DROPWISE CONDENSATION OF STEAM RELATIVE TO N-ALKYL ALCOHOLS AND ACIDS

Thesis for the Degree of M. S.
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James Edward Packer
1956

This is to certify that the

thesis entitled

Dropwise Condensation of Steam
Relative to N-Alkyl Alcohols and Acids

presented by

James Edward Packer

has been accepted towards fulfillment
of the requirements for

Master of Science **degree in** Chemical Engineering

C. C. DeWitt
Major professor

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By

JAMES EDWARD PACKER

AN ABSTRACT

Submitted to the College of Engineering of Michigan
State University of Agriculture and Applied Science
in partial fulfillment of the requirements
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Department of Chemical Engineering

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Approved: C C DeWitt

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The results are compared by plotting the reciprocal of the overall heat transfer coefficient, U, versus the reciprocal of the eight tenths power of the cooling water velocity, V. The data shows that the alcohols are of no value as dropwise condensation promoters. The normal acids were fairly good promoters; the longest chain length gave the best dropwise condensation. Both the nitrile and the mercaptan were very good promoters. The mercaptan was by far the better. Further study of these compounds is recommended.

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TABLE OF CONTENTS

PAGE

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ACKNOWLEDGEMENT

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INTRODUCTION

INTRODUCTION

The well known phenomenon of condensation takes place when a saturated vapor comes in contact with a surface whose temperature is lower than the dewpoint of the vapor. The vapor, cooled at the surface, undergoes a change of state, and is deposited in the liquid state on the surface. The latent heat evolved during this change in state heats the surface up to a temperature approaching the temperature of the vapor. This basic phenomenon has been put to extensive use in industry wherever steam or other vapors find use either in the generation of power or as a heat transfer medium.

Two modes of condensation, or varying degrees of each, are possible on a metal surface. The first of these is characterized by the formation of a continuous film of liquid upon the surface. The film builds up and runs off continuously. This type has been named "filmwise" or "filmtype" condensation. Pure filmwise condensation is the condition where the entire condensing surface is wetted by a continuous liquid film.

The other kind of condensation is characterized by the formation of tiny droplets. These droplets enlarge both by continued condensation and by merging with other droplets until they form a drop which is large enough to be swept away by its own weight. The falling drop slides downward carrying with it other droplets, sweeping the surface clear in its wake. Tiny droplets re-form on the cleared surface, and the cycle repeats itself. This mode of condensation is called "dropwise" condensation.

It has been found that the rate of heat transfer from the condensing vapor to the surface is dependent upon the type of condensation taking place. Dropwise condensation gives much faster heat transfer than filmwise. The film of water on the condensing surface during filmwise condensation actually insulates the surface, thereby decreasing the driving force tending to heat up the surface. This effect is illustrated in diagram 1.

Dropwise condensation is brought about by a contamination of the metal condensing surface which renders it relatively non-wettable. The contaminant is a compound characterized by having one or more non-polar hydrocarbon groups connected to an active polar group. The polar group attaches itself to the metal surface forming an insoluble mono-molecular film with the non-polar hydrocarbon groups causing the surface to be non-wettable to water (10).

Scope of this Investigation:

The purpose of this study was threefold: first to compare the effects as drop-wise promoters of two groups of compounds of different polarity, namely normal alkyl alcohols and acids; second, to determine the effect of their chain lengths upon over-all heat transfer coefficients;

and third, to break the ground for further study on compounds containing -SH groups and -CN groups.

Figure 1.

Filmwise Condensation

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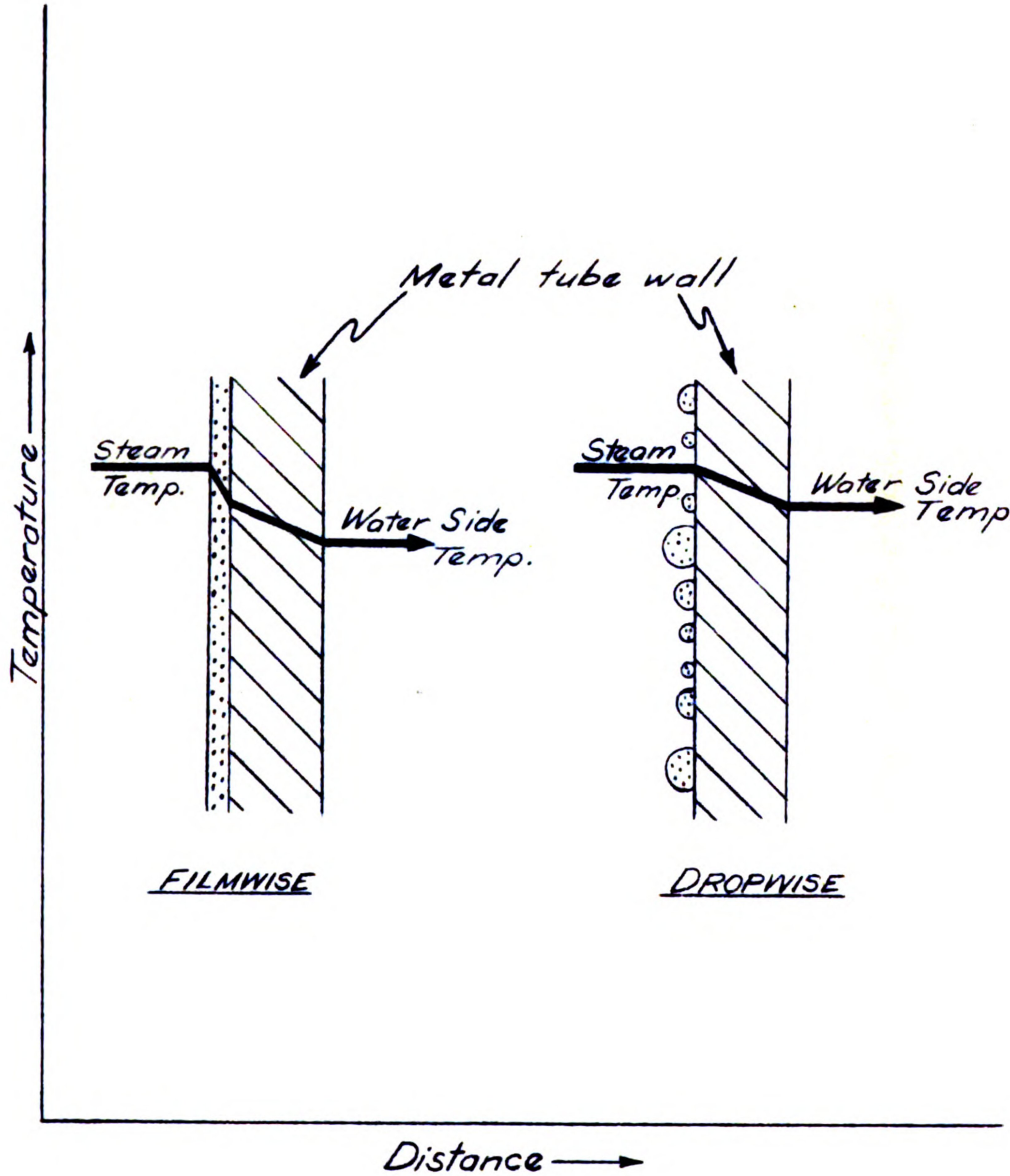
Diagram I.

EFFECT OF MODE OF CONDENSATION ON DRIVING FORCE



HISTORY

HISTORY

The initial study of dropwise condensation was done in Germany in 1930 by Schmidt, Schuring, and Sellschopp (15). They obtained dropwise condensation by condensing steam containing small amounts of an oil on a water cooled disc. They found that the steam side coefficients obtained in this manner were five to seven times as large as the values predicted by the Nusselt equation

While working in a Javanese sugar mill, Spoelstra (17) observed that lower heat transfer coefficients resulted after the cleaning of fouled evaporator tubes. Upon investigation he concluded that a small amount of oil in the steam was condensing on the tubes, giving them a non-wettable surface and hence promoting dropwise condensation. He found that tubes with even a thin scale, if oily, gave higher overall heat transfer coefficients than perfectly clean tubes.

In 1932 another German, Jakob, (8), found that the type of condensation was dependent on the velocity of the condensing steam. He reported that when mixed condensation was taking place at low steam velocities, it changed to filmwise condensation as the velocity was increased.

In 1933 Nagle and Drew (12) published the results of a study in which they qualitatively compared the effects of various promoters on various metal surfaces. They tried such ~~such~~ diverse compounds as beeswax, kerosene, mutton tallow, olive oil, and stearic acid, on surfaces of copper, brass, steel, monel metal, chromium-plated copper, nickel, and chrome-nickel steel. They obtained pure dropwise condensation with some and varying degrees of mixed condensation with others.

Nagle (10) was issued a patent in 1935 as a result of the studies done by him and Drew. The patent covered the use of certain promotors as a means of increasing the over-all heat transfer coefficient and disclosed the conditions necessary for the promotion of dropwise condensation. Briefly, these conditions were: modifying the surface so as to make it non-wettable by the use of a compound having a non-polar hydrocarbon group attached to a polar group, the polar group being adsorbed on the metal surface providing a mono-molecular non-wettable film. Oleic and stearic acids were suggested as compounds which had been used successfully for this purpose.

Nagle and associates (11), made another study of dropwise condensation by the use of a 24" by 2 7/8" vertical, water cooled, copper pipe. They reported steam side coefficients of about 14,000 B.T.u./hr. sq. ft. ^{o}F. Their inadequate system of measuring surface temperatures gave rather erratic results.

Drew, Nagle, and Smith (2) published a paper setting forth the following necessary conditions for promoting dropwise condensation:

(1) clean steam and a clean condensing surface are necessary to obtain pure filmwise condensation for a point of reference,

(2) the cooling surface must be contaminated in some way to effect dropwise condensation,

(3) only agents that firmly attach themselves to the metal surface are effective as dropwise promoters,

(4) dropwise condensation is more likely to occur on a smooth surface than a rough one.

In 1939 Fitzpatrick, Baum, and McAdams (6) used vertical tubes to study the effect of benzyl mercaptan on various metal condenser surfaces. Although they were not able to obtain pure filmwise condensation because of a fatty acid promoter present in the steam, they were able to raise the overall coefficient of 900 B.t.u./ hr. sq. ft. °F. before treatment with the mercaptan to 1650 B.t.u./hr. sq. ft. °F. after treatment.

In 1939 Emmons (3) discussed the mechanism of the promotion of dropwise condensation. He affirmed the theory already advanced by Nagle (10) concerning the attachment of the polar group of the semi-polar molecule to the surface. He also concluded that the number of molecular layers on the surface had very little effect on the degree of dropwise condensation since any additional layers would have to attach to the non-polar ends of the molecules and would be relatively unstable.

Fatica and Katz (5) in 1949 studied the problem from the variables of surface tension, angle of inclination of the condensing surface, contact angle of the droplets, and density of the condensate. They found that all of these factors were important and attempted to correlate them to predict the type of condensation. In 1951 Hampson (7) verified the importance of these factors, but also found that the shape of the condensing surface, rate of runoff, and method of application of promoter were also important.

Erickson (4) and Squire (20) began the work leading to this study at this institution in 1955. They used normal alkyl amines as promoters. The apparatus used in this investigation was a modification of the equipment originally used by them.

