar to that of Jeffrey and Moynihan (17). However, a copper tube which indicated an overall coefficient of 900 Btu./Hr./Sq.Ft./°F. before treating with benzyl mercaptan, showed 1650 Btu./Hr./Sq.Ft./°F. after treatment. The apparatus used in this study required the measurement of the condensing surface temperature with grooved thermocouples. The authors emphasized the need for further investigation of the optimum quantity of promoter required in practice.

Emmons (7) postulated the molecular mechanism of the promoter action. He states that drop-wise condensation will occur if a promoter with the following properties is present on the condensing surface. The promoter molecules must have one part which has very little affinity for vapor molecules and an active group which has a large affinity for the condensing surface. These molecules must be constructed in such a way that a monomolecular layer is formed with the inactive part exposed to the vapor and the active group adsorbed on the cooling surface. The presence of this monomolecular layer is the necessary and sufficient condition for drop-wise condensation. A second layer of molecules would have to be attached to the inactive part of the first layer. This second layer would form an unstable condition and is not likely to occur. A procedure for depositing stearate layers on the cooling surface was also presented.

The apparatus of Shea and Krase (30) appears to be the soundest thus far devised for accurate measurement of steam side coefficients. A vertical plate 0.25" thick, 5" wide, and 24" long was exposed to steam contained in a steam chest. The plate was divided into five sections with controllable water rate to each. The condensing surface temperature was measured with accurately located thermocouples in the condenser plate. The effect of steam velocity, length of condensing surface, and heat flux were studied for film type condensation as well as the drop-wise condition.

Fatica and Katz (8) studied the mechanism of drop-wise condensation by measuring the contact angle of the droplets on the cooling surface. They attempted to predict the mode of condensation by correlating the heat conducted through the drops formed and the resistance between the vapor and condensate free.surface.

There appears to have been as many different methods of approach to the study of drop-wise condensation as there were investigators. The approach first undertaken in this study entailed the design and construction of an apparatus for measuring the condensing surface temperature as well as a knowledge of the other parameters. A second apparatus of simple design was also built and proved to be a better tool for this study.

APPARATUS

Finger-Type Condenser

The apparatus used for this study was similar to that of Drew, Negle, and Smith (6). The cooling surface was a 5-1/2 inch piece of 1/2 inch copper tubing, sealed at one end with solder, inside of which was placed a finger of 1/4 inch copper tubing. The open end of the inside tube was 1/16 inch from the sealed end of the outer tube. The inside tube was held rigidly in place by a 1/2 x 1/4 inch reducer fitting. An outlet was made by drilling a hole in the outside tube and soldering a short section of 1/4 inch tubing in place. Cooling water traveled down the inside tube, through the annulus, thence to the outlet. See Figure 2.

The outside tube measured 0.500" O.D., 0.435" I.D. The inside tube measured 0.250" O.D., 0.190" I.D. The actual length of the outside tube exposed to condensation was 3.5".

The condensing surface was prepared by polishing with various gradues of fine emery paper. Crocus cloth was used to obtain the finished surface. The excess polishing compound was removed by scrubbing with Ajax* cleaner with intermittent rinsing. A more detailed explanation of the surface conditioning is given in the section dealing with procedure.

A two liter Erlenmeyer flask served as a condensing jacket as well as the boiler. A standard laboratory glass reflux condenser was used to maintain nearly atmospheric pressure in the system and to condensate the excess vapors. This combination kept the material under study at a nearly constant concentration.

* A commercial scouring compound.

A cork stopper with appropriate holes was used to hold the test condenser, reflux condenser, and steam thermometer in place. The cork stoppers were previously placed in boiling distilled water to extract the natural resins and other water soluble impurities. The extraction process was repeated, boiling water until there was no noticeable color from the cork. The stoppers were then dried in an oven.

The cooling water inlet temperature was measured with a Beckmann thermometer which had been calibrated with a standard thermometer. The cooling water outlet temperature was measured with a glass thermometer calibrated in increments of 0.1F° from which 0.05F° could be estimated with confidence. The steam temperature was also measured with a glass thermometer calibrated in 0.2F°. The cooling water rate was determined by weighing the throughput for a given time interval. A scales calibrated to 1/64 of a pound intervals was used. The throughput could be estimated to 0.01 lbs./min. with fair accuracy.

<u>Sectional Coil-Type Condenser</u>

The apparatus shown in Figures 3 and 4 was designed and constructed for the purpose of determining steam side coefficients by measuring wall temperatures. The body of this condenser was a spun casting of brass made with an outside diameter of 5-1/2" with a 0.4" wall thickness and 15" long. Copper tubing was coiled around this casting in four separate sections and soldered in place. Additional solder was used for fill between the shell and the tubing. The purpose of the four separate sections was to allow for independent measurement of the cooling water rates and, thus, a simultaneous study of each vertical section.

Two iron-constantan thermocouples displaced by 180° were used to measure the wall temperature in each vertical section. The thermocouples were imbedded into the wall of the casting 0.25" from the outside surface. Each couple was then soldered in place with a fusible alloy melting approximately at 300°F.

The end pieces of the condenser were made of 3/8" brass plate and held in place with twelve 1/4" x 1" fillister head bolts. A rubber gasket was used to form a seal.

A vent was provided to allow for the escape of air which may have been present in the steam. The steam pressure was measured with a pressure gage located on top of the condenser. The steam temperature, condensate temperature, and cooling water inlet temperature were measured with iron-constantan thermocouples placed in wells as shown in Figure 3. The cooling water outlet temperature from each section was measured by thermocouples soldered to 1/4" copper tubes through which water flowed. A sixteen station electronic temperature recorder was used to record all temperatures.

A spring loaded diaphram type pressure regulator was used to maintain constant pressure to the test condenser. The cooling water from each section and the condensate were collected in pails and weighed.

One of the standard chemical feed pumps was used to feed the desired quantity of test material into the steam. Further discussion concerning this apparatus with sample data is presented in Appendix B.

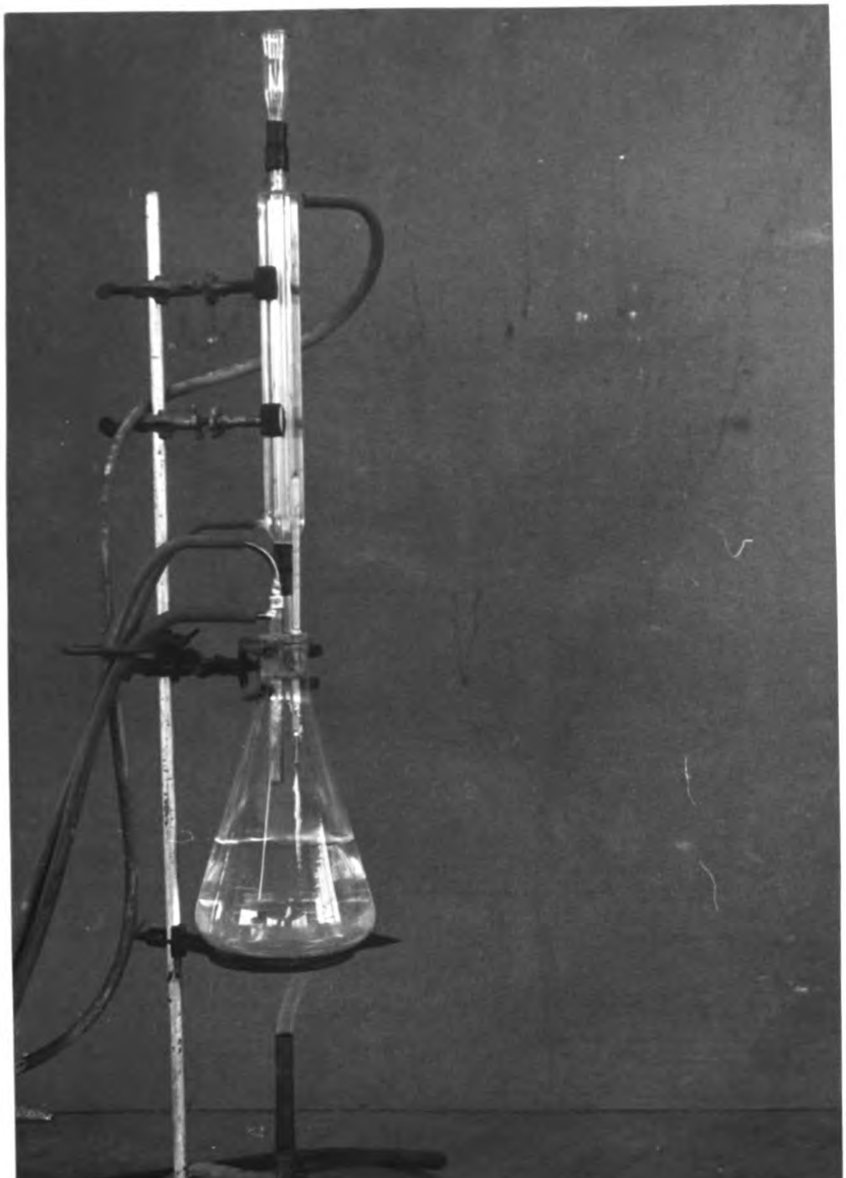
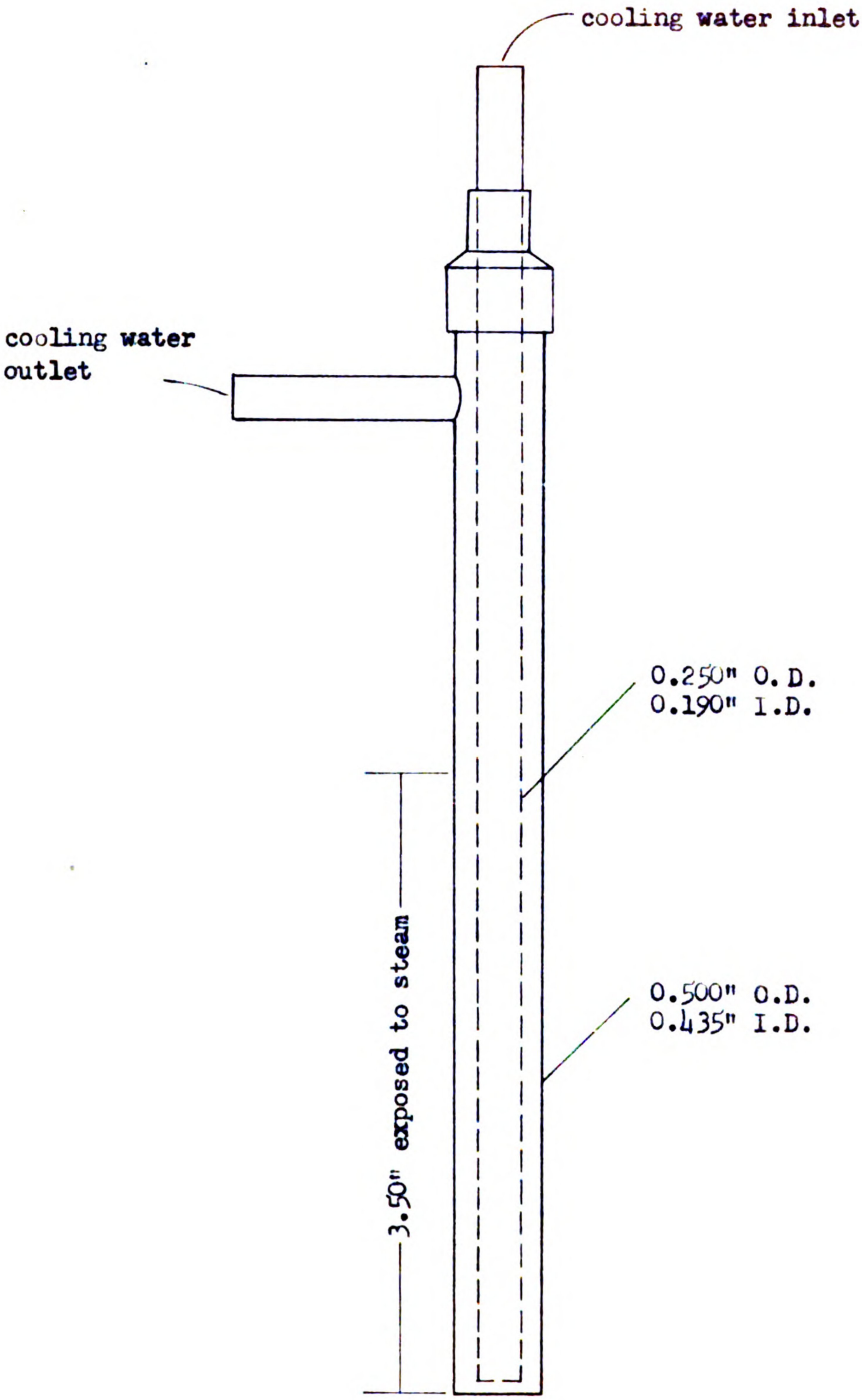


