AN INVESTIGATION OF THE EFFECT OF VISCOSITY UPON THE PLATE EFFICIENCY IN A BUBBLE-TRAY TOWER

Thesis for the Degree of M. S.

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Robert Asa Smith

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THESIS

AN INVESTIGATION OF THE EFFECT OF VISCOSITY UPON THE PLATE EFFICIENCY IN A BUBBLE-TRAY TOWER

By

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A THESIS

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HISTORY

In 1943 Drickamer and Bradford presented a correlation between viscosity and plate efficiency in the Transactions of the American Institute of Chemical Engineers.(4) They pointed out that the tray efficiency of fractionating columns is a function of many things. Some of these are temperature, pressure, tray design, column load, physical properties of the liquid, etc. When all other things are constant, such as in columns of similar design or for similar purposes, the efficiency may then be a function of the physical properties of the liquid.

It is obvious that the efficiency would not be a function of just any one physical property, but of many. It is desired in this problem, then, to study the effect of liquid viscosity upon the efficiency of a bubble-tray tower. A water solution of a soluble cellulose gum was metered on to the top tray of the tower. The effect of the gum was to vary the liquid viscosity in the tower. By analyzing various liquid and vapor samples from the tower, the efficiencies and viscosities were determined.

The results obtained by Drickamer and Bradford were drawn from test data on 54 refinery fractionating columns and dealt wholly with hydrocarbons. They checked their resulting curve against data on 30 commercial columns taken from the literature. The literature data used was also from hydrocarbon columns, except for four points. Two of these points were Beer Stills, one on Acetic Acid-Water tower, and the other an average of five tests on commercial Alcohol-Water towers.

Their results are shown in figures (1) and (2). The curve is of the form

$$E = 0.17 - 0.616 \log_{10} (\Sigma Mu)$$

for efficiencies (E) of fractionating columns using hydrocarbon mixtures with viscosities (u) varying from 0.06 to 1.5.

Walter and Sherwood have also dealt slightly with this problem.(10) They suggested a general equation for Murphree efficiencies for gas absorption, taking into account the effect of viscosity. They assume that

> Although it is highly probable that the individual gas and liquid film coefficients are different functions of viscosity, the present data can be correlated fairly well by assuming both liquid and gas film coefficients to be inversely proportional to viscosity to the 0.68 power.