APPARATUS AND PROCEDURE

APPARATUS

The condenser used for this study was similar to the finger type condenser originally used by Emmons (3). It consisted of two concentric copper tubes, the outside one being ½ inch in diameter and the inside one ¼ inch. The larger tube was sealed off with solder at its lower end, and the inner tube extended down into it to a distance of 1/16 inch from the sealed end. The tubes were so fitted at the top end that the cooling water could enter the smaller tube, travel down through it, reverse itself and leave through the annulus. For detailed measurements see Figure 2.

The surface of the condenser was polished first with a very fine grade of emery cloth and then scrubbed with Ajax cleanser, a commercial scouring powder containing a very fine abrasive. This scrubbing gave the surface a very smooth, shiny finish.

The steam jacket was a two liter Erlenmeyer flask fitted with a water cooled glass reflux condenser. A Bunsen burner under the flask boiled distilled water which provided the necessary supply of steam. The excess steam was condensed in the reflux condenser which also served as a means of maintaining a pressure as nearly equal to atmospheric as possible. A cork stopper fitted with two holes provided the means of inserting the reflux and finger-type condensers into the flask. The stoppers previously had been boiled in distilled water several times to remove all traces of steam-soluble compounds in the cork.

The inlet cooling water was run directly from a tap into a four liter beaker from whence it was drawn by a model EH-1 Eastern centrifugal pump and pumped through the finger-type condenser. The temperature of the inlet water was measured in the four liter beaker by a Beckman thermometer. Its temperature could be read accurately to 0.01° Centigrade. After being heated in the condenser, the water was pumped into the bottom of a 12 inch by 1½ inch glass overflow tube in which was placed a similar Beckman thermometer. This system gave a very quick thermometer response to any change in outlet temperature.

Flow measurements were made by allowing the outlet water to flow into a four liter beaker for one minute periods and weighing it on a scale which could be read accurately to ½ ounce. The higher flow rates were weighed for 30 second periods. Readings taken in this manner during a single flow rate were quite consistant.

When the project was first begun, an attempt was made to draw cooling water directly from the tap using a ½ inch gate valve to adjust the flow rate. It was soon found, however, that this method was undesirable since the line pressure varied intermittently from 45 p.s.i. to 60 p.s.i. The method previously described of drawing from a constant level overflow container was then tried and gave the desired results. The adjustment of flow rate was made by a C-clamp on the downsteam side of the pump.

The tubing used in this apparatus was heavy walled rubber tubing with a ½ inch inside diameter and a 3/4 inch outside diameter.

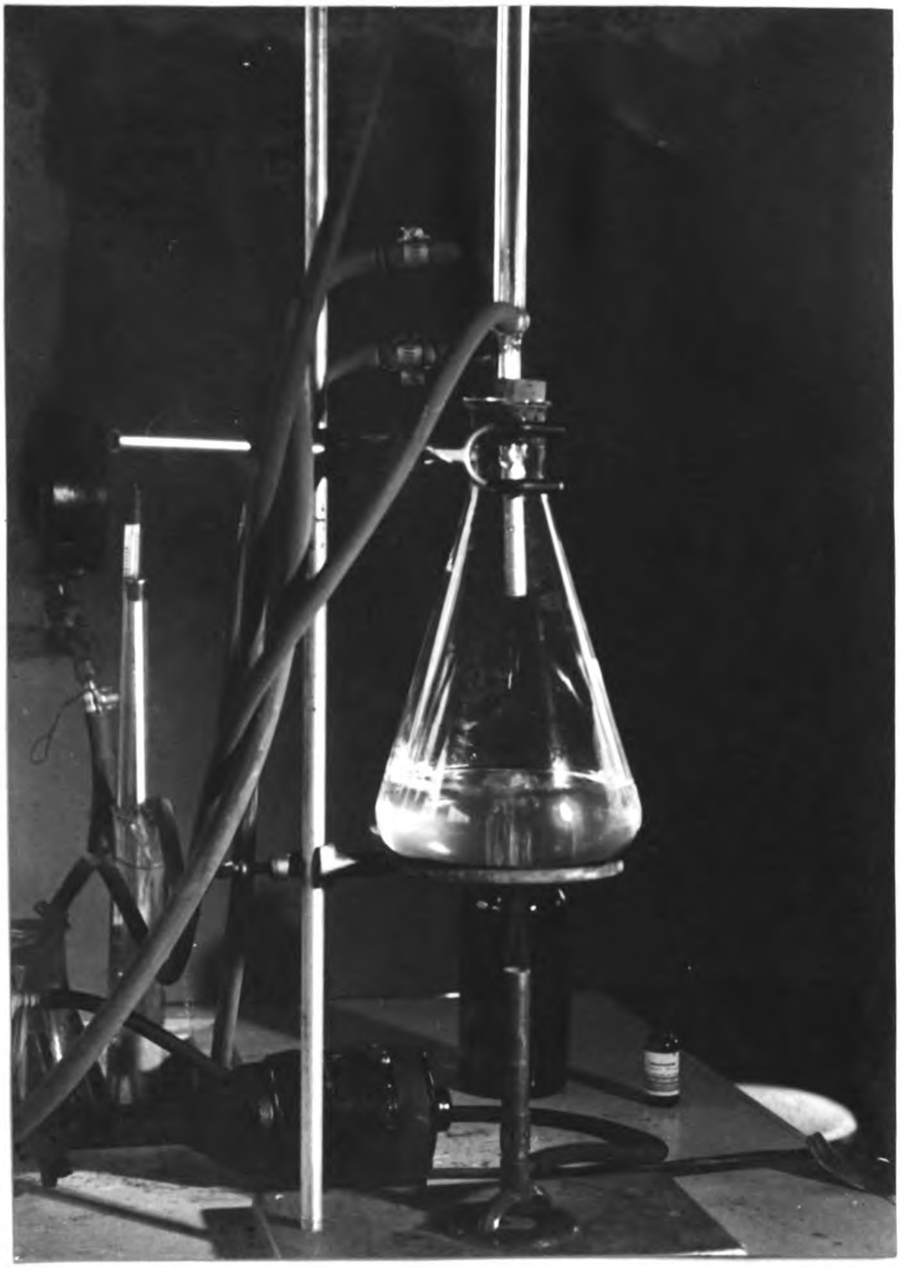
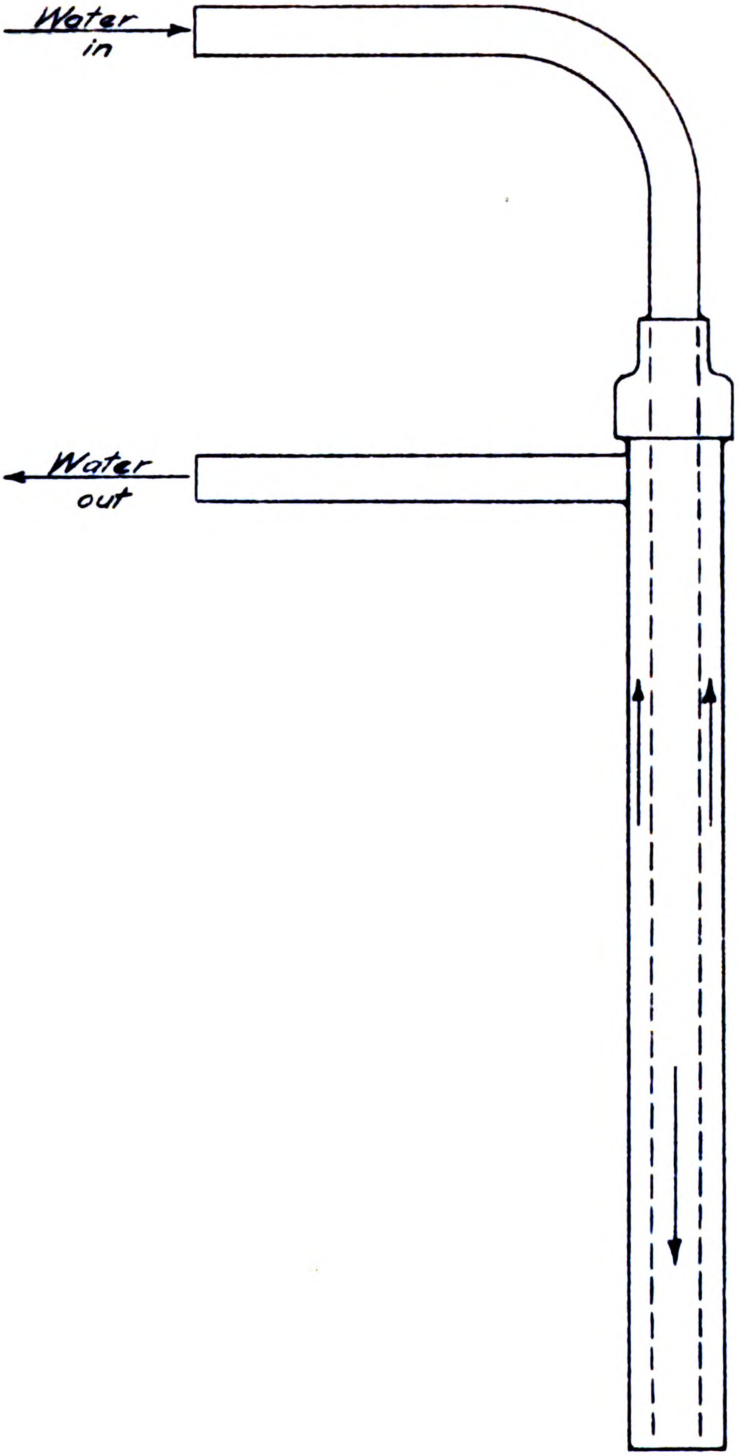


Figure 3.

Finger Type Condenser Apparatus

Diagram 2.

FINGER-TYPE CONDENSER
(Actual Size)



PROCEDURE

In making a normal run the first step was the cleaning of the copper condenser. It was scrubbed thoroughly with Ajax Cleanser and hot water, rinsed in hot water, and rescrubbed until the hot water would form a continous film on the entire surface of the condenser. It was then placed in a beaker of boiling distilled water and left there approximately ten minutes. Next it was scrubbed again, rinsed with distilled water and submerged in distilled water until ready for use.

The cork was extracted several times in boiling distilled water until it would no longer color the boiling water. The glass condenser and the two liter flask were scrubbed thoroughly with brushes using hot water and a strong detergent. They were rinsed first with hot water and then several times with distilled water. They were considered clean when distilled water would leave a continuous film on their surfaces when they were rinsed with it. This cleanliness was considered very critical to the success of the experiments.

Approximately one liter of distilled water was placed in the Erlenmeyer flask along with several glass beads and approximately .005 gram of the compound to be studied. The glass beads previously had been boiled in distilled water. The cork with the two condensers inserted in it was placed in the top, the rubber tubings were attached and the run was ready to begin. The glass reflux condenser was inserted just far enough into the cork so that its opening was not below the bottom of the cork. The finger-type condenser extended exactly 3.50 inches below the bottom of the cork.

The pump was started and the flow adjusted to the desired rate. The water was heated to boiling and allowed to reflux enough so that one drop of condensate came out of the reflux condenser every three or four seconds. The heat was adjusted to give this amount of reflux in every run in an attempt to maintain a constant source of steam as an equal basis of comparison of results.