Figure 1. Finger-Type Apparatus

Figure 2. Finger-Type Condenser



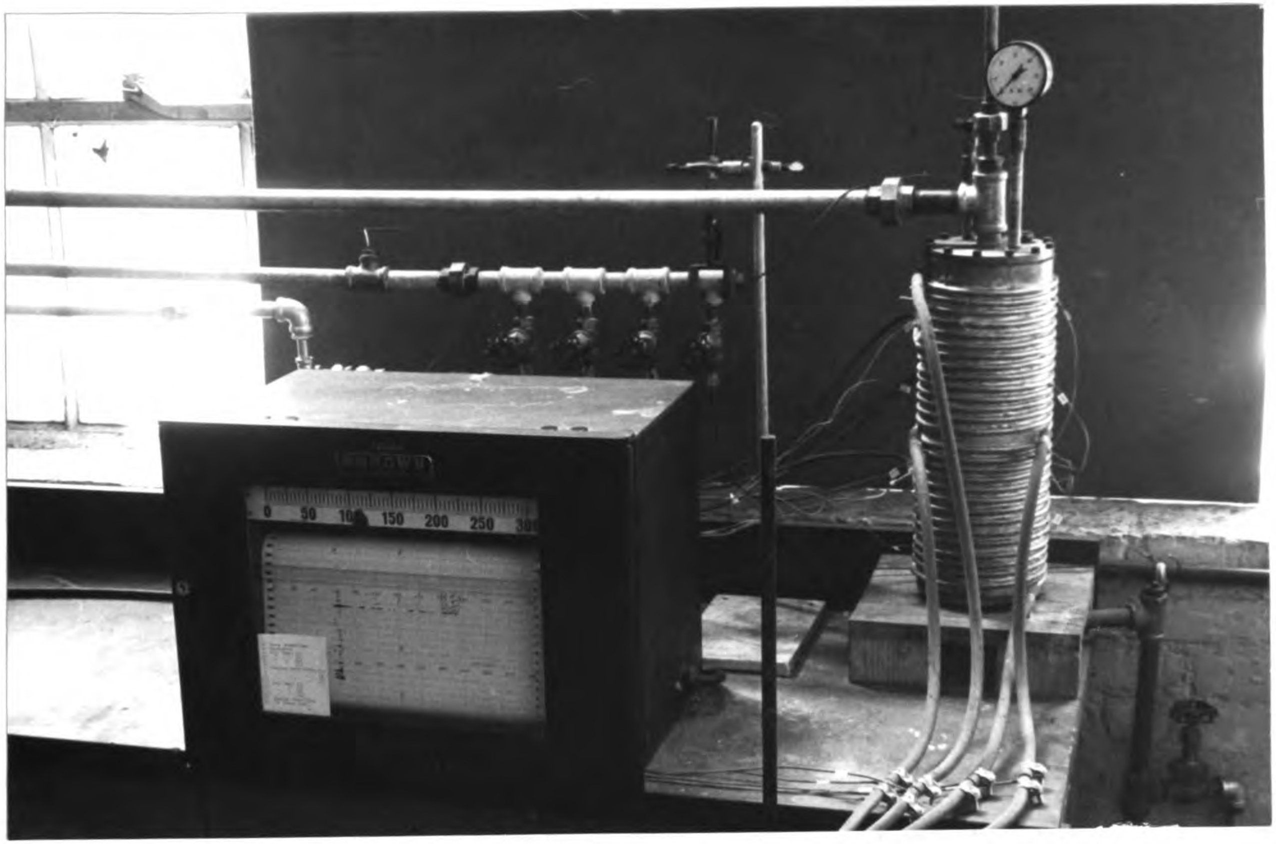
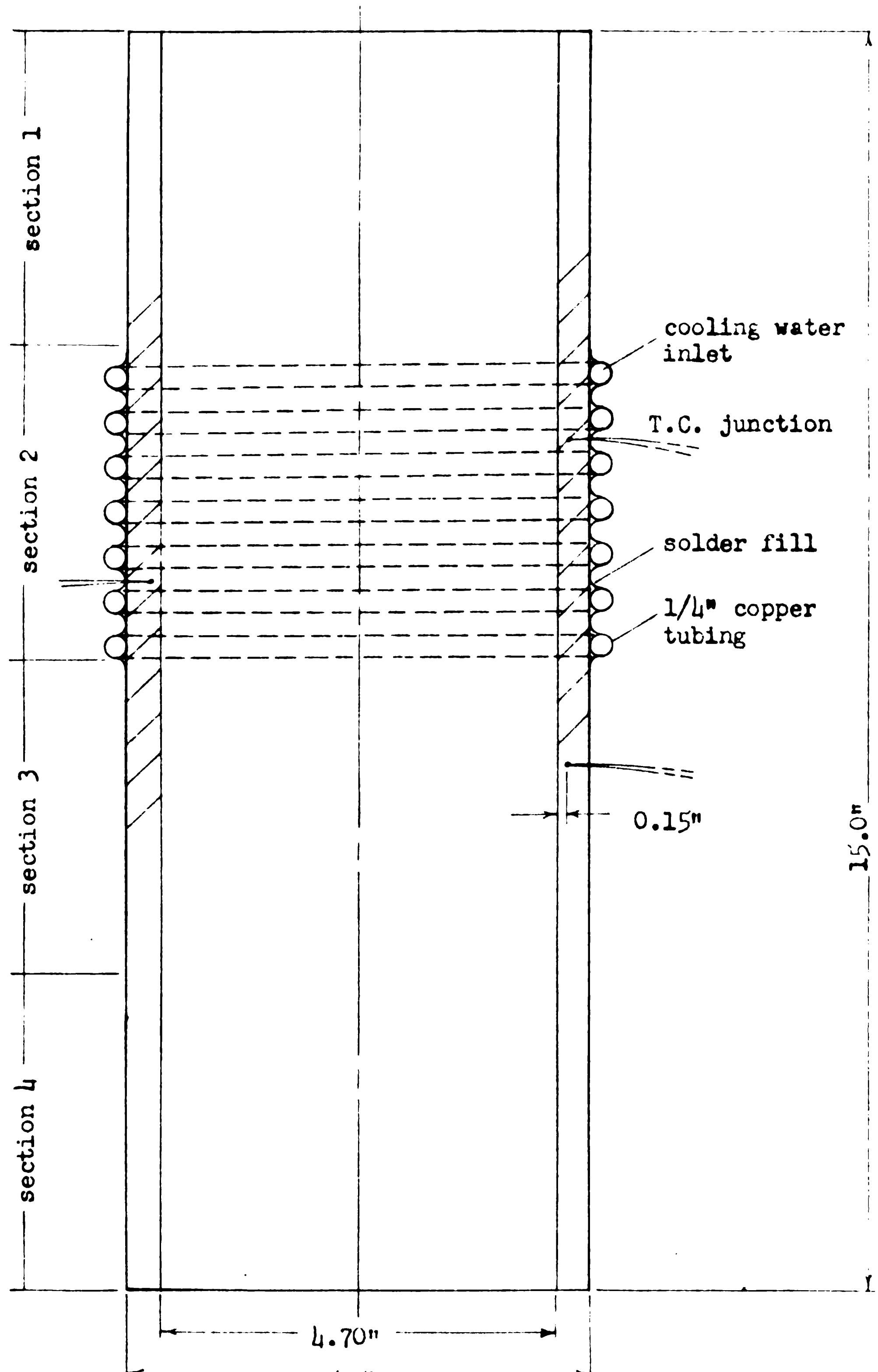


Figure 3. Sectional Coil-Type Apparatus

Figure 4. Cross-Section of Coil-Type Condenser



Note: Sections 1, 3, and 4 same as 2.

PROCEDURE

The reported work of all previous investigators indicated that initial surface cleanliness is the most important factor in the study of drop-wise condensation. For this reason, extreme care was taken to minimize the presence of foreign substances which would possibly alter the effects under study. The equipment was cleaned in the following manner before each of the five studies. The Erlenmeyer flask was scrubbed thoroughly with Ajax cleaning compound. After rinsing with both tap and distilled water, the flask was washed with dilute hydrochloric acid and finally rinsed with distilled water. The inner tube of the reflux condenser and the steam thermometer were cleaned in a similar manner.

The copper condensing surface was prepared by polishing with various grades of fine emery paper terminating with a crocus cloth treatment. The surface was then scrubbed with Ajax cleaner to remove the excess polishing compound. The tube was rinsed with water and treated for a few seconds with a dilute solution of hydrochloric acid, after which the tube was immediately rinsed in distilled water. At this point, the tube was submerged in distilled water to reduce oxide formation and the possibility of impurities gathering on the surface. The tube remained under water until used.

Cork stoppers were used in preference to rubber for reasons given earlier. A different stopper was used for each study and treated in the following manner. The stoppers were boiled in distilled water for the purpose of removing the natural resins present in cork. The extracting process was repeated with fresh water until there was no noticeable coloring from the cork. The corks were then soaked in distilled water and finally dried in an oven.

The cooling water inlet temperature was measured with a Beckmann thermometer calibrated to 0.01C°. The Beckmannwas previously adjusted to read temperature differences in the desired range and standardized to read actual temperatures. The bulb of this thermometer was placed in a jar into which cooling water flowed. This arrangement made it possible to observe a cooling water inlet temperature at any desired time.

The cooling water outlet temperature was measured with a glass thermometer calibrated to 0.1F°. A temperature difference of 0.5F° could be estimated from this thermometer. The cooling water was mixed thoroughly before measuring the outlet temperature. This gave an average outlet temperature for the period of a single run.

The steam temperature varied nearly 0.5F° for each run; it was measured with a glass thermometer calibrated to 0.2F°. The steam temperatures reported were, therefore, an average for any given run.

The flow rate of cooling water was determined by weighing the throughput for an observed time interval. The time interval was one minute for the low flow rates and fifteen seconds for the higher rates.

The first trial was made with distilled water. A quantity of 1400 CC of distilled water was introduced into the flask. A Bunsen burner served as the heat source. Fresh boiling chips were added and the apparatus assembled. Sufficient cooling water was allowed to flow to the reflux condenser with another portion flowing to a jar containing a Beckmann thermometer. The flow of cooling water to the experimental condenser was controlled by the tap valve. A period of 30 minutes after boiling commenced was allowed for equilibrium to be obtained. The cooling water inlet and outlet temperatures, and the steam temperature for various flows were observed and recorded.

The procedures for studying octadecylamine, dodecylamine, octylamine, and stearic acid were identical to that for water with the exception of the introduction of the promoting agent. In each case the surface was cleaned as described above. The copper surface was treated by rubbing with the desired agent. An additional portion of amine was added which amounted to 5 ppm (weight basis) for each case. The time required for obtaining the data was approximately three hours for each amine studied.

This data was used to determine the overall heat transfer coefficients at corresponding water velocities. A method devised by Wilson (35) for correlating the overall coefficient with the water velocity was used. This entailed the plotting of $1/V^{0.8}$ versus $1/U$. The factor, $1/V^{0.8}$, demands that the cooling water flow in turbulent fashion. This restriction was investigated. It was found that all of the data correspond to Reynold's Numbers greater than 2500, thus, indicating turbulent flow. These results were then plotted and the method of least squares applied to determine the best straight line. A complete sample calculation is presented in Appendix A.

TABULATED DATA

I. Control (Distilled Water)

Run No.	Cooling Water Temperatures Inlet (t_1) °F	Outlet (t_2) °F	Steam Temp. (t_s) °F	Cooling Water Rate (W') lb/min.
1	53.79	56.60*	207.5	7.96
2	53.75	56.40	207.5	7.96
3	53.74	56.30	207.5	7.55
4	53.71	56.25	207.5	7.63
5	53.71	56.38	207.5	7.59
6	53.67	56.10	207.5	7.56
7	53.65	55.40	208.0	10.91
8	53.62	55.35	208.0	10.97
9	53.60	55.40	207.6	10.97
10	53.60	55.30	208.0	11.06
11	53.58	55.25	207.6	11.02
12	53.56	54.96	207.5	14.91
13	53.53	54.90	207.8	14.92
14	53.51	54.87	207.8	14.75
15	53.49	54.95	207.6	14.50
16	53.49	54.93	207.5	14.54
17	53.62	55.40	207.5	14.44
18	53.53	54.90	207.5	15.75
19	53.49	54.80	207.6	15.56
20	53.52	54.80	207.5	15.94
21	53.21	54.80	207.6	15.69

I. Control (Distilled Water) (Cont.)

Run No.	Cooling Water Temperatures Inlet (t_1) °F	Outlet (t_2) °F	Steam Temp. (T_s) °F	Cooling Water Rate (W') lb/min.
22	53.56	55.75	208.0	9.06
23	53.60	55.80	208.4	9.00
24	53.62	55.78	208.2	9.02
25	53.64	55.90	208.3	9.00
26	53.62	55.85	208.0	8.88

Barometric Pressure = 29.07 in.-Hg.

* Last digit estimated

II. Octadecylamine

Run No.	Cooling Water Temperatures Inlet (t_1) °F	Outlet (t_2) °F	Steam Temp. (T_s) °F	Cooling Water Rate (W') lb/min.
1	53.87	58.10	207.6	4.91
2	53.78	55.75	208.2	11.39
3	53.74	55.65	208.5	11.34
4	53.78	55.60	208.0	11.25
5	53.78	55.65	208.1	11.34
6	53.74	55.60	208.2	11.20
7	53.72	55.30	208.3	15.75
8	53.72	55.10	208.2	15.81
9	53.69	55.15	207.8	15.69
10	53.71	55.20	207.7	15.69
11	53.71	55.30	207.9	15.50
12	53.80	56.90	208.3	6.31
13	53.82	57.10	207.9	6.19
14	53.82	57.20	208.0	6.06
15	53.82	57.10	208.2	6.00
16	53.80	57.15	208.0	5.95
17	53.76	56.10	208.5	9.42
18	53.76	56.05	208.6	9.19
19	53.78	56.00	208.3	9.38
20	53.78	56.05	208.3	9.47
21	54.03	56.40	208.6	9.19

II. Octadecylamine (Cont.)

Run No.	Cooling Water Temperatures Inlet (t_1) °F	Outlet (t_2) °F	Steam Temp. (T_s) °F	Cooling Water Rate (W') lb/min.
22	54.21	57.10	208.3	7.56
23	54.28	57.00	208.8	7.49
24	54.34	57.05	208.4	7.44
25	54.34	57.05	208.5	7.48
26	54.32	57.05	208.7	7.39
27	54.43	57.50	209.0	7.81
28	54.37	57.20	208.9	7.66
29	54.36	57.15	208.7	7.63
30	54.37	57.15	209.0	7.50

Barometric Pressure = 29.20 in-Hg.

III. Dodecylamine

Run No.	Cooling Water Temperatures Inlet (t_1) °F	Outlet (t_2) °F	Steam Temp. (T_s) °F	Cooling Water Rate (W') lb/min.
1	53.69	56.40	207.4	8.59
2	53.71	56.30	207.3	8.53
3	53.69	56.30	208.0	8.44
4	53.64	56.10	208.1	8.84
5	53.64	56.20	208.3	8.50
6	53.65	55.90	207.3	12.88
7	53.65	55.50	207.2	13.25
8	53.65	55.50	207.0	12.75
9	53.65	55.30	207.1	13.14
10	53.65	55.50	208.2	13.13
11	53.74	58.80	208.2	4.89
12	53.74	58.40	207.8	4.69
13	53.71	56.30	207.8	9.13
14	53.69	56.10	208.5	9.19
15	53.67	56.10	208.3	9.19
16	53.65	55.90	207.2	9.20
17	53.65	56.10	208.1	9.00
18	53.64	55.50	207.8	12.69
19	53.62	55.40	207.8	12.75
20	53.60	55.30	207.8	14.94
21	53.58	55.30	207.9	15.37

III. **Dodecylamine** (Cont.)

Run No.	Cooling Water Temperatures Inlet (t_1) °F	Outlet (t_2) °F	Steam Temp. (T_s) °F	Cooling Water Rate (W') Lb/Min.
22	53.56	55.20	208.5	15.13
23	53.58	55.30	208.5	15.03
24	53.60	55.40	207.8	14.75

Barometric Pressure = 29.12 in-Hg.

IV. Octylamine

Run No.	Cooling Water Temperatures Inlet (t_1) °F	Outlet (t_2) °F	Steam Temp. (T_s) °F	Cooling Water Rate (W') lb/min.
1	54.14	56.75	206.4	7.22
2	54.16	56.60	206.1	6.75
3	54.16	56.70	206.1	6.67
4	54.21	56.75	205.8	6.66
5	54.25	56.65	205.6	6.69
6	54.21	55.80	205.5	12.31
7	54.18	55.60	206.1	12.66
8	54.16	55.55	206.0	12.80
9	54.21	55.60	205.9	12.84
10	54.07	55.50	205.7	12.80
11	54.07	56.45	206.0	6.72
12	54.09	56.00	206.9	8.66
13	54.09	56.20	207.2	8.28
14	54.10	56.05	205.8	8.72
15	54.16	56.10	205.9	8.56
16	54.19	56.20	205.6	8.59
17	54.19	55.60	205.8	14.63
18	54.12	55.35	205.5	14.75
19	54.05	55.30	205.6	14.25
20	54.00	55.20	205.4	14.27
21	53.98	55.25	206.0	14.50

IV. Octylamine (Cont.)

Run No.	Cooling Water Temperatures Inlet (t_1) °F	Outlet (t_2) °F	Steam Temp. (T_s) °F	Cooling Water Rate (W') lb/min.
22	54.00	55.20	206.0	14.44
23	54.05	56.90	206.7	6.56
24	54.00	56.10	206.2	8.14
25	53.96	55.70	207.0	9.94
26	53.96	55.50	206.5	9.94
27	53.96	55.55	206.2	10.00
28	53.96	55.50	206.8	10.06
29	53.92	55.60	206.7	10.03

Barometric Pressure = 29.07 in-Hg.