When the outlet temperature leveled off, the readings were begun. First the inlet and outlet temperatures were read and recorded and then a flow rate was taken in the manner previously described. Three such readings were taken before changing the flow rate. Three separate flow rates were run for each compound. The only exception to this rule was in the case of water in which several rates were used.

The method of handling this data is shown by a sample calculation in Appendix A. The over-all heat transfer coefficients were calculated and plotted as $\frac{1}{U}$ vs. $\frac{1}{V^{.8}}$. This method of correlation was devised by Wilson (19).

A steam thermometer placed in the cork next to the finger-type condenser was tried at first, but proved to be useless because slight variations in pressure due to the irregular boiling caused the steam temperature to fluctuate about ½ to 3/4 of a centigrade degree. Therefore the steam temperature was determined by the barometric pressure. A graph of saturation pressure vs. temperature was drawn from which the steam temperatures for a given barometer reading could be easily read. The barometer readings were obtained from the U. S. Weather Bureau in East Lansing (station pressures).

CONTROL - DISTILLED WATER

A. Observed Data:

Rdg. No.	Water Rate (#/min.)	Inlet Temp. (°F.)	Outlet Temp. (°F.)	Steam Temp. (°F.)
1.	4.25	51.94	54.74	210.17
2.	4.13	52.00	54.86	"
3.	4.13	52.07	54.99	"
4.	4.13	52.04	54.97	"
5.	4.19	52.14	54.94	"
6.	4.19	52.18	55.01	"
7.	4.88	52.47	55.03	210.00
8.	4.88	52.52	55.15	"
9.	5.06	52.58	55.13	"
10.	5.00	52.58	55.21	"
11.	5.06	52.54	55.22	"
12.	5.00	52.50	55.17	"
13.	8.31	52.15	54.01	211.65
14.	8.25	52.13	54.01	"
15.	8.19	52.13	54.06	"
16.	8.25	52.11	54.06	"
17.	8.25	52.09	53.97	"
18.	8.25	52.07	53.88	"
19.	8.25	52.06	53.92	"
20.	8.19	52.06	53.92	"

CONTROL - DISTILLED WATER
(Continued)

B. Calculated Data:

Rdg. No.	Water Rate (ft./sec.)	U (Btu/hr.ft.^{2}°F.)	$\frac{1}{U} \times 10^5$	$\frac{1}{V^{.8}} \times 10^3$
1.	1.64	119.35	838	673
2.	1.60	118.54	844	687
3.	1.60	121.10	826	687
4.	1.60	121.50	823	687
5.	1.62	117.82	849	680
6.	1.62	119.12	839	680
7.	1.89	125.59	796	601
8.	1.89	129.28	774	601
9.	1.96	129.90	770	584
10.	1.93	132.51	755	591
11.	1.96	136.44	732	584
12.	1.93	134.54	743	591
13.	3.21	153.28	652	393
14.	3.19	153.85	650	395
15.	3.19	156.82	637	397
16.	3.19	159.59	627	395
17.	3.19	153.81	650	395
18.	3.19	152.13	675	395
19.	3.19	152.13	657	395
20.	3.17	151.03	662	397

OCTANOIC ACID

A. Observed Data:

Rdg. No.	Water Rate (#/min.)	Inlet Remp. (°F.)	Outlet Temp. (°F.)	Steam Temp. (°F.)
1.	6.38	52.90	55.64	209.97
2.	"	53.08	55.91	"
3.	"	53.04	55.80	"
4.	2.28	52.90	60.38	"
5.	"	52.88	60.49	"
6.	"	52.88	60.34	"
7.	14.88	52.54	53.66	"
8.	"	52.49	53.70	"
9.	"	52.54	53.68	"

B. Calculated Data:

Rdg. No.	Water Rate (ft./sec.)	U (Btu/hr.ft.^{2}°F.)	$\frac{1}{U} \times 10^5$	$\frac{1}{V^{.8}} \times 10^3$
1.	2.47	176.61	566	485
2.	"	182.67	547	"
3.	"	178.07	562	"
4.	.88	174.96	572	1107
5.	.89	180.39	554	1097
6.	"	176.75	566	"
7.	5.76	167.11	598	246
8.	"	180.53	554	"
9.	"	170.11	588	"

LAURIC ACID

A. Observed Data:

Rdg. No.	Water Rate (#/min.)	Inlet Temp. (°F.)	Outlet Temp. (°F.)	Steam Temp. (°F.)
1.	6.62	52.54	54.73	209.97
2.	"	52.56	54.67	"
3.	"	52.52	54.62	"
4.	2.75	52.43	57.41	"
5.	"	52.40	57.46	"
6.	"	52.38	57.35	"
7.	17.75	52.20	53.02	"
8.	"	52.16	53.02	"
9.	"	52.16	53.02	"

B. Calculated Data:

Rdg. No.	Water Rate (ft./sec.)	U (Btu/hr.ft.^{2}°F.)	$\frac{1}{U} \times 10^5$	$\frac{1}{V^{.8}} \times 10^3$
1.	2.56	145.88	685	472
2.	"	140.53	712	"
3.	"	139.82	715	"
4.	1.06	138.94	720	1048
5.	"	141.18	708	"
6.	"	138.60	722	"
7.	6.86	145.49	687	467
8.	"	152.57	655	"
9.	"	152.57	655	"

STEARIC ACID
Run No. 1.

Observed Data:

Rdg. No.	Water Rate (#/min.)	Inlet Temp. (°F.)	Outlet Temp. (°F.)	Steam Temp. (°F.)
1.	4.00	54.50	58.47	210.27
2.	"	54.36	58.25	"
3.	"	54.23	58.18	"
4.	8.19	54.13	55.82	"
5.	"	54.02	55.79	"
6.	"	53.96	55.70	"
7.	20.5	53.71	54.31	"
8.	"	53.62	54.22	"
9.	"	53.60	54.27	"

Calculated Data:

Rdg. No.	Water Rate (ft./sec.)	U (Btu/hr.ft.^{2}°F.)	$\frac{1}{U} \times 10^5$	$\frac{1}{V^{.8}} \times 10^3$
1.	1.55	162.42	615	704
2.	"	158.96	629	"
3.	"	161.31	620	"
4.	3.17	140.20	713	397
5.	"	146.76	681	"
6.	"	144.21	693	"
7.	7.93	123.82	808	525
8.	"	123.75	808	"
9.	"	138.20	724	"

STEARIC ACID
Run No. 2.

A. Observed Data:

Rdg. No.	Water Rate (#/min.)	Inlet Temp. (°F.)	Outlet Temp. (°F.)	Steam Temp. (°F.)
1.	4.34	54.83	58.49	209.52
2.	4.38	54.81	58.40	"
3.	"	54.86	58.43	"
4.	5.81	54.94	57.35	"
5.	"	54.92	57.30	"
6.	"	54.92	57.28	"
7.	12.88	55.15	56.13	"
8.	"	55.22	56.11	"
9.	"	55.26	56.22	"

B. Calculated Data:

Rdg. No.	Water Rate (ft./sec.)	U (Btu/hr.ft.^{2} °F.)	$\frac{1}{U}$ x10^5	$\frac{1}{V^{.8}}$ x 10^3
1.	1.68	163.46	612	662
2.	"	161.74	618	"
3.	"	160.68	622	"
4.	2.25	143.41	697	523
5.	"	140.41	712	"
6.	"	140.40	712	"
7.	4.98	128.86	776	276
8.	"	117.04	854	"
9.	"	126.31	792	"

STEARIC ACID
Run No. 3.

A. Observed Data:

Rdg. No.	Water Rate (#/min.)	Inlet Temp. (°F.)	Outlet Temp (°F.)	Steam Temp. (°F.)
1.	15.81	54.81	56.40	210.62
2.	"	54.85	56.42	"
3.	"	54.85	56.36	"
4.	6.59	54.79	58.29	"
5.	"	54.74	58.38	"
6.	"	54.70	58.36	"
7.	4.19	54.84	60.27	"
8.	"	54.83	60.59	"
9.	"	54.83	60.49	"

B. Calculated Data:

Rdg. No.	Water Rate (ft./sec.)	U (Btu/hr.ft.^{2}°F.)	$\frac{1}{U} \times 10^5$	$\frac{1}{V^{.8}} \times 10^3$
1.	6.12	255.08	392	235
2.	"	251.93	397	"
3.	"	242.24	413	"
4.	2.55	235.47	425	473
5.	"	244.92	408	"
6.	"	246.22	406	"
7.	1.62	235.35	425	680
8.	"	248.29	403	"
9.	"	243.88	410	"

n-OCTANOL

A. Observed Data:

Rdg. No.	Water Rate (#/min.)	Inlet Temp. ($^\circ$F.)	Outlet Temp. ($^\circ$F.)	Steam Temp. ($^\circ$F.)
1.	15.06	51.66	52.66	210.71
2.	15.00	51.53	52.44	"
3.	"	51.43	52.40	"
4.	5.94	51.52	54.38	"
5.	"	51.46	54.24	"
6.	"	51.48	54.31	"
7.	2.59	51.59	58.11	"
8.	2.62	51.53	57.66	"
9.	"	51.46	57.70	"

B. Calculated Data:

Rdg. No.	Water Rate (ft./sec.)	U (Btu/hr.ft.^{2} $^\circ$F.)	$\frac{1}{U} \times 10^5$	$\frac{1}{V^{.8}} \times 10^3$
1.	5.82	149.41	669	244
2.	5.80	135.27	739	245
3.	"	144.13	694	"
4.	2.30	169.39	590	513
5.	"	164.55	608	"
6.	"	167.56	597	"
7.	1.00	170.43	587	100
8.	1.01	161.83	618	"
9.	"	164.71	607	"

n-DODECANOL

A. Observed Data:

Rdg. No.	Water Rate (#/min.)	Inlet Temp. ($^{\circ}$F.)	Outlet Temp. ($^{\circ}$F.)	Steam Temp. ($^{\circ}$F.)
1.	7.12	53.06	55.23	210.40
2.	7.19	53.06	55.21	"
3.	"	53.10	55.28	"
4.	2.53	53.24	59.41	"
5.	2.56	53.24	59.28	"
6.	"	53.24	59.24	"
7.	15.38	52.97	53.93	"
8.	"	52.87	53.83	"
9.	"	52.85	53.81	"

B. Calculated Data:

Rdg. No.	Water Rate (ft./sec.)	U Btu/hr.ft.^{2} $^{\circ}$F.)	$\frac{1}{U}$ x 10^{5}	$\frac{1}{V^{.8}}$ x 10^{3}
1.	2.75	155.53	643	445
2.	2.78	155.61	643	442
3.	"	157.83	634	"
4.	0.98	159.36	628	1016
5.	0.99	157.79	634	1008
6.	"	156.73	638	"
7.	5.95	147.98	676	240
8.	"	147.88	"	"
9.	"	147.86	"	"

1-OCTADECANOL

A. Observed Data:

Rdg. No.	Water Rate (#/min.)	Inlet Temp. (°F.)	Outlet Temp. (°F.)	Steam Temp. (°F.)
1.	5.50	52.99	55.14	210.07
2.	"	52.97	55.12	"
3.	"	52.96	55.17	"
4.	2.75	52.99	57.41	"
5.	"	53.01	57.37	"
6.	"	53.03	57.32	"
7.	13.25	53.10	54.19	"
8.	"	53.03	57.32	"
9.	"	53.05	54.27	"