V. Stearic Acid

Run No.	Cooling Water Temperatures Inlet (t_1) °F	Outlet (t_2) °F	Steam Temp. (T_s) °F	Cooling Water Rate (W') lb/min.
1	53.45	56.30	208.4	8.66
2	53.44	56.20	208.8	8.81
3	53.44	56.25	208.6	8.88
4	53.40	56.00	208.3	8.78
5	53.40	55.95	208.7	8.69
6	53.20	56.05	209.0	10.22
7	53.20	55.50	208.8	10.41
8	53.20	55.70	208.9	10.05
9	53.20	55.40	208.8	10.59
10	53.20	55.50	209.0	10.36
11	53.20	54.90	208.8	14.62
12	53.20	54.90	208.3	14.75
13	53.20	54.90	208.8	14.62
14	53.30	55.00	209.0	14.53
15	53.40	55.20	208.3	14.62
16	53.60	56.80	208.5	7.19
17	53.60	56.80	208.5	7.28
18	53.60	56.80	208.2	7.13
19	53.60	56.80	208.5	7.16
20	53.60	56.80	208.5	7.13
21	53.60	56.10	209.0	11.77

V. Stearic Acid (Cont.)

Run No.	Cooling Water Temperatures Inlet (t_1) °F	Outlet (t_2) °F	Steam Temp. (T_s) °F	Cooling Water Rate (W') lb/min.
22	53.53	55.90	209.1	11.77
23	53.50	55.60	208.7	11.48
24	53.50	55.50	209.0	11.72

Barometric Pressure = 29.21 in-Hg.

TABULATED RESULTS

I. Control (Distilled Water)

Run No.	Overall Coefficient (U) Btu./Hr./Sq.Ft./°F	Water Velocity (V) Ft./Sec.	$1/V^{0.8}$	$1/U \times 10^3$
1	223.0	2.974	0.419	4.484*
2	210.2	2.974	0.419	4.757*
3	199.2	2.290	0.424	5.020
4	199.7	2.950	0.421	5.008
5	209.2	2.937	0.423	4.780*
6	189.3	2.925	0.424	5.283
7	195.4	4.218	0.316	5.118*
8	194.3	4.242	0.315	5.147*
9	202.8	4.242	0.315	4.931
10	192.5	4.280	0.312	5.195*
11	188.8	4.261	0.313	5.297*
12	214.2	5.766	0.246	4.669
13	209.2	5.772	0.245	4.780
14	205.2	5.706	0.248	4.873
15	217.0	5.609	0.252	4.608
16	214.5	5.622	0.252	4.662
17	263.2	5.584	0.250	3.799*
18	221.4	6.092	0.236	4.512
19	209.0	6.020	0.238	4.785
20	209.2	6.164	0.234	4.780
21	255.2	6.068	0.235	3.918*

I. Control (Distilled Water) (Cont.)

Run No.	Overall Coefficient (U) Btu./Hr./Sq.ft./°F	Water Velocity (V) Ft./Sec.	$1/V^{0.8}$	$1/U \times 10^3$
22	203.6	3.505	0.367	4.912
23	202.5	3.481	0.368	4.938
24	199.4	3.487	0.368	5.015
25	208.3	3.481	0.368	4.801
26	203.0	3.433	0.372	4.926

* These points were not used to calculate the best straight line by the method of least square.

II. Octadecylamine

Run No.	Overall Coefficient (U) Btu./Hr./Sq.Ft./°F	Water Velocity (V) Ft./Sec.	$1/V^{0.8}$	$1/U \times 10^3$
1	215.1	1.898	0.598	4.649*
2	229.9	4.406	0.306	4.349
3	221.3	4.388	0.307	4.518
4	209.9	4.352	0.310	4.764*
5	217.3	4.388	0.307	4.601
6	213.3	4.333	0.309	4.688*
7	254.3	6.093	0.237	3.932*
8	223.0	6.068	0.237	4.484
9	234.5	6.068	0.237	4.264
10	239.7	6.068	0.237	4.171
11	252.4	5.995	0.240	3.961*
12	201.2	2.442	0.490	4.970
13	209.3	2.394	0.497	4.777
14	211.2	2.345	0.505	4.734
15	202.6	2.321	0.510	4.935
16	205.5	2.302	0.513	4.866
17	225.6	3.645	0.354	4.432
18	215.1	3.554	0.363	4.649
19	213.3	3.626	0.358	4.688
20	220.2	3.663	0.354	4.541
21	223.0	3.554	0.362	4.481

II. Octadecylamine (Cont.)

Run No.	Overall Coefficient (U) Btu./Hr./Sq.Ft./°F	Water Velocity (V) Ft./Sec.	$1/V^{0.8}$	$1/U \times 10^3$
22	225.0	2.925	0.423	4.444
23	208.9	2.895	0.427	4.786
24	207.4	2.877	0.430	4.821
25	208.6	2.895	0.427	4.793
26	207.3	2.859	0.430	4.823
27	246.3	3.022	0.414	4.060*
28	222.4	2.961	0.418	4.496
29	218.6	2.949	0.421	4.574
30	213.9	2.901	0.427	4.675

* These points were not used to calculate the best straight line by the method of least square.

III. **Dodecylamine**

Run No.	Overall Coefficient (U) Btu./Hr./Sq.Ft./°F	Water Velocity (V) Ft./Sec.	$1/V^{0.8}$	$1/U \times 10^3$
1	240.3	3.324	0.383	4.161
2	228.0	3.300	0.385	4.385
3	226.2	3.264	0.388	4.420
4	223.1	3.421	0.374	4.482
5	222.9	3.288	0.387	4.486
6	296.5	4.980	0.276	3.372*
7	252.4	5.125	0.272	3.961
8	243.1	4.932	0.279	4.113
9	223.3	5.083	0.273	4.478*
10	248.4	5.077	0.273	4.025
11	213.5	1.891	0.601	4.683
12	226.3	1.813	0.621	4.418*
13	243.9	3.530	0.364	4.100
14	226.6	3.554	0.363	4.414
15	230.2	3.554	0.363	4.344
16	212.1	3.560	0.362	4.714*
17	226.2	3.481	0.368	4.420
18	242.1	4.908	0.280	4.130
19	232.7	4.932	0.279	4.297
20	260.2	5.778	0.246	3.843
21	270.7	5.946	0.241	3.694*

III. Dodecylamine (Cont.)

Run No.	Overall Coefficient (U) Btu./Hr./Sq.Ft./°F	Water Velocity (V) Ft./Sec.	$1/V^{0.8}$	$1/U \times 10^3$
22	253.0	5.850	0.243	3.952
23	263.7	5.814	0.245	3.792
24	272.2	5.705	0.249	3.673

*These points were not used to calculate the best straight line by the method of least square.

IV. Octylamine

Run No.	Overall Coefficient (U) Btu./Hr./Sq.Ft./°F	Water Velocity (V) Ft./Sec.	$1/V^{0.8}$	$1/U \times 10^3$
1	196.2	2.792	0.440	5.096 *
2	171.8	2.611	0.463	5.820
3	176.7	2.581	0.469	5.659
4	176.7	2.575	0.469	5.659
5	168.0	2.587	0.467	5.952
6	204.4	4.762	0.287	4.892*
7	186.8	4.895	0.281	5.353
8	184.9	4.950	0.279	5.408
9	185.7	4.968	0.278	5.385
10	190.5	4.950	0.279	5.249
11	166.8	2.599	0.466	5.995
12	171.2	3.348	0.380	5.841
13	180.7	3.203	0.393	5.534
14	177.2	3.373	0.377	5.643
15	173.1	3.312	0.383	5.777
16	180.5	3.324	0.382	5.540
17	214.7	5.657	0.250	4.657*
18	189.0	5.705	0.248	5.291
19	185.5	5.512	0.256	5.390
20	178.5	5.518	0.256	5.602
21	191.2	5.609	0.251	5.230

IV. Octylamine (Cont.)

Run No.	Overall Coefficient (U) Btu./Hr./Sq.Ft./°F.	Water Velocity (V) Ft./Sec.	$1/V^{0.8}$	$1/U \times 10^3$
22	179.8	5.585	0.252	5.561
23	194.4	2.539	0.474	5.144*
24	177.8	3.149	0.400	5.624
25	178.6	3.844	0.341	5.599
26	158.4	3.844	0.341	6.313*
27	165.1	3.868	0.338	6.056*
28	160.1	3.892	0.337	6.246*
29	174.2	3.880	0.337	5.740

* These points were not used to calculate the best straight line by the method of least square.

V. Stearic Acid

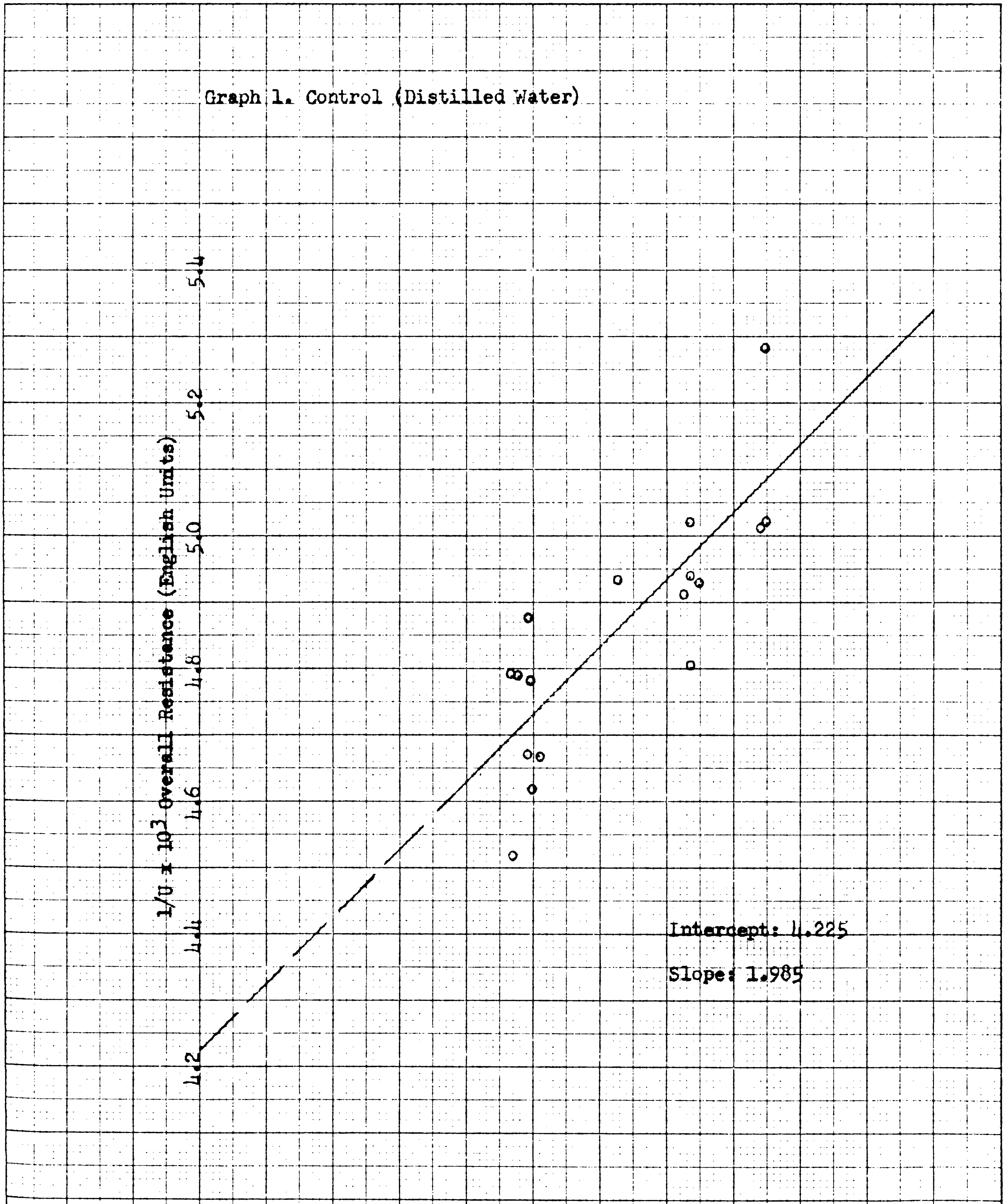
Run No.	Overall Coefficient (U) Btu./Hr./Sq.ft./°F.	Water Velocity (V) Ft./Sec.	$1/V^{0.8}$	$1/U \times 10^3$
1	252.4	3.348	0.380	3.962
2	248.3	3.409	0.376	4.027
3	253.9	3.433	0.372	3.939
4	233.6	3.397	0.377	4.281
5	226.0	3.361	0.379	4.425
6	296.4	3.952	0.333	3.374*
7	243.6	4.025	0.328	4.105
8	255.5	3.886	0.337	3.914
9	237.0	4.097	0.323	4.210
10	242.2	4.007	0.329	4.129
11	252.4	5.657	0.250	3.962
12	255.6	5.706	0.249	3.912
13	252.4	5.657	0.250	3.962
14	250.8	5.621	0.251	3.987
15	268.5	5.657	0.250	3.724
16	235.8	2.780	0.441	4.241
17	238.9	2.817	0.436	4.186
18	234.2	2.756	0.444	4.270
19	234.8	2.768	0.443	4.259
20	233.8	2.756	0.444	4.277
21	300.0	4.551	0.298	3.333*

V. Stearic Acid (Cont.)

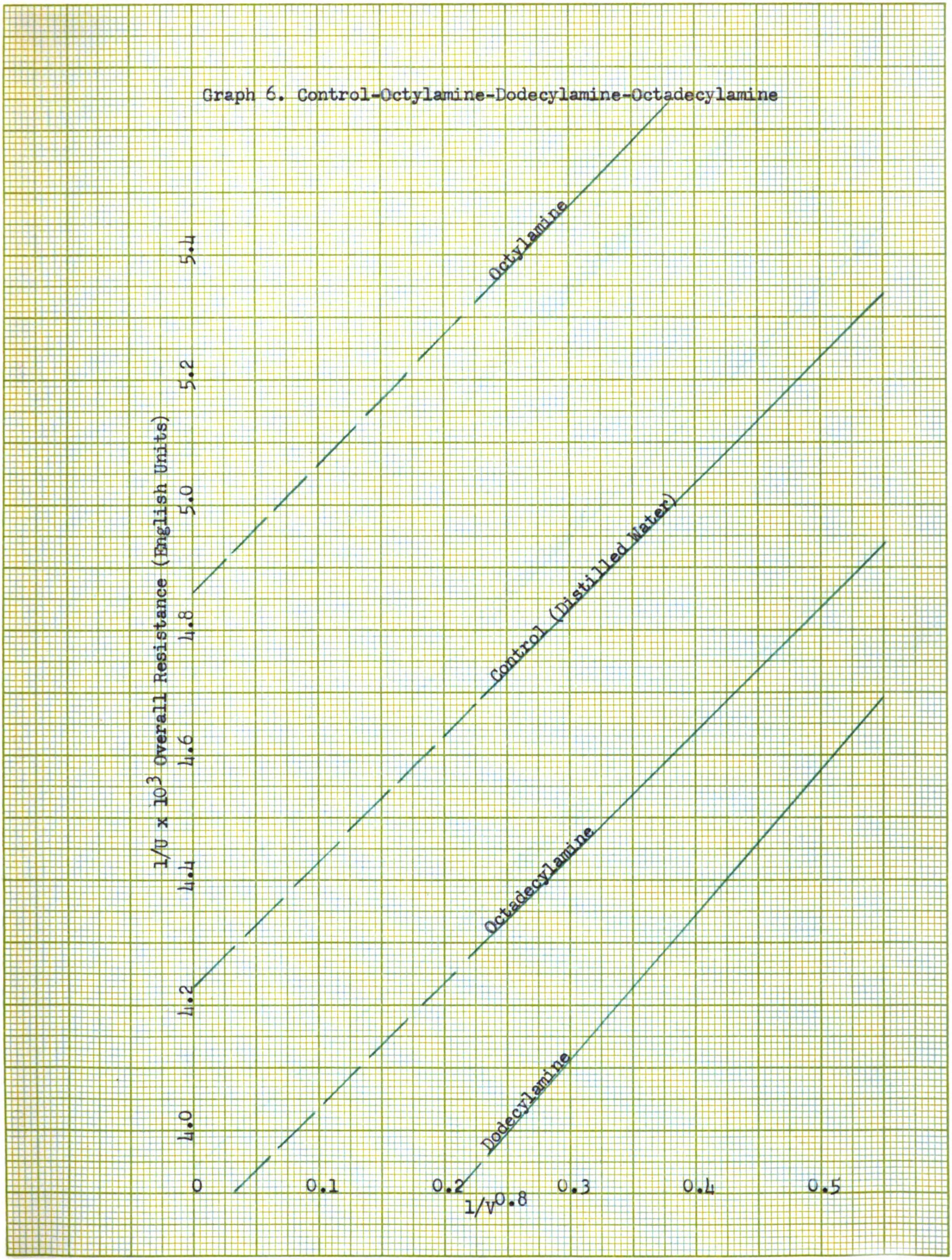
Run No.	Overall Coefficient (U) Btu./Hr./Sq.Ft./°F.	Water Velocity (V) Ft./Sec.	$1/V^{0.8}$	$1/U \times 10^3$
22	281.7	4.551	0.298	3.550
23	245.9	4.442	0.304	4.067
24	238.4	4.533	0.298	4.195

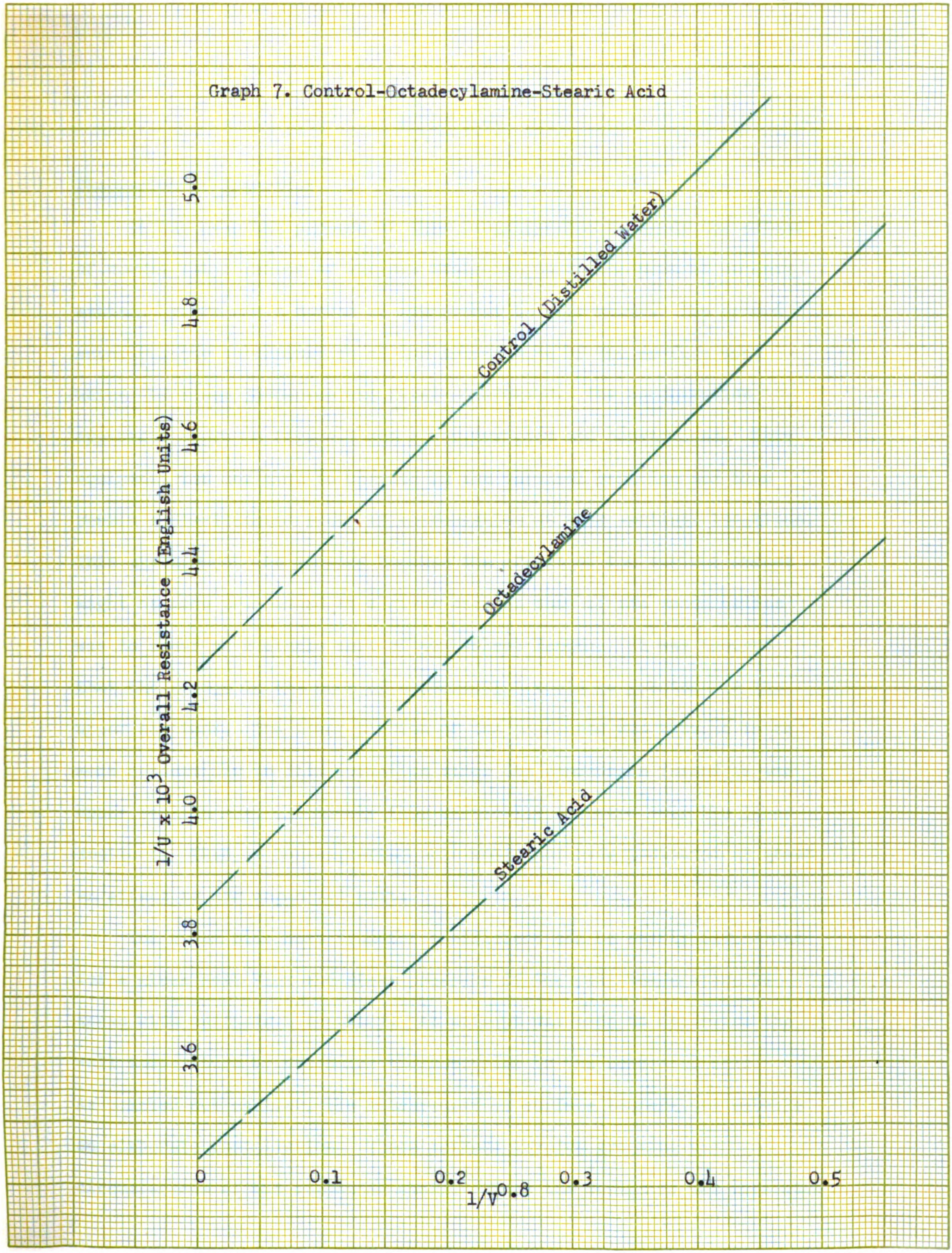
* These points were not used to calculate the best straight line by the method of least square.