B. Calculated Data:

Rdg. No.	Water Rate (ft./sec.)	U Btu/hr.ft.^{2}°F.)	$\frac{1}{U} \times 10^{5}$	$\frac{1}{V.8} \times 10^{3}$
1.	2.13	119.23	839	546
2.	"	119.21	"	"
3.	"	122.55	816	"
4.	1.06	123.46	810	954
5.	"	121.77	821	"
6.	"	119.81	835	"
7.	5.12	145.23	688	271
8.	"	145.24	"	"
9.	"	162.57	615	"

TRIDECANENITRILE

A. Observed Data:

Rdg. No.	Water Rate (#/min.)	Inlet Temp. (°F.)	Outlet Temp. (°F.)	Steam Temp. (°F.)
1.	13.75	53.42	55.14	209.77
2.	"	53.44	55.05	"
3.	"	53.48	55.00	"
4.	6.44	53.30	56.40	"
5.	"	53.32	56.44	"
6.	"	53.32	56.49	"
7.	4.12	53.28	57.93	"
8.	"	53.46	58.02	"
9.	"	53.49	58.05	"

B. Calculated Data:

Rdg. No	Water Rate (ft./sec)	U Btu/hr.ft.^{2}°F.)	$\frac{1}{U} \times 10^{5}$	$\frac{1}{V^{.8}} \times 10^{3}$
1.	5.32	239.25	418	262
2.	"	223.89	447	"
3.	"	211.38	473	"
4.	2.49	202.71	493	483
5.	"	204.05	490	"
6.	"	207.35	482	"
7.	1.59	195.47	512	690
8.	"	191.86	521	"
9.	"	193.14	518	"

1-DODECANETHIOL

A. Observed Data:

Rdg. No.	Water Rate (#/min.)	Inlet Temp. (°F.)	Outlet Temp. (°F.)	Steam Temp. (°F.)
1.	16.75	53.89	55.37	211.08
2.	"	53.87	55.50	"
3.	"	53.87	55.46	"
4.	6.56	53.64	57.07	"
5.	"	53.68	57.14	"
6.	"	53.71	57.30	"
7.	4.00	53.73	59.39	"
8.	"	53.73	59.19	"
9.	"	53.73	59.30	"

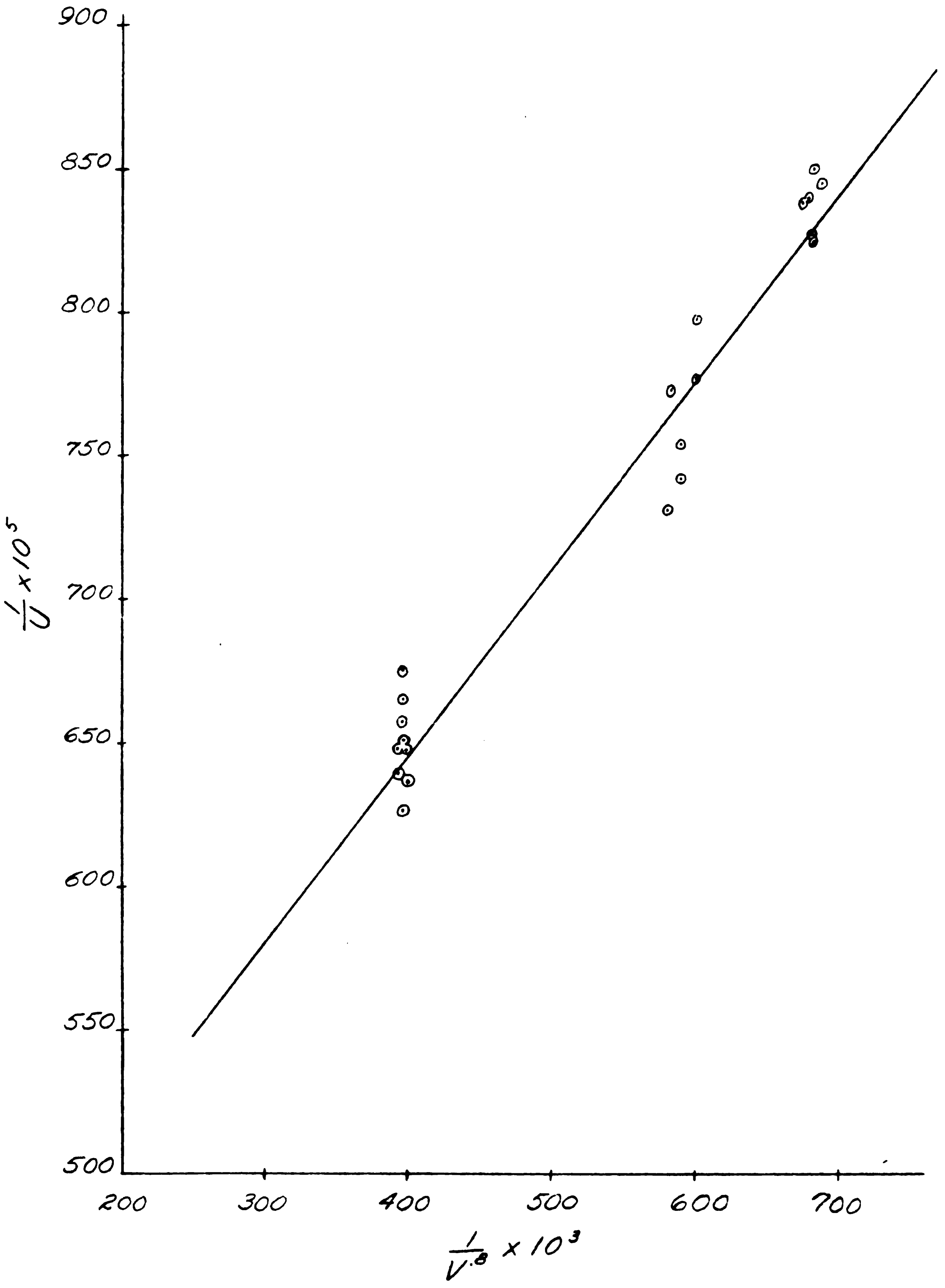
B. Calculated Data:

Rdg. No.	Water Rate (ft./sec.)	U (Btu/hr.ft.^{2}°F.)	$\frac{1}{U} \times 10^5$	$\frac{1}{V^{.8}} \times 10^3$
1.	6.48	249.25	401	224
2.	"	274.60	364	"
3.	"	267.60	373	"
4.	2.54	227.29	440	474
5.	"	228.69	437	"
6.	"	238.11	420	"
7.	1.55	230.47	434	704
8.	"	222.18	450	"
9.	"	226.75	441	"

RESULTS

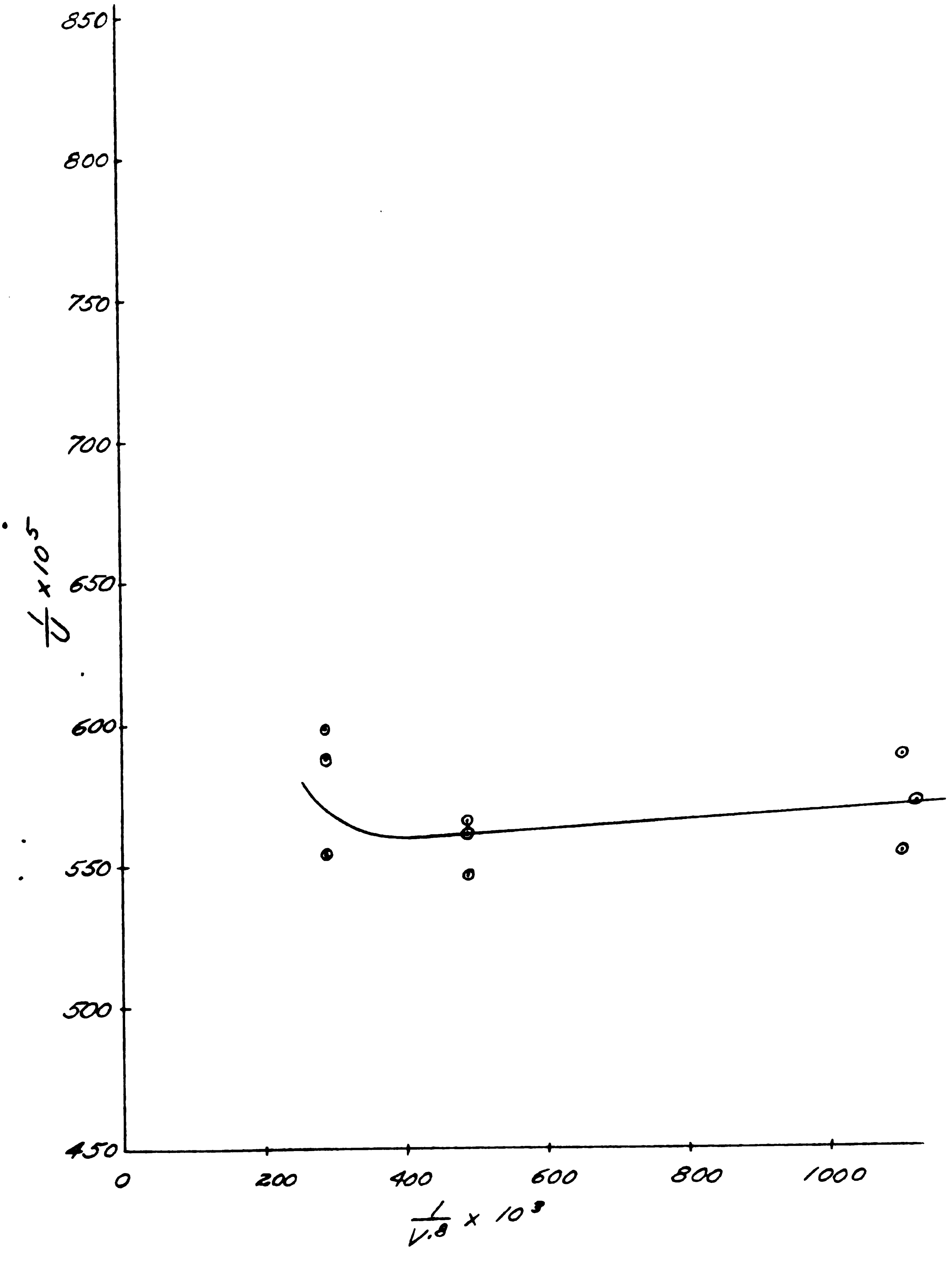
Graph No. 1.