GRAPHS



Graph 1. Control (Distilled Water)
1/U x 10^3 Overall Resistance (English Units)
5.4
5.2
5.0
4.8
4.6
4.4
4.2
0
0.1
0.2
0.3
0.4
0.5
1/V^0.8
Intercept: 4.225
Slope: 1.985


Graph 6. Control-Octylamine-Dodecylamine-Octadecylamine
Octylamine
Control (Distilled Water)
Octadecylamine
Dodecylamine
1/U x 10³ Overall Resistance (English Units)
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0
0
0.1
0.2
0.3
0.4
0.5
1/V^0.8


Graph 7. Control-Octadecylamine-Stearic Acid
Control (Distilled Water)
Octadecylamine
Stearic Acid
1/U x 10^3 Overall Resistance (English Units)
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
0
0.1
0.2
0.3
0.4
0.5
1/V$^{0.8}$

DISCUSSION

Discussion of Apparatus

It has been the purpose of this investigation to study the effect of normal alkyl amines of various chain-length on the mode of condensation. There are a number of approaches to this study. The method entailing the determination of the temperature of the surface upon which the steam condenses was first considered. The condensation apparatus shown in Figure 3 and 4 was designed and constructed. This equipment was designed to operate in the vertical position and thus permit a simultaneous study of condensation at four vertical locations. This arrangement was adopted because the effect of the various amines might be more pronounced at a given section than if the condensation was to occur on a single unit of equivalent length. It was thought that the change in the mode of condensation would be greatest in the upper sections. The lower portion of the condenser was thought to be more susceptible to film formation since the condensate formed in the upper section must ultimately flow vertically downward over the lower sections. Thus, a non-segmented unit would not have indicated as great an effect as the segmented unit.

The steam side heat transfer coefficient can be easily determined for a given heat flux and steam pressure if the wall temperature is known with sufficient accuracy. An attempt was made to determine the wall temperature by imbedding thermocouples in the condenser wall. As pointed out earlier, the measurement of surface temperature entails an elaborate installation. These methods involve grooving the circumference of the condenser shell. Since the design of the apparatus calls for the fixation of cooling coils to the outer circumference with uniform metallic contact, the difficulty in keeping solder from flowing into the grooves during construction arose. Further preliminary design indicated complicated installation procedures which were not possible with the available equipment. The thermocouples were, therefore, imbedded by drilling appropriate holes into the condenser wall and fixing in position with a fusible alloy.

In order to calculate the temperature of the condensing surface of the apparatus described, the thermal conductivity of the material separating the junction from the surface and the location of the junction must be accurately known.

The material of the condenser shell was generically brass. The value for the thermal conductivity was not known with sufficient accuracy to precisely calculate the wall temperatures. Even if the exact value for the thermal conductivity of the brass were known, there would still be the question of the thermal conductivity effect of the fusible alloy used to hold the junction in place. This factor did not appear important until calculations showed that the thermal conductivity had a great effect on the calculated steam side coefficients.

The objections to the coil-type apparatus were: (1) the lack of a means for visual observation, (2) the possibility of impure steam, and (3) the difficulty in measuring other required parameters with sufficient accuracy. Basically, the lack of knowledge about the effective resistance between the wall and the actual position of the junction was the main reason for discontinuing work on the coil-type apparatus. Further information regarding this apparatus is presented in Appendix B.

The simple apparatus of Drew, Nagle, and Smith (5) was assembled to continue this study. This apparatus appeared to be a better tool for determining the effect in question. The details of this set-up have been discussed.

This system permitted visual observation of the condensing surface; the mode of condensation was thus readily determined. The amine concentration was readily held at a fairly constant level; this made it possible to study each of the various amines under similar conditions. All surfaces to which steam was exposed were readily available for cleaning. This factor was important since surface phenomenon is greatly altered by minute quantities of foreign materials. Low steam currents and condensation rates are attained in this apparatus. Nagle and Drew (24) suggested that these factors are necessary for drop-wise condensation.

Discussion of Results

Using the finger-type apparatus, data was obtained for distilled water, octadecylamine, dodecylamine, octylamine, and stearic acid. This data was used to calculate the overall heat transfer coefficient for corresponding water velocities. The method of calculation is presented in Appendix A.

The overall resistance to heat transfer or the reciprocal of the overall coefficient was plotted against the reciprocal of the velocity raised to 0.8 power. The best straight line through the results and the calculated line through the results are shown in Graphs 1-5 along with the corresponding slope and intercept of each line.

The first study was made on distilled water and served as a control to which the results for the various amines were compared. Complete filmwise condensation was observed throughout the entire test. The mode of condensation was identical to that shown in Figure 5-a.

The slope of the best straight line through a plot of $1/V^{0.8}$ versus $1/U \times 10^3$ was 1.985 while an extrapolation to the ordinate gave 4.225×10^{-3} for the intercept. This value for the intercept corresponds to the overall resistance to heat transfer at infinite water velocity. Since the resistance due to water flowing at infinite velocity is zero, the overall coefficient at this point was the sum of resistances on the steam side, in the metallic wall, and resistance resulting from a fouled surface. In this case neither surface was fouled and the resistance of the metal tube was negligible. The steam side coefficient was, therefore, approximately the reciprocal of the overall resistance at infinite velocity.

Using the value for the extrapolated resistance of 4.225×10^{-3}, the corresponding steam side coefficient was calculated to be 236.7 Btu./Hr./Sq.Ft./°F. This value is low for condensing steam on a non-fouled surface. The presence of a small quantity of air would cause this value to be low. For this reason, the steam side coefficient was not used directly as a basis for comparing the promoting agents. Instead, the entire range studied for each promoter was compared.

Data using octadecylamine was then obtained by following the procedure presented earlier. Very fine drops formed on the cooling surface during the first few moments of boiling. This mode of condensation continued for 10 minutes after which broad riverlets formed. After 25 minutes of condensation, the riverlets decreased in width and a large portion of the surface exhibited drop-wise condensation. During the following 10 minutes a thin white film formed over the surface of the condenser with apparent condensation between the cooling surface and the white film. This film seemed to ripple as condensate flowed beneath. After a few minutes this film slid free of the surface along with a quantity of condensate. The mode of condensation was then drop-wise until this process was repeated.

Riverlets were noted to form, but did not remain stationary, Instead, they moved across the surface coalescing drops previously formed. For the most part, partial drop-wise condensation was observed throughout this study.

The results obtained for octadecylamine showed a slope of 2.012 and an intercept of 3.836×10^{-3}. The calculated slope in this case was nearly the same as the slope of the lines for the control test. However, the values for the intercept were quite different. These results showed a 10 percent decrease in the extrapolated resistance for octadecylamine compared to distilled water. This comparison is shown in Graph 6.

The next study was made using dodecylamine. Drop-wise condensation was observed over the entire surface 25 minutes after boiling commenced. This mode of condensation continued for 30 minutes after which a white film formed similar to that observed for octadecylamine. This film was present for only a few minutes and did not reoccur as in the previous case. Mixed condensation was then observed throughout the remainder of the study with approximately 60 percent of the surface covered with a film layer. A condition similar to Figure 5-b and c, were observed during this study.

Graph 3 shows the calculated line through the results for dodecylamine with a slope of 2.376 and an intercept of 3.419×10^{-3}. This slope varies somewhat from the slopes for the control and octadecylamine, but is thought to be sufficiently close for the sake of comparison. The extrapolated resistance in this case is nearly 20 percent less than that indicated for the control and 10 percent less than that obtained for octadecylamine. This comparison is shown in Graph 6.

Octylamine was studied in the same manner as octadecylamine and dodecylamine. This material exhibited the best grade of drop-wise condensation observed in this study. Complete drop-wise condensation was observed throughout the entire test of nearly three hours duration. This mode of condensation was very similar to that exhibited in Figures 6-a, b, and c.

Figure 6-a shows the formation of tiny droplets on the bare surface. These droplets grew in size until conditions shown in Figure 6-b were obtained. These drops continued to grow until they reached a size where they rolled down the condensing surface. Drops rolling down the surface coalesced with drops vertically below and left a bare path behind them for a subsequent similar condensation run-off cycle.

The test surface became discolored during this test presumably due to the addition of octylamine. The discoloring was thought to be due to a complex formation between the amine and the copper. This formation, a fouling condition, gave the expected additional resistance.

The results obtained for octylamine showed a slope of 2.052 and an intercept of 4.866×10^{-3} as shown in Graph 4. This slope was nearly equal to the values obtained for the previous tests which distilled water and octadecylamine. The extrapolated resistance was approximately 15 percent greater for octylamine than for distilled water, in spite of the fact that complete dropwise condensation was observed during this test. The difference in resistance was most likely caused by the fouling effect of the copper-amine complex.

The results obtained for the control test and the various amines were compared in Graph 6. These results indicated that the amine with a chain length of eight carbon atoms increased the resistance to heat transfer compared to a clean surface condensing distilled water. On the other hand, octadecylamine and dodecylamine showed a decrease in resistance for the same comparison. The amine with twelve carbon atoms indicated a greater effect in the reduction of resistance to heat transfer than the eighteen carbon atom chain.

The fifth study was made with stearic acid as the promoting agent. Stearic acid and octadecylamine are both straight chain molecules, each containing eighteen carbon atoms. These materials have different active groups appended to the carbon chain. The amine has a $-NH_2$ group, while the acid has a $-COOH$ group.

The results for stearic acid are shown in Graph 5. The calculated slope was 1.809 and the intercept was 3.450×10^{-3}. The slope was somewhat less in this case, but was sufficiently close to the previous tests to make a comparison. The mode of condensation was very similar to that shown in Figures 6-a, b, and c.

Distilled water, octadecylamine, and stearic acid were compared in Graph 7. This comparison indicated that stearic acid was more effective in reducing the steam side resistance than octadecylamine. The difference in molecular structure was possibly the cause for this result.

The determination of the temperature rise of the cooling water was the limiting parameter in calculating the overall heat transfer coefficients. In order to interpret the data by a plot of $1/V^{0.8}$ versus $1/U$, the cooling water must have been turbulent flow. For this condition and for Reynold's Numbers greater than 2500, the cooling water rate must have been greater than 5 lbs./min. At this rate a corresponding temperature rise of approximately 6F° was observed. However, at a flow rate of 16 lbs./min. the corresponding temperature rise was nearly 1.5F°. Since the Beckmann thermometer indicated temperatures with an error not exceeding $\pm$ 0.01C° and the thermometer used to measure the cooling water outlet temperature had a maximum error of $\pm$ 0.1F°, the greatest error for a given temperature rise could have been $\pm$ 0.12F°. The percent error in measuring the cooling water rise was, therefore, 2% and 8% for the lowest and highest flow rates,respectively.

The error involved in measuring the cooling water throughput was estimated to be $\pm$ 0.01 lbs./min. The resulting maximum percent error for measuring the water rate was, therefore, 0.2% at the low velocities.

The overall temperature difference between the steam and the cooling water was of the order of 150F° for all cases studied. The estimated error in measuring the steam temperature was $\pm$ 1.0F°. The percent error introduced by measuring the steam temperature could have been no greater than 0.7%.

Assuming that the errors were all cumlative, the greatest error for the overall heat transfer coefficients resulting from experimental measurement was 8.9%. The corresponding water velocities would have a maximum percent error of 0.2%.

The geometric conditions regarding flow through the test condenser were not clearly understood. The method of calculating the overall coefficients involved the substitution of data into the well known equation, $Q = UA\,\Delta t$, where Δt was taken to be the difference between the steam temperature and the arithmetic-mean temperature of the cooling water. At the present there appears to be no objection to this method of interpreting the results, but a better knowledge of the geometric factors involved is needed for a better understanding of the results.

As stated before, the purpose of this investigation was to study drop-wise condensation as related to normal alkyl amines. With the limitations involved in culling and interpreting data, no absolute relationship between the alkyl amines of various chain lengths and the resulting mode of condensation for each case was established. There was, however, a very good indication that the carbon chain length of the various amines studied had a marked difference in effect on the mode of condensation.

Theoretical Discussion

The effects which cause drop-wise condensation to occur or not to occur are clearly a result of a surface phenomenon and should be studied as such. Nagle and Drew (26) suggested that the formation of tiny stable droplets or the establishment of a uniform film of condensate depends on the molecular forces of attraction between two condensate molecules and between condensate and surface molecules. If cohesion between the condensate molecules is great and adhesion between the condensate and surface is sufficiently small, stable droplets will form since the condensate would be unstable as a film. On this basis, a relationship between interfacial tensions and the wettability of a solid surface was developed. It appears that the above conditions are a result of an interaction of more fundamental nature, namely; molecular orientation of the promoter molecules.

In order that drop-wise condensation may occur, the molecules of the promoting agent must be adsorbed upon the condensing surface and not be washed away with the condensate. This requires that these molecules be composed of two parts, (1) an active group which is capable of being adsorbed upon the surface, and (2) a non-polar part which has only a small affinity for the condensate. As the length of the hydrocarbon chain of the amines increases, the solubility becomes very small (1), but the energy of adhesion remains nearly the same (33). The $-NH_2$ group for the amines and the -COOH group for stearic acid are responsible for the affinity between the promoter molecules and the metallic surface. Figure 7 shows the orientation of a molecular layer of promoter molecules.

If the area occupied by the active group of the promoter molecule is circular, a top view of the orientation would be identical to Figures 8 and 9. Figure 8 represents the closest possible orientation with the least molecules while Figure 9 shows the closest stable orientation with the maximum number of molecules. The area of the metallic surface which is not protected by the filming agent is the surface bounded by the circumferences of the active groups sitting on the surface.

The area taken up by the -COOH group of stearic acid is 22 $\mathring{A}^2$ (33). The corresponding diameter of this group was calculated to be 5.28 $\mathring{A}$. The largest circle which can be inscribed between the molecules was calculated for each case and shown in Figures 8 and 9. The largest diameter for the inscribed circles for the minimum and maximum spacing are 0.80 $\mathring{A}$ and 2.20 $\mathring{A}$ respectively.

The area occupied by some "contaminating" molecules are; N_2 = 13.8 $\mathring{A}^2$, O_2 = 12.1 $\mathring{A}^2$, and CO_2 = 14.1 $\mathring{A}^2$ (33). Since the area enclosed by the inscribed circles having diameters of 0.80 $\mathring{A}$ and 2.20 $\mathring{A}$ are 0.50 $\mathring{A}^2$ and 3.80 $\mathring{A}^2$, respectively, it is not possible for any of the above molecules to reach the metallic surface for the orientations under consideration, unless a much more open arrangement of adsorbed molecules is postulated. A water molecule occupies a greater surface than N_2, O_2, or CO_2 and, therefore, could not be orientated on the metallic surface exposed.

The size relationships for the condensate and the long chain amine promoter group are thought to be the basis for wettability and, therefore, a partial criterion for predicting the mode of condensation.

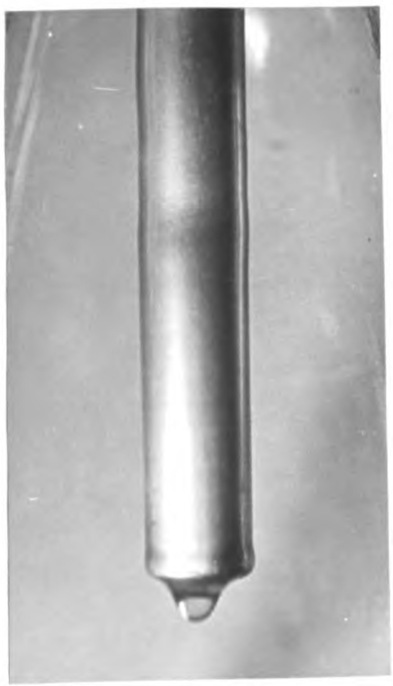


Figure 5-a. Film-Type Condensation

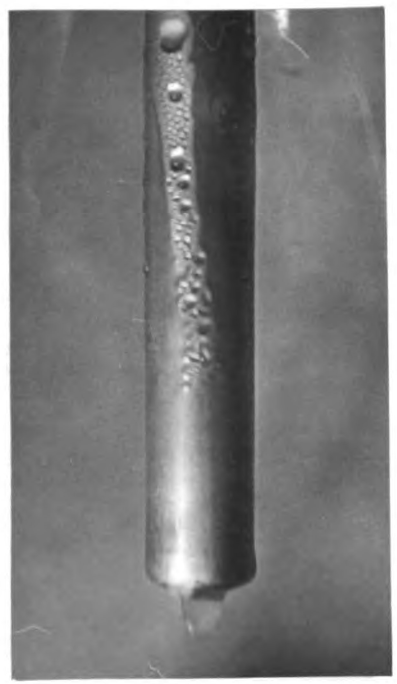


Figure 5-b. Mixed Condensation

Figure 5-c. Mixed Condensation

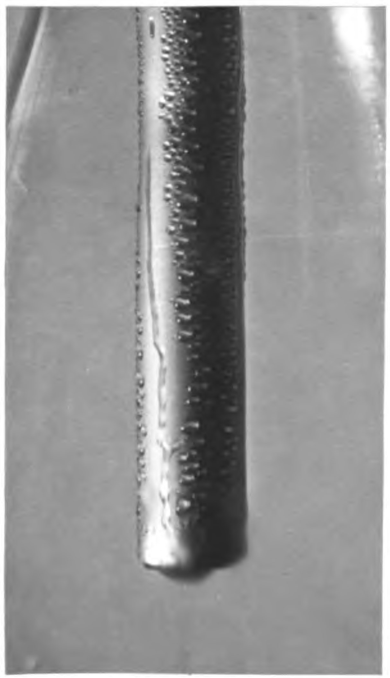


Figure 6-a. Initial Drop Formation in Drop-Wise Cycle

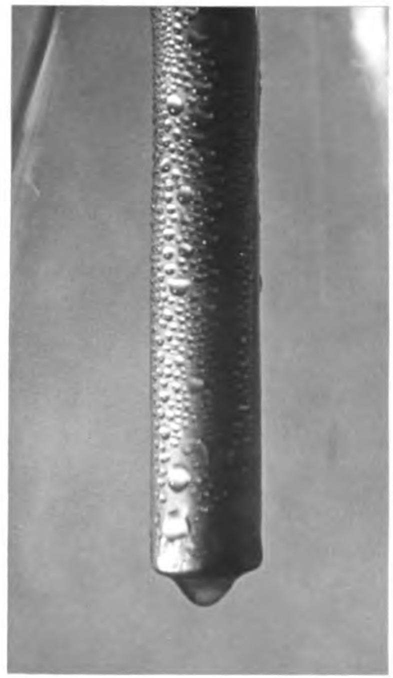


Figure 6-b. Growing Stage of Drops in Drop-Wise Cycle

Figure 6-c. Bare Surface Exposed by Rolling Drops

Figure 7. Orientation of Promoter Molecules on Metallic Surface

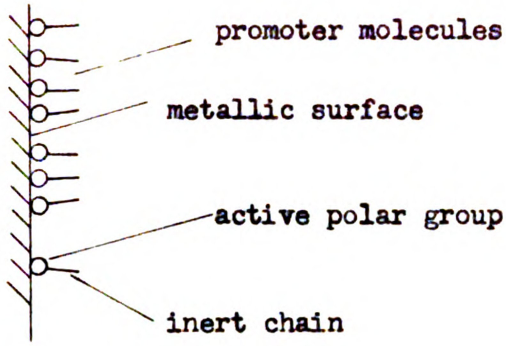
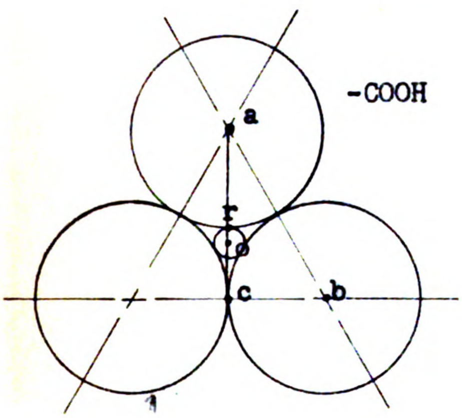


Figure 8. Minimum Molecular Spacing of Circular Groups with Minimum Number



$ab = 5.28\ \text{Å}$

$ac = ab \sin 60° = 4.57\ \text{Å}$

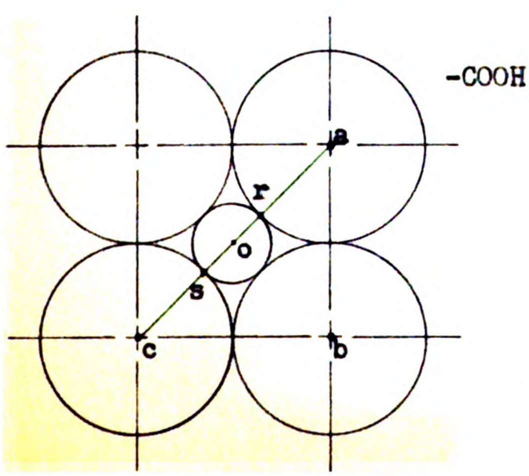
$ao = 2/3\ ac = 3.04\ \text{Å}$

$or = ao - ar = 0.40\ \text{Å}$

$\text{Area of circle (o)} = 3.14\ (0.40)^2$

$= 0.50\ \text{Å}^2$

Figure 9. Minimum Molecular Spacing of Circular Groups with Maximum Stable Number



$ab = 5.28\ \text{Å}$

$ac = 1.414\ (5.28) = 7.48\ \text{Å}$

$rs = ac - (ar + cs)$

$= 7.48 - 5.28 = 2.20\ \text{Å}$

$\text{Area of circle (o)} = 0.786\ (2.20)^2$

$= 3.80\ \text{Å}^2$

CONCLUSIONS

The observed quantitative results of this study indicate that, of the three normal alkyl amines used, the C_{12} amine is responsible for a higher heat transfer coefficient than that shown by the C_{18} amine, while the C_8 amine, likewise, referred to distilled water, actually hinders heat transfer.