Control- Distilled Water

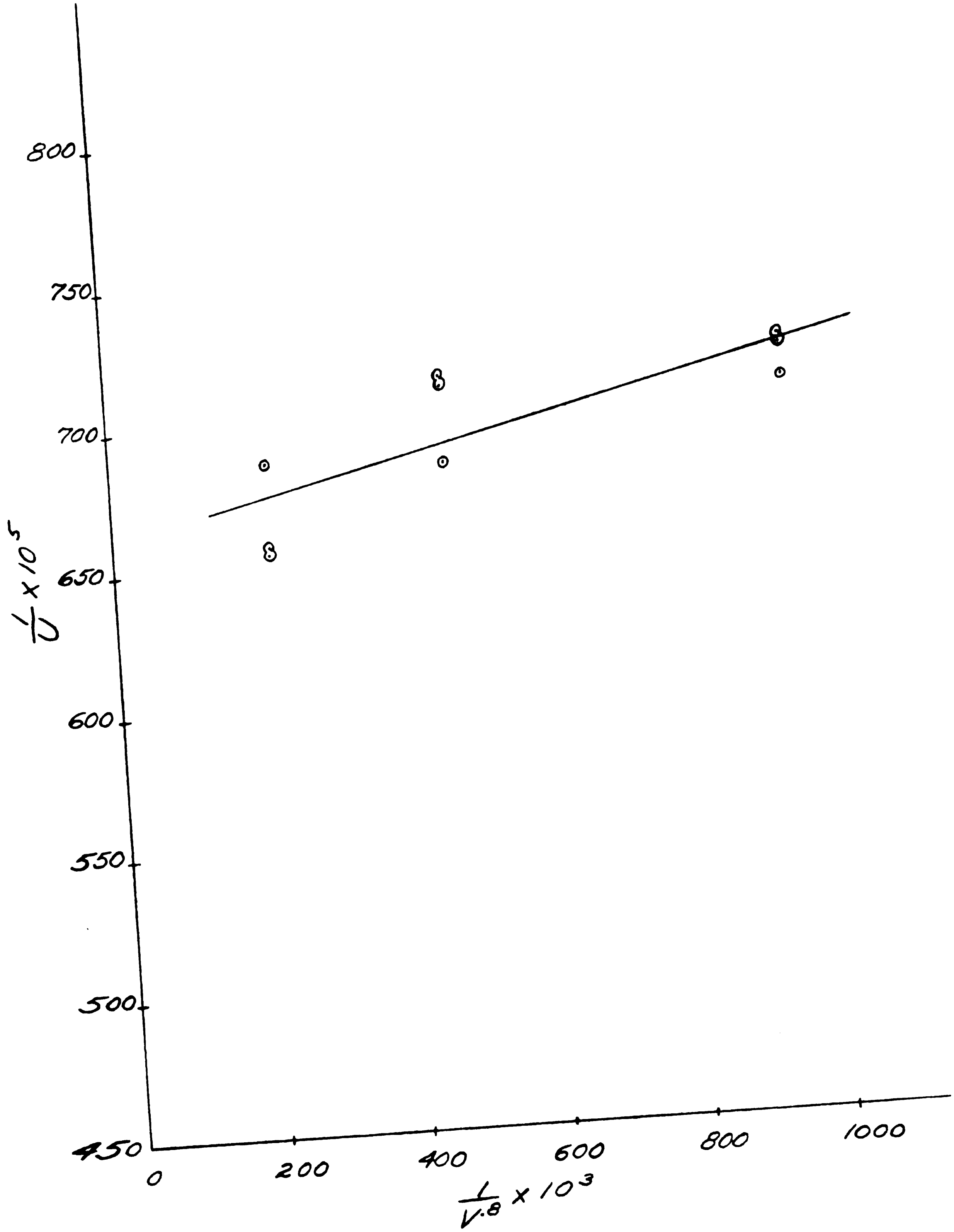


Graph No. 2.