APPENDIX A

Sample Calculation

The quantity of heat required to increase the temperature of a given amount of water flowing is equal to the heat transferred through the condensing surface. A mathematical relationship is obtained by equating the expression for the quantity of heat transferred to the quantity of heat absorbed by the water.

$$Q = UA\,(T_s - t) = W\,C_p\,(t_2 - t_1)$$

where W = cooling water rate, lbs./hr.

Q = quantity of heat transferred, Btu./Hr.

U = overall coefficient, Btu./Hr./sq.ft./ °F.

A = surface through which heat flows, sq.ft.

C_p = heat capacity, Btu./lb./°F.

t_1 = cooling water inlet temperature, °F.

t_2 = cooling water outlet temperature, °F.

T_s = steam temperature, °F.

t = temperature of cooling water at any point, °F

(For the calculations to follow an arithmetic mean temperature, $t_a = (t_1 + t_2)/2$, will be used.)

The heat transfer surface is the same for all trials and is calculated from the measured diameter and tube length which are 0.500" and 3.50" respectively.

$$A = \frac{\pi(0.500)}{(12)}\frac{(3.50)}{(12)} = 0.03817 \text{ sq.ft.}$$

Rearranging the above relationships and substituting the numerical values for the heat transfer surface and heat capacity, the following equation from which the overall heat transfer coefficient may be calculated is obtained.

$$U = \frac{60\ W'\ (t_2 - t_1)}{.03817\ (T_s - t_a)}$$

$$U = 1572\ W' \frac{(t_2 - t_1)}{(T_s - t_a)} \quad \text{Btu./Hr./Sq.Ft./°F.}$$

where W' = cooling water rate, lbs./min.

The linear water velocity expressed in ft./sec. was calculated for the corresponding coefficient by knowing the flow rate, the size of the annulus, and the density of water flowing. The inside and outside diameters of the annulus were 0.250" and 0.435" respectively. Since the cooling water temperature was always in the range 54-59°F., the specific volume was taken to be 0.01604 cu.ft./lb. For the system under study, the linear water velocity (V) was related to the flow rate (W') by the following equation:

$$V = \frac{4\ W'}{60 \pi \rho (D_o^2 - D_i^2)}$$

$$V = 0.3868\ W' \text{ ft./sec.}$$

For the purpose of illustration the method of calculating the results obtained by using octadecylamine will be shown.

Run No. 2 $\quad t_1 = 53.78$°F., $t_2 = 55.75$°F., $T_s = 208.2$°F., and $W' = 11.39$ lbs./min.

$$U = 1572\ (11.39) \frac{(55.75 - 53.78)}{(208.2 - 54.8)} = 229.9 \text{ Btu/Hr/Sq.Ft./°F.}$$

$$V = 0.3868\ (11.39) = 4.406 \text{ ft./sec.}$$

The corresponding values for $1/V^{0.8}$ and $1/U \times 10^3$ were determined and are found to be,

$$1/V^{0.8} = 0.306$$

$$1/U \times 10^3 = 4.349$$

This procedure was repeated for the remaining runs. The resulting values are tabulated and the method of least squares is applied to determine the best straight line through the data when $1/V^{0.8}$ versus $1/U \times 10^3$ is plotted (31). The equation for a straight line is y = b + a. The y intercept and slope are a and b respectively. The values for a and b may be calculated from the following equations:

$$a = \frac{\Sigma(x) \cdot \Sigma(xy) - \Sigma(x^2) \cdot \Sigma(y)}{[\Sigma(x)]^2 - n\ \Sigma(x^2)}$$

$$b = \frac{\Sigma(x) \cdot \Sigma(y) - n \cdot \Sigma(xy)}{[\Sigma(x)]^2 - n\ \Sigma(x^2)}$$

let $1/V^{0.8} = x$ and $1/U \times 10^3 = y$.

Run No.	x	y	x^2	xy
1	0.598	4.649	0.358	2.780
2	0.306	4.349	0.094	1.331
3	0.307	4.518	0.094	1.387
4	0.310	4.764	0.096	1.477
5	0.307	4.601	0.094	1.413
6	0.309	4.688	0.095	1.449
7	0.237	3.932	0.056	0.932
8	0.235	4.484	0.055	1.054
9	0.237	4.264	0.056	1.011
10	0.237	4.171	0.056	0.989
11	0.240	3.961	0.058	0.951
12	0.490	4.970	0.240	2.435

Run No.	x	y	x^2	xy
13	0.497	4.777	0.247	2.374
14	0.505	4.734	0.255	2.391
15	0.510	4.935	0.260	2.517
16	0.513	4.866	0.263	2.496
17	0.354	4.432	0.125	1.569
18	0.363	4.649	0.132	1.688
19	0.358	4.688	0.128	1.678
20	0.354	4.541	0.125	1.608
21	0.362	4.484	0.131	1.623
22	0.423	4.444	0.179	1.880
23	0.427	4.786	0.182	2.044
24	0.430	4.821	0.185	2.073
25	0.427	4.793	0.182	2.047
26	0.430	4.823	0.185	2.074
27	0.414	4.060	0.171	1.681
28	0.418	4.496	0.175	1.879
29	0.421	4.574	0.177	1.926
30	0.427	4.675	0.182	1.996

Totals (N) = 30

$(x) = 11.446$

$(y) = 136.929$

$(x^2) = 4.636$

$(xy) = 52.753$

$$a = \frac{(11.446)(52.753) - (4.636)(136.929)}{(11.446)^2 - 30\ (4.636)} = 3.841$$

$$b = \frac{(11.446)(136.929) - 30\ (52.753)}{(11.446)^2 - 30\ (4.636} = 1.896$$

Using these values of a and b a straight line is drawn through the data. Run No's. 1, 4, 6, 7, 11, and 27 deviate a great deal from the calculated line. The above procedure is then repeated omitting runs No's. 1, 4, 6, 7, 11, and 27. The final values of a and b are then 3.837 and 2.012 respectively. Using these values of a and b, the best straight was drawn as shown by Graph 2.

APPENDIX B

Further Discussion of Coil-Type Condenser

The main reason for discontinuing the study using the coil-type condenser was the lack of knowledge about the effective thermal resistance between the wall surface and the actual position of the thermocouple junction. The following is a mathematical treatment showing the limitations of the coil-type condenser using sample data.

Using college steam with no known promoter, the following sample data was obtained on the coil-type condenser. See Figure 4 for section location.

Section No.	Cooling Water Rate, lbs./hr.	Temp. Rise of Water, F°	Average Wall Temp. at 0.15", °F.
1	594	42.5	176.7
2	585	45.5	184.3
3	621	40.5	173.0
4	600	34.0	153.5

Steam Temperature = 240.0°F.

The average temperature drop from the 0.15" location to the inner wall surface was calculated from the following equation:

$$Q = \frac{kA \cdot \Delta t}{x}$$

where Q = heat transferred, Btu./Hr./Sq.Ft.

k = thermal conductivity, Btu./Hr./Sq.Ft./°F/Ft.

Δt = temperature drop through system in question, F°.

A = area perpendicular to the direction of heat flow, sq.ft.

x = distance through which the temperature acts as a driving force, ft.

Rearranging,

$$\Delta t = \frac{Q\,x}{kA}$$

where $x = 0.15/12 = 0.0125$ ft.

$A = 0.385$ sq.ft. (cross-section of 1/4 the total condensing surface.)

The expression for the temperature drop from 0.15" to the wall surface is,

$$\Delta t = 0.0325\ Q/k$$

The effect of various assumed values for the effective thermal conductivity between the 0.15" location and the wall surface is tabulated.

Section Location	Temperature Drops Corresponding To Assumed Conductivities, F°. 40	60	80
1	20.5	13.7	10.3
2	21.6	14.4	10.8
3	20.4	13.6	10.2
4	16.6	11.0	8.3

From these values the average inside wall surface temperature for a given section was calculated. The temperature drop across the steam film was calculated next from which the condensing film coefficient was really determined. The calculated results follow:

Section Location	Steam Side Coefficients Corresponding to Assumed Conductivities, Btu/Hr/Sq.Ft/°F. 40	60	80
1	1983	1322	922
2	2511	1674	1256
3	1835	1223	917
4	1433	955	716

Similar sample data was obtained from the same apparatus using octadecylamine acetate as a promoting agent. The amine was painted on the condensing surface from a water slurry. The excess amine was washed off by allowing steam to pass through the system for approximately 1/2 hour before recording data.

Section No.	Cooling Water Rate, lbs./hr.	Temp. Rise of Water, F°	Average Wall Temp. at 0.15" °F.
1	372	65.1	179.0
2	372	72.8	189.5
3	384	69.8	193.7
4	378	63.8	177.5

Steam Temperature = 243.7°F.

A similar method for calculating the steam side coefficients for corresponding assumed values of the thermal conductivity was used and gave the following results.

Section Location	Steam Side Coefficients Corresponding To Assumed Conductivities, Btu/Hr/Sq.Ft/°F. 40	60	80
1	1829	1219	914
2	2672	1781	1336
3	2942	1961	1471
4	1766	1177	883

These calculations show the necessity for knowing the thermal conductivity with considerable accuracy if steam side coefficients are to be calculated by this method. If the effective conductivity between the junction and the surface could be determined experimentally for each junction, the steam side coefficient at a given section could be calculated.

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