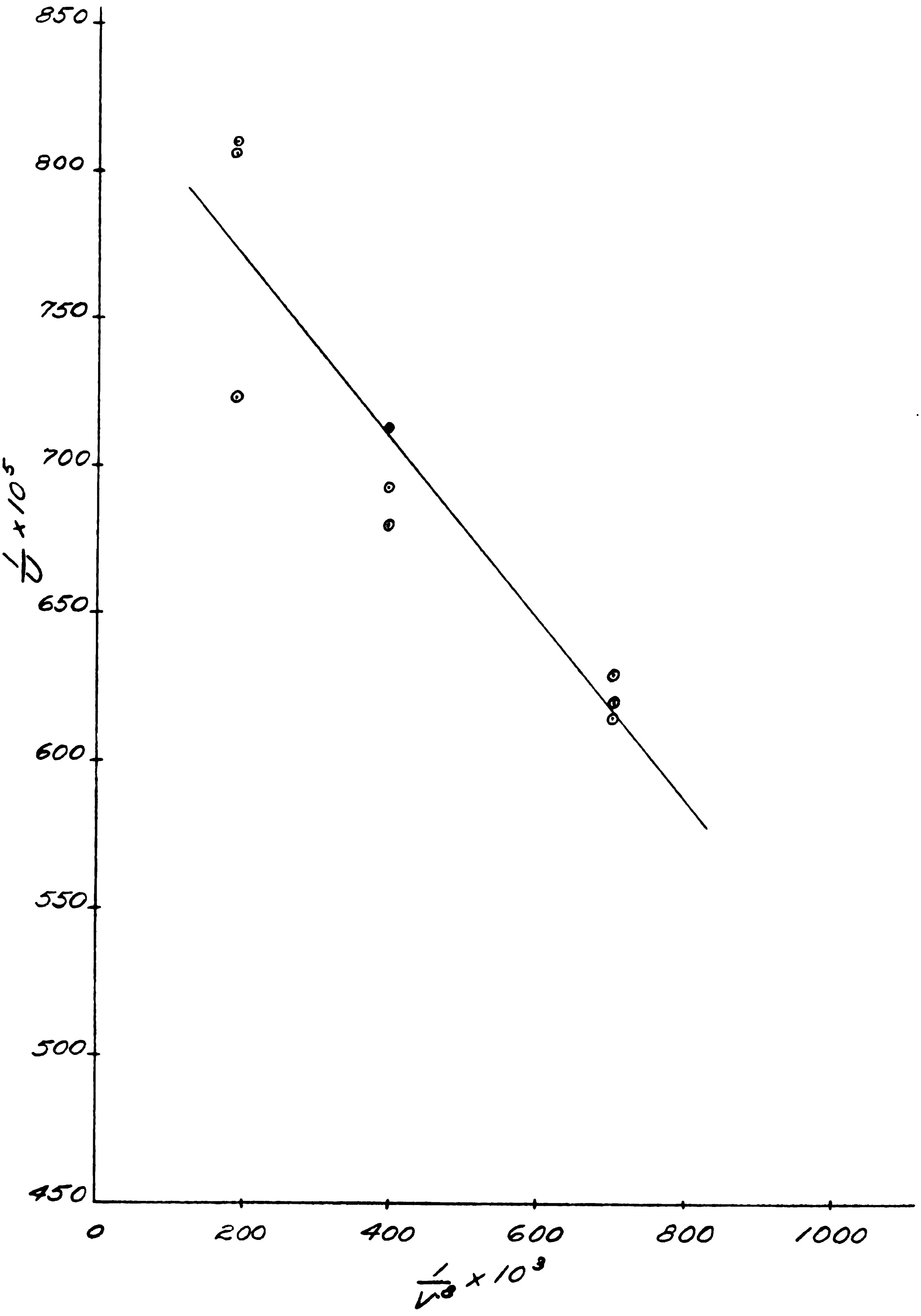
OCTANOIC ACID



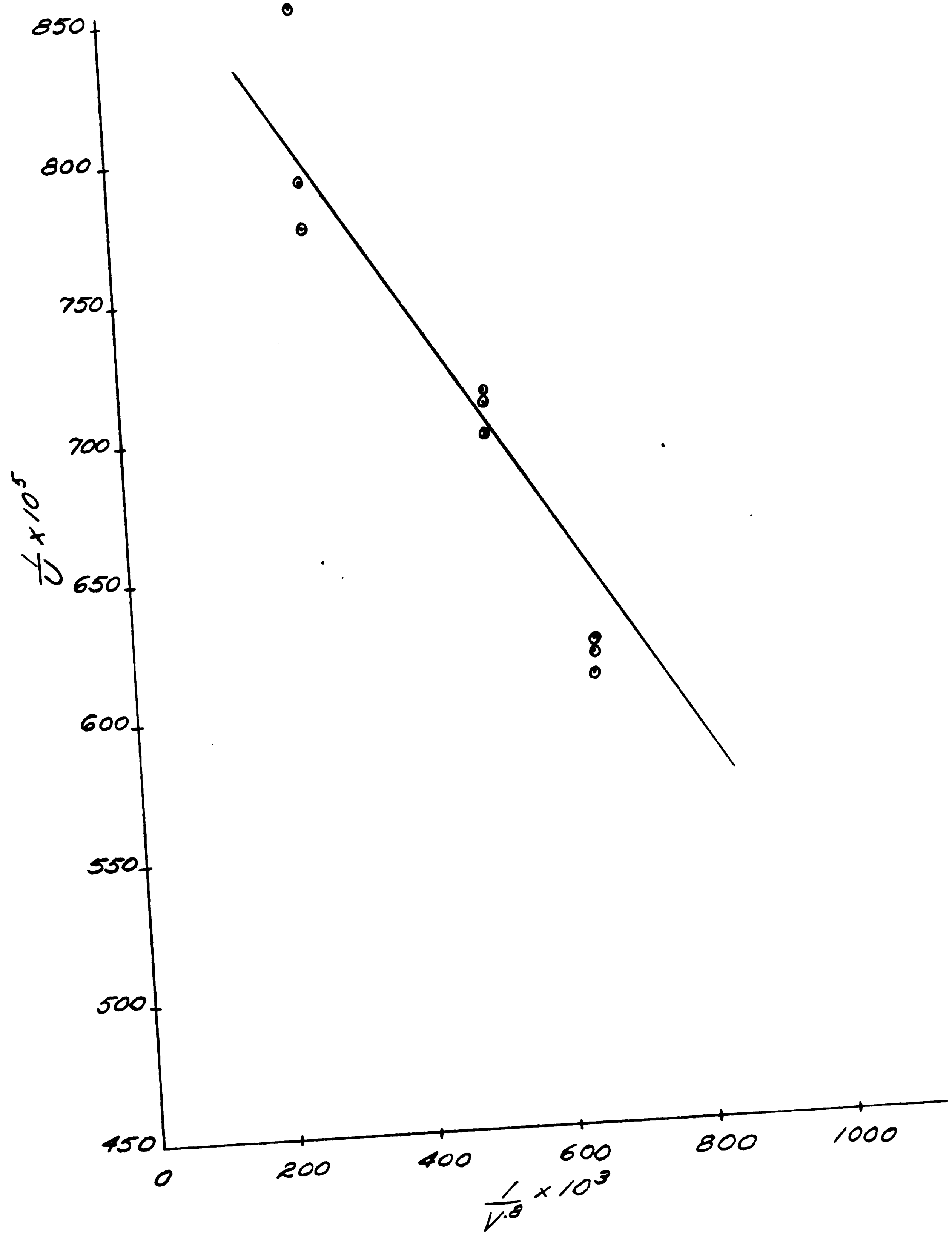
Graph No. 3.
LAURIC ACID



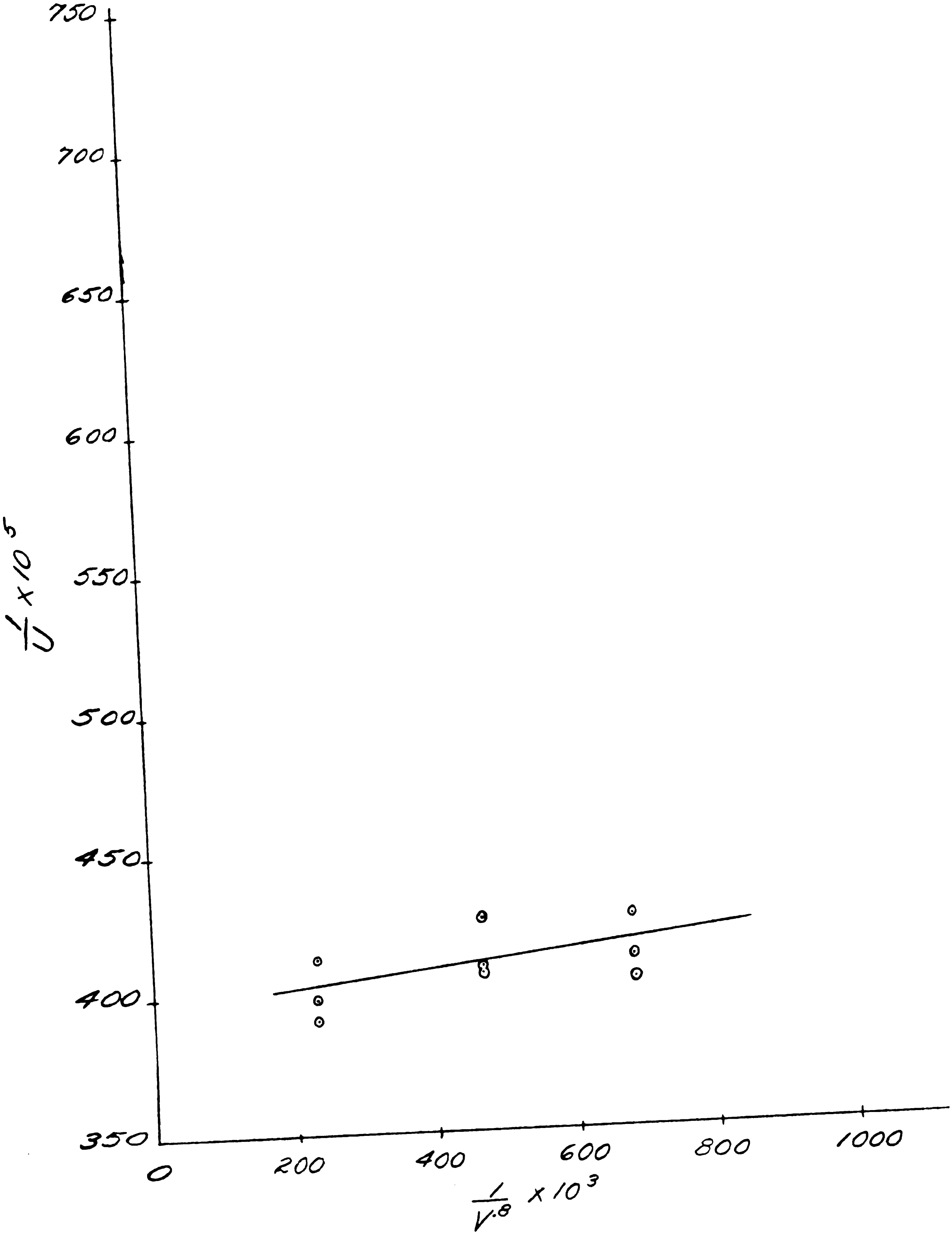
Graph No. 4.
STEARIC ACID – Run 1.



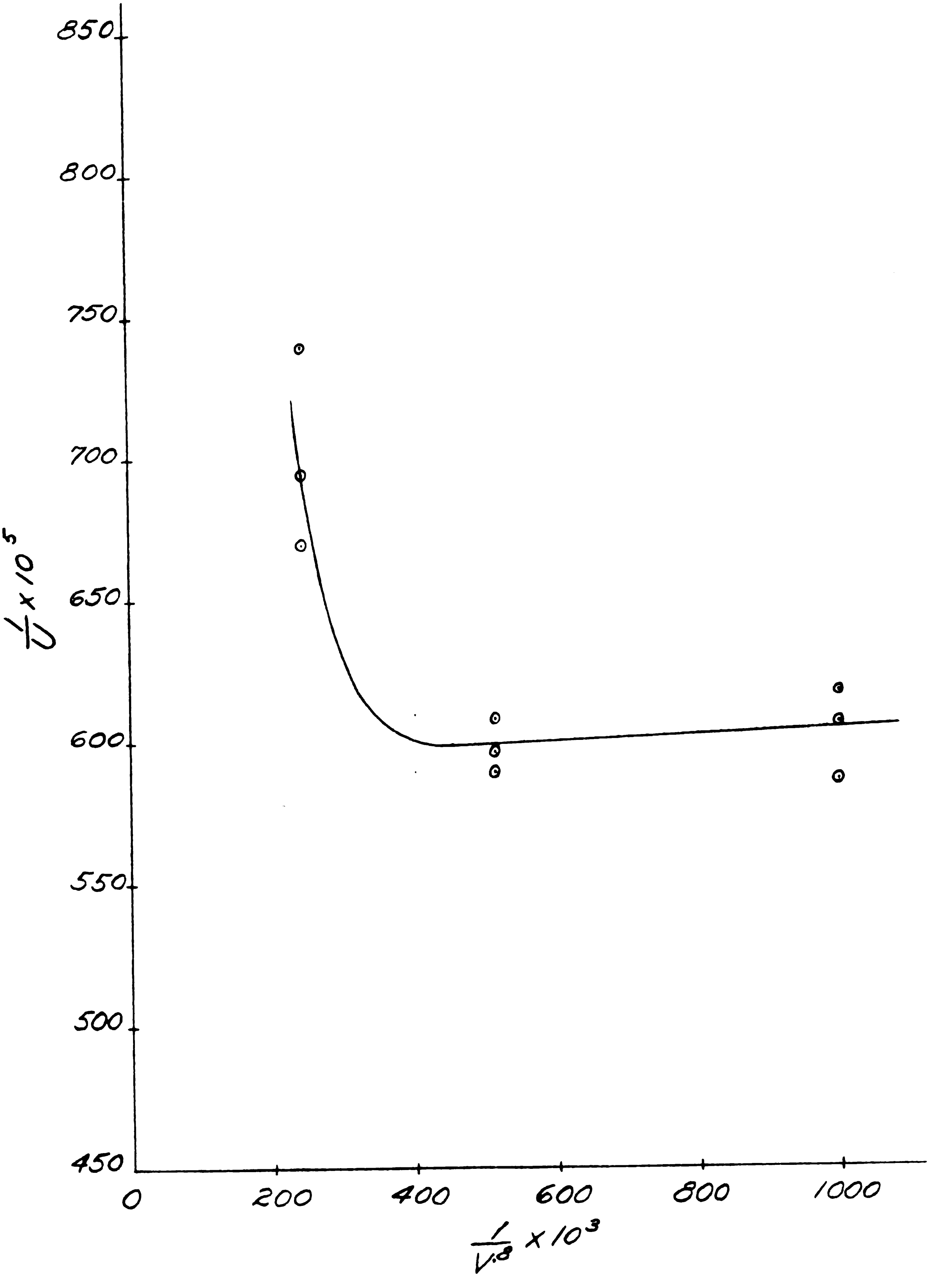
Graph No. 5.
STEARIC ACID - Run 2.



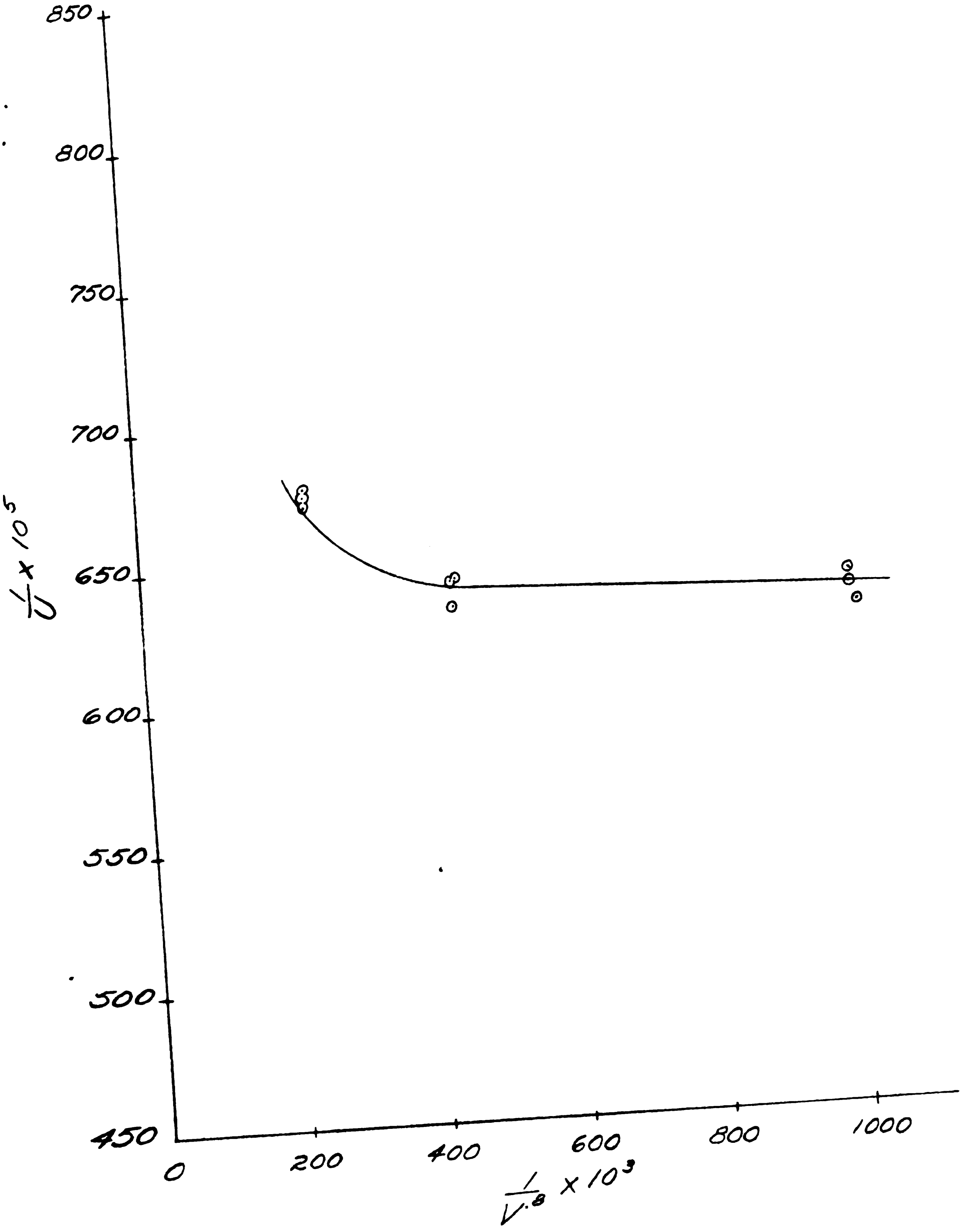
Graph No. 6.
STEARIC ACID - Run 3



Graph No. 7.
n- OCTYL ALCOHOL

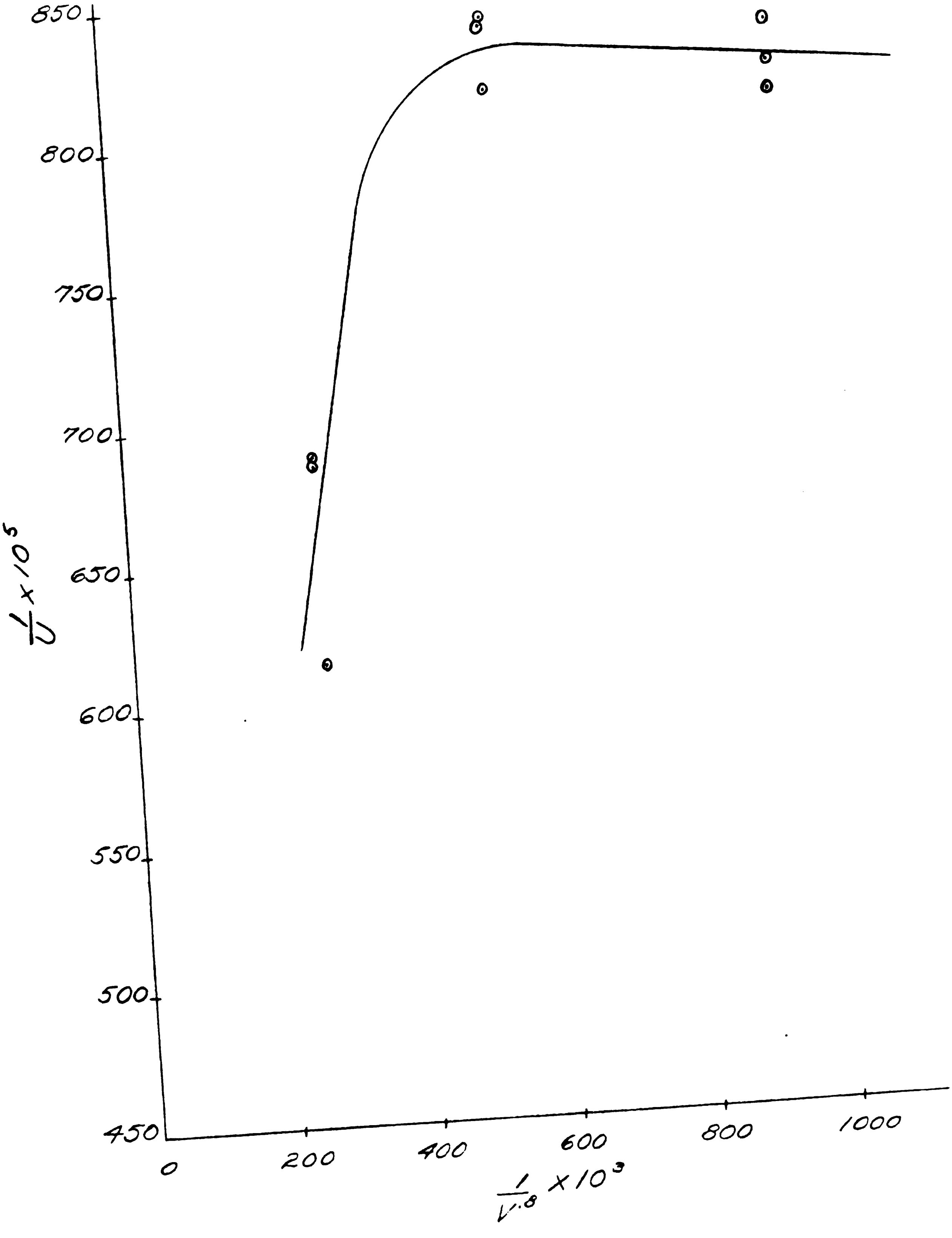


Graph No. 8.
DODECYL ALCOHOL



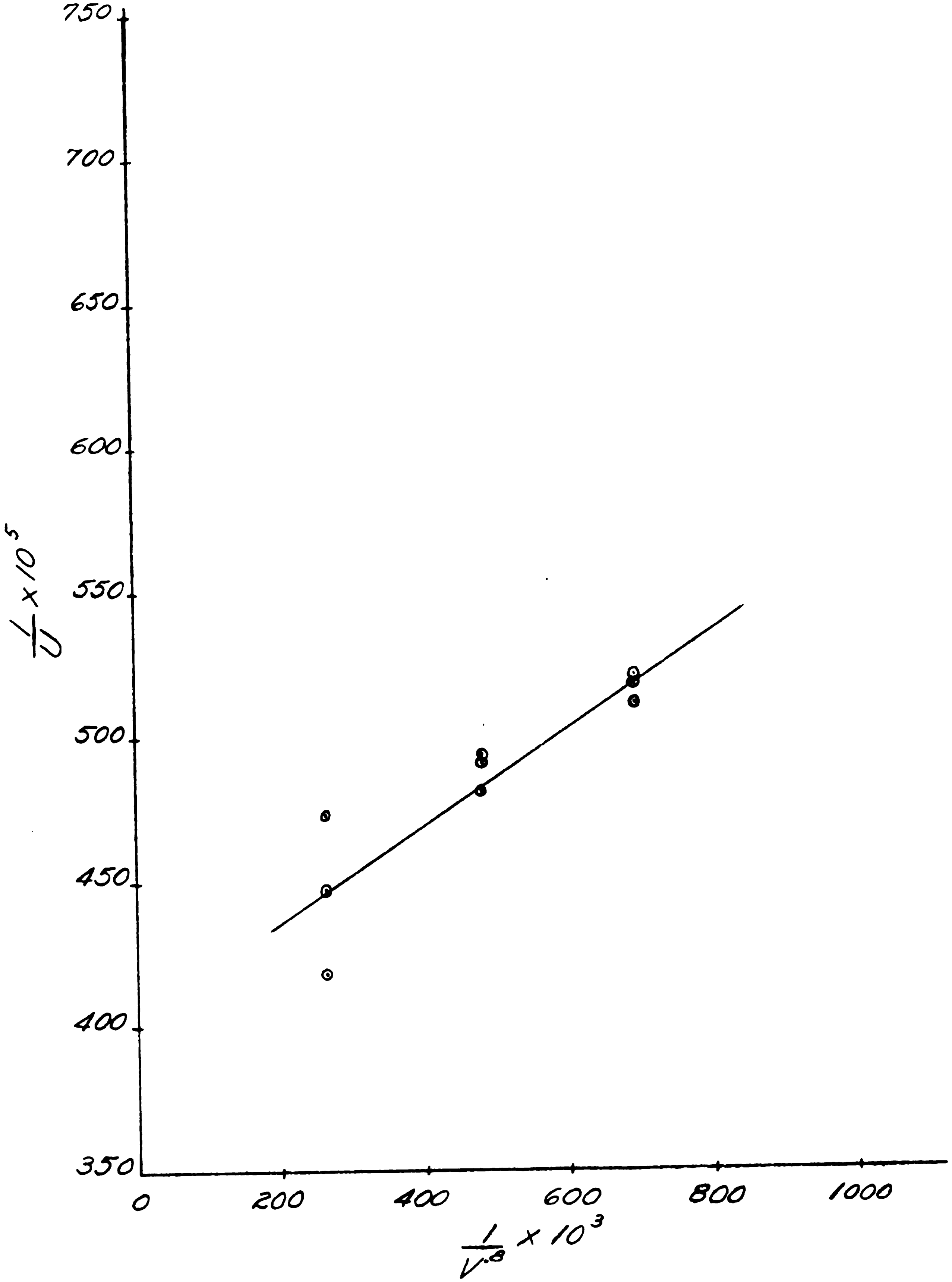
Graph No. 9.

1- OCTADECANOL

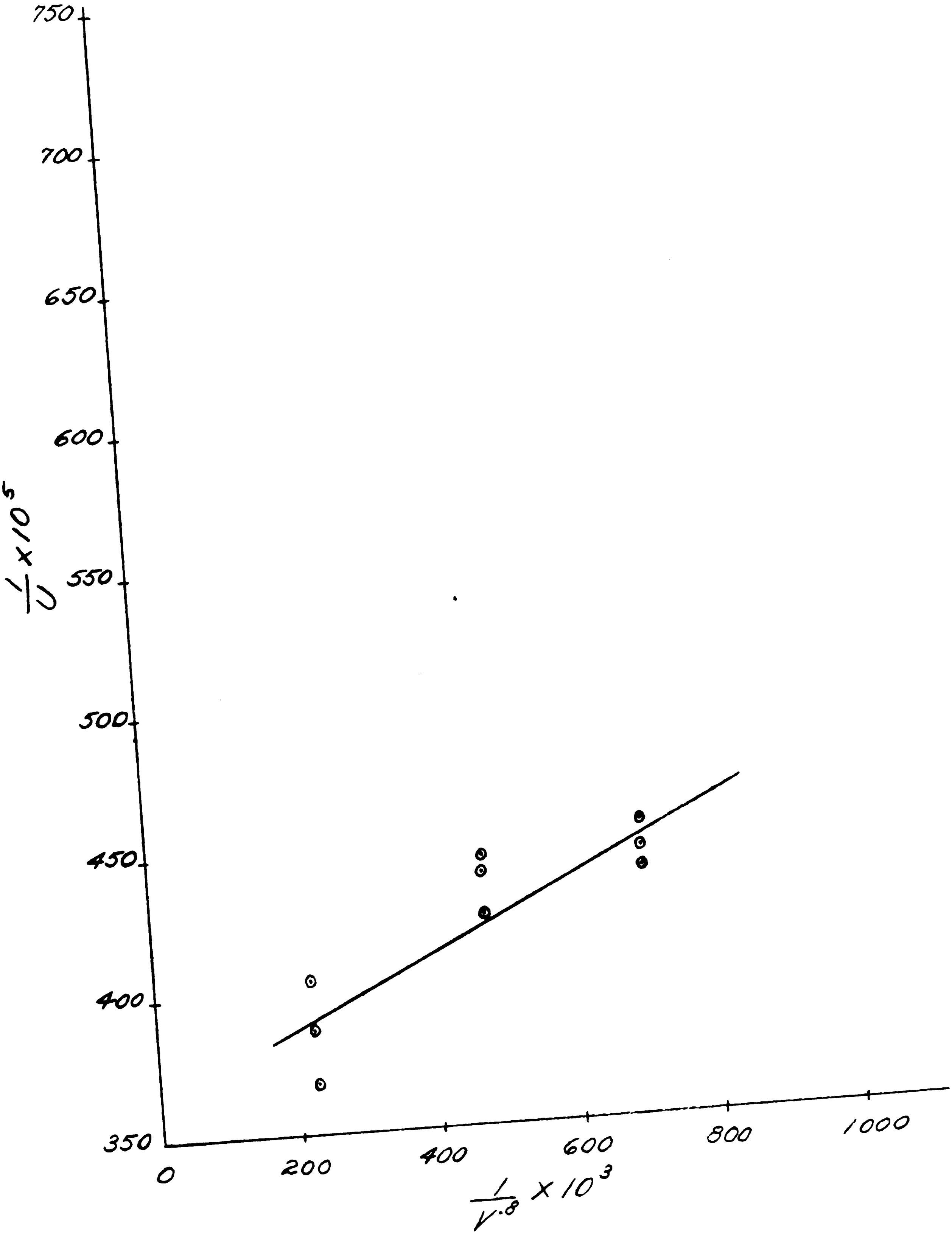


Graph No. 10.

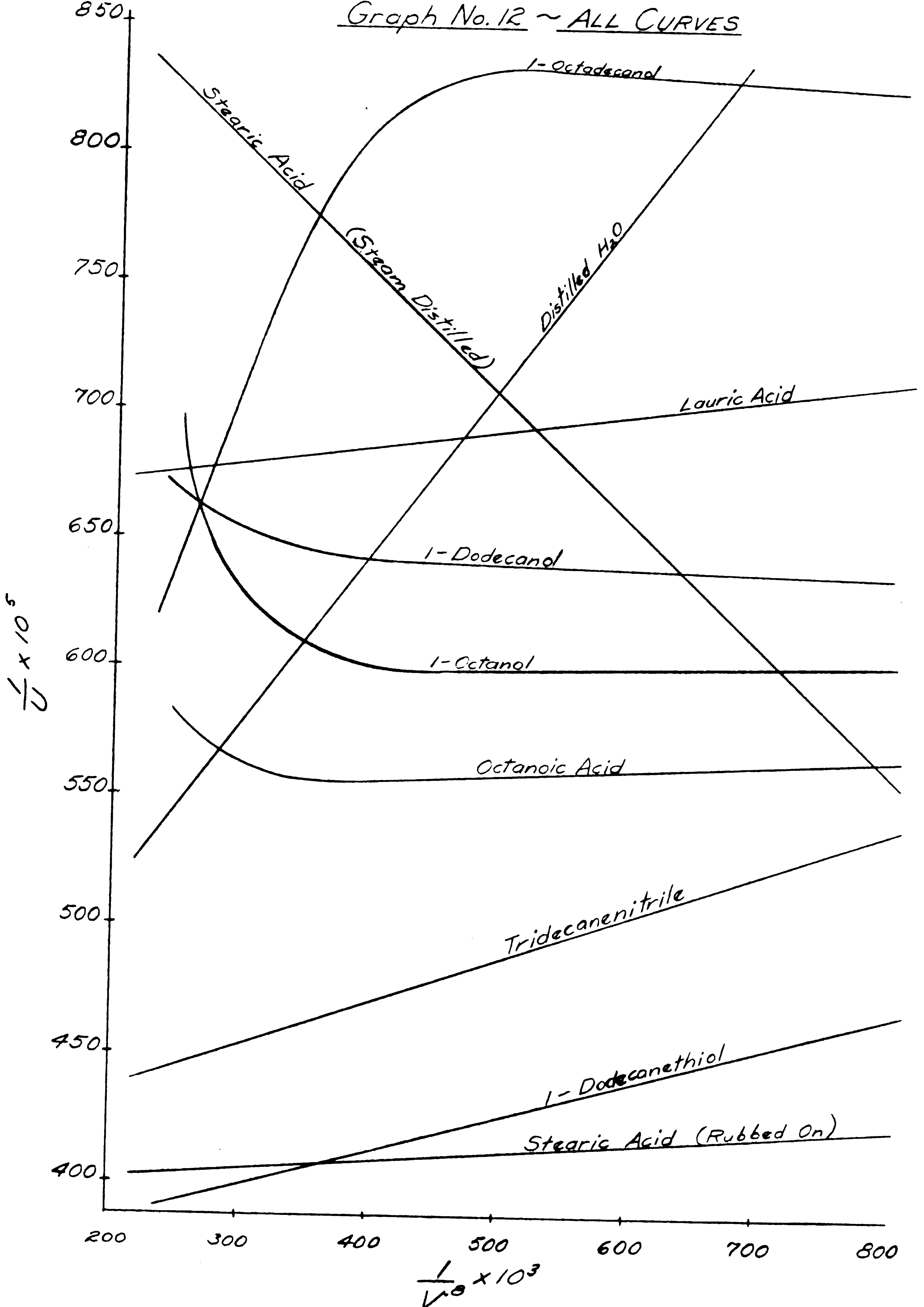
TRIDECANENITRILE



Graph No. 11.
1-DODECANETHIOL



Graph No. 12 ~ ALL CURVES



DISCUSSION

DISCUSSION

A. Results

The method of least squares was used for drawing the best straight line through the plotted points. This method is shown in the sample calculation in Appendix A. Some of the compounds did not give points which approximated a straight line, so appropriate curves were drawn through them. Since there were only three groups of points in each case, these curved lines can only be indicative.

The alcohols were of no value in promoting dropwise condensation. They formed a visible, bag-like film which seemed to have a thin layer of condensate between it and the metal. The alcohol bag thus formed, filled up with water and hung down about ½ inch below the bottom of the condenser. Finally, when it got too heavy, the whole bag slid off and the cycle repeated itself.

The alcohol buildup on the surface was more rapid for the smaller chain, more volatile molecules, but they also seemed to form a thinner, weaker sack than the larger molecules. As the rate of condensation was increased the film buildup increased rapidly for octyl alcohol, somewhat less rapidly for dodecyl alcohol, and decreased for octadecanol. This is shown quite vividly by the three curves of $\frac{1}{V^{.8}}$ vs $\frac{1}{U}$ for these compounds. As V is increased, octanol slopes upward sharply, dodecanol slopes up less sharply, and octadecanol slopes downward sharply. The change in relative thickness of the alcohol film increases the resistance to heat transfer for the first two and decreases it for the latter. This change can be accounted for by their relative difference in volatility due to their chain lengths.

The failure of the alcohols to promote dropwise condensation is due to the poor chemisorption properties of the alcohols. Chemisorption involves the weak pairing of unpaired electrons at the surface of the metal and leads to a monomolecular film. The alcohols do not have enough unpaired electrons to be chemisorbed (13).

The acids proved to be much better dropwise promoters. This could be expected, since the carbon-oxygen double bond may be broken, giving rise to two unshared electrons (13). The longer chain acid was the best promoter. This is in agreement with the findings of Erickson (4) in his work with normal alkyl amines. The upward slope at the left of the octanoic acid curve probably was due to the higher volatility of the eight carbon acid. Just as in the case of actyl alcohol, the buildup of octanoic acid increased so much that it caused a resistance to heat transfer.

The low volatility of stearic acid made it necessary to pre-coat the condenser before the run. The precoated stearic acid run is run number three. Runs one and two were made by the usual procedure, except that run number one was allowed to operate for two hours before readings were taken. The negative slope for these two runs probably is due to the slow rate of steam distillation of stearic acid. At the higher rates of condensation, insufficient stearic acid was deposited to promote dropwise condensation.

As shown by their plots, both dodecanethiol and tridecanenitrile were very good dropwise promoters. The dodecanethiol was especially good. It produced a film so nonwettable that the droplets slid off before they had a chance to grow large. The runoff seemed to be much faster than it had been with the acids. Both of these compounds seem to have good possibilities; further studies are recommended.

B. Apparatus

The apparatus used in this work had both advantages and disadvantages. One advantage was that it was so simple that each of the steam-contacted parts could be easily cleaned. This is very important; less than one part per million of foreign matter could contaminate the condensing surface. Another important advantage was that the mode of condensation was completely visible at all times. The cleanliness of the system could be checked before each run by seeing if pure filmwise condensation would take place.

Probably the worst disadvantage that could be noticed during these runs was that it was very difficult to control the convection effect of the steam. The somewhat violent boiling necessary to supply sufficient steam set up varying degrees of convection currents. When the system was operating at a given rate there was an observable rise in outlet temperature when the heat input, and hence the rate of boiling, was increased. An attempt was made to control this effect by adjusting the rate of boiling in each run so that one drop of water fell from the reflux condenser every three or four seconds.

For future study on this subject, the author would like to make the following suggestions toward improving the apparatus:

(1) Have a steam generating chamber separate from the steam condensing chamber;

(2) Have a longer finger-type condenser with a smaller annulus;

(3) Use a two liter round bottom flask as a steam condensing chamber;

(4) Use two reflux condensers, one in each chamber.

The separate steam generation flask would be an attempt to control the convection due to vigorous boiling. The longer condenser should give more accuracy in calculating overall heat transfer coefficients due to its larger area. The smaller annulus would result in higher velocities for the presently available mass flow rates. This would be a decided advantage, since it was difficult to pump at very high flow rates through the existing apparatus. The round bottom flask would give more distance between the condenser and the comparatively cool glass surface; it would also allow the steam to get to the upper portion of the finger more easily. Two reflux condensers should help to stabilize the steam pressure and temperature; slight variations of these were observed in this work.

These suggestions may be helpful, but in adapting them care should be taken to maintain the simplicity of the present equipment.

CONCLUSIONS

CONCLUSIONS

I. The alcohols were of no value as dropwise condensation promoters.

II. The acids promoted fairly good dropwise condensation.

III. The longest chain acid was the best promoter.

IV. The tridecanenitrile gave very good dropwise condensation.

V. Dodecanethiol caused by far the best dropwise condensation and the fastest runoff thus far observed.

VI. Further study with nitriles and mercaptans is recommended.

APPENDIX

APPENDIX A

Sample Calculation:

The amount of heat transfered from the condensing steam to the metal surface is equal to the amount of heat picked up by the cooling water, or

$$Q_{in} = Q_{out} = WC(t_o - t_i) = UA(t_s - t_a)$$

$$A = 3.1416Dh \qquad \text{Where } D = 0.50''$$

$$\& \quad h = 3.50''$$

$$A = 3.1416(.50/12)(3.50/12)$$

$$\text{or} \quad A = .038179 \text{ ft.}^2$$

The temperature ranges from 11° to 14° C., so the heat capacity of water, C, is 1.001 B.t.u./#°F. and the density, d, is 62.34 #/cu.ft.

Therefore from above

$$U = \frac{1.001\ W'(60)(t_o - t_i)}{.039179(t_s - t_a)}$$

$$\text{Or} \quad U = 1573\ W' \frac{(t_o - t_i)}{(t_s - t_a)} \qquad (1)$$

To calculate the linear velocity:

$$V = \frac{W'}{60\ A_a\ d} \qquad \text{Where } A_a = \frac{3.1416}{4}(D_o^2 - D_i^2)$$

$$D_o = .435''$$
$$D_i = .250''$$

$$\text{or} \quad A_a = \frac{.7853(.1892 - .0625)}{144}$$

$$A_a = 0.0995/144 \text{ ft.}^2$$

$$V = \frac{144\ W'}{60(.0995)(62.34)}$$

or $V = 0.3868\ W'$ (2)

APPENDIX B

Nomenclature:

Q	Amount of heat transfered (B.t.u./hr.)
W	Water mass flow rate(#/hr.)
W'	" " " " (#/min.)
C	Heat capacity of water (B.t.u./#°F.)
t_o	Outlet temperature of water (°F.)
t_i	Inlet temperature of water (°F.)
U	Over all heat transfer coefficient (B.t.u./hr.ft.^{2}°F.)
t_s	Steam temperature (°F.)
t_a	Average water temperature (°F.)
V	Linear water velocity (ft./sec.)
d	Density of cooling water (#/ft.^{3})
A	Area of finger condenser (ft.^{2})
Aa	Cross sectional area of annulus (ft.^{2})

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