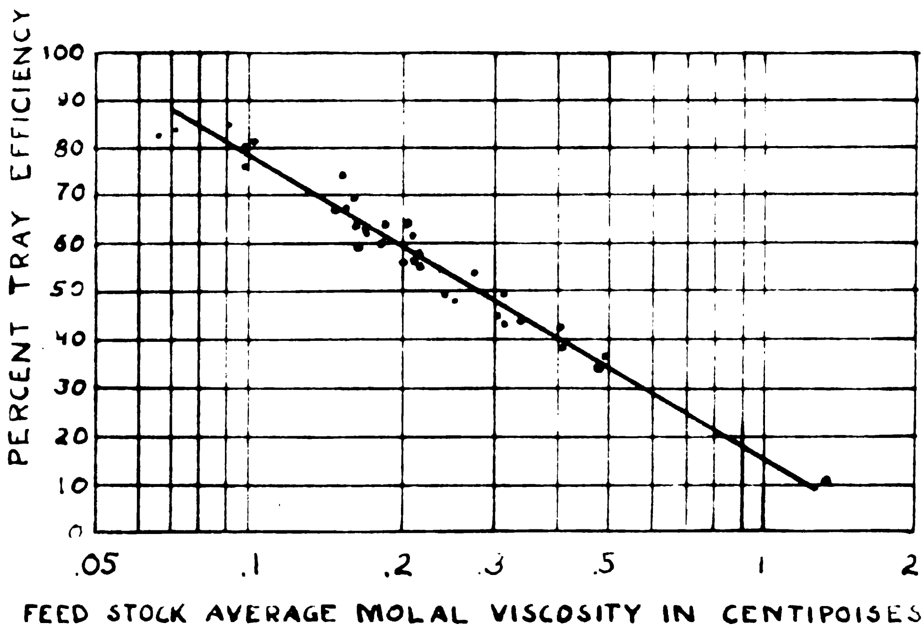
Their equation is

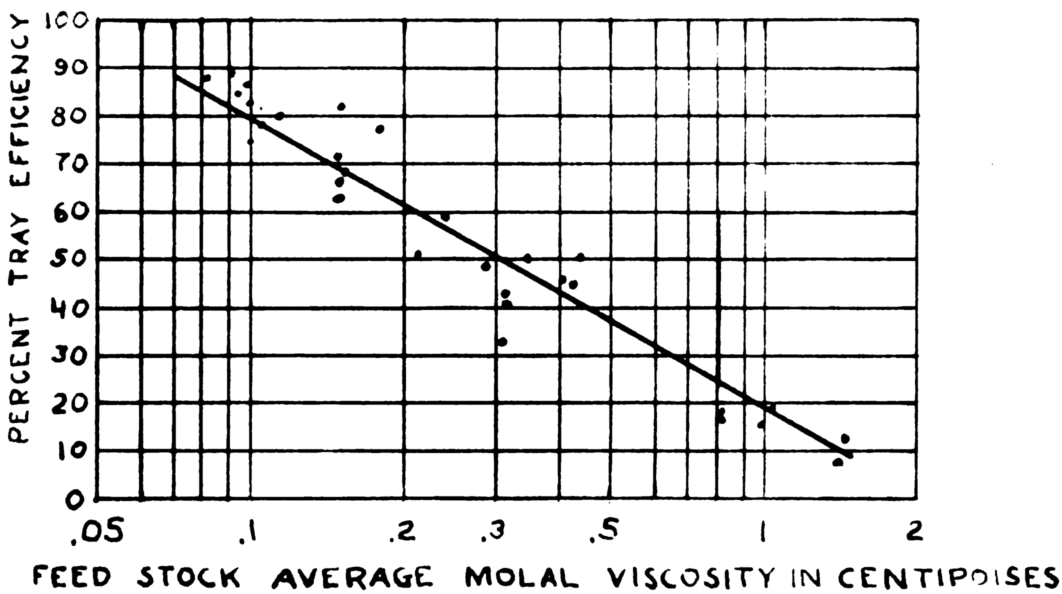
$$E_{MV} = (1 - e^{-m})$$

where

$$m = \frac{h_1}{(2.50 + 0.370/H_c P)\, u^{0.68}\, w^{0.33}}$$

Efficiencies estimated by this equation were a maximum of 60% different from the experimental results. The average deviation was 22%. The equation covered values of E_{MV} from 0.0065 to 0.75, u from 0.70 to 22, h_1 from 1.0" to 1.8", gas rates from 0.70 to 2.4 pound mols per hour per square inch of


PERCENT TRAY EFFICIENCY
100
90
80
70
60
50
40
30
20
10
0
.05
.1
.2
.3
.5
1
2
FEED STOCK AVERAGE MOLAL VISCOSITY IN CENTIPOISES


PERCENT TRAY EFFICIENCY
100
90
80
70
60
50
40
30
20
10
0
.05
.1
.2
.3
.5
1
2
FEED STOCK AVERAGE MOLAL VISCOSITY IN CENTIPOISES

slot area, and H_c from 0.0013 to 8.0.

EQUIPMENT

The problem here involved was attacked in a different manner. Formerly many different systems, types and sizes of columns, tray designs, and conditions were used. Here conditions were maintained as constant as possible with only the liquid viscosity as a variable factor.

Therefore, to maintain these conditions, a single distillation column was used to gather all the data. The column was an experimental laboratory distillation unit of 24 bubble-trays. It is a portion of the equipment available in the Unit Operations Laboratory of the Department of Chemical Engineering at Michigan State College. This column was designed for use for either batch or continuous fractionation. It was fitted with sampling taps for liquid and vapor on each tray.

The system Ethanol-Water was chosen due to the large amount of information available about equilibrium curves, density-concentration curves, etc., and for the ease and inexpense of obtaining the components.

The major problem with this method then, was one of varying and controlling the variation of the viscosity. The problem was overcome by the use of a water soluble cellulose gum which greatly increases the viscosity of water when in even very dilute solutions. Solutions of this cellulose gum were metered into the top of the bubble-tray column during operation. In this manner the viscosity of the liquid throughout the column could be altered to a predetermined degree.

The bubble-tray column used was an experimental laboratory distillation unit, type A-2, built by the Vulcan Copper and Supply Company of Cincinnati, Ohio. The column shell was fabricated from 8" SPS copper pipe. It was furnished with 24 bubble-cap trays spaced on 6" centers. Each tray had two three inch Vulcan pressed bubble-cap assemblies. (See Figure 4). Each tray and vapor space was fitted with a 3/8 inch globe valve and union to facilitate sampling.

The system necessary to feed the viscous solutions into the top of the column was not a regular part of the column, but was constructed especially for that use. (See Figures 5 and 6) Essentially it was simply a pressurized tank with a sight glass and a plug valve to allow the solution to flow on to the top tray of the column.

A small refrigerated coil was used to take the liquid and vapor samples directly from the column. (Plates 21, 22 and 23 only). This sampling device was fabricated from six feet of 1/8" copper tubing formed in a coil inside of a three quart steel can. The upper end of the coil was brazed to the male half of a 3/8" union. The lower end of the tubing drained into the test tubes that were used to take the samples. During operation the coil was surrounded by crushed ice and water. An illustration of the sampling apparatus is shown in Figure 7. For clarity the ice was left out of the container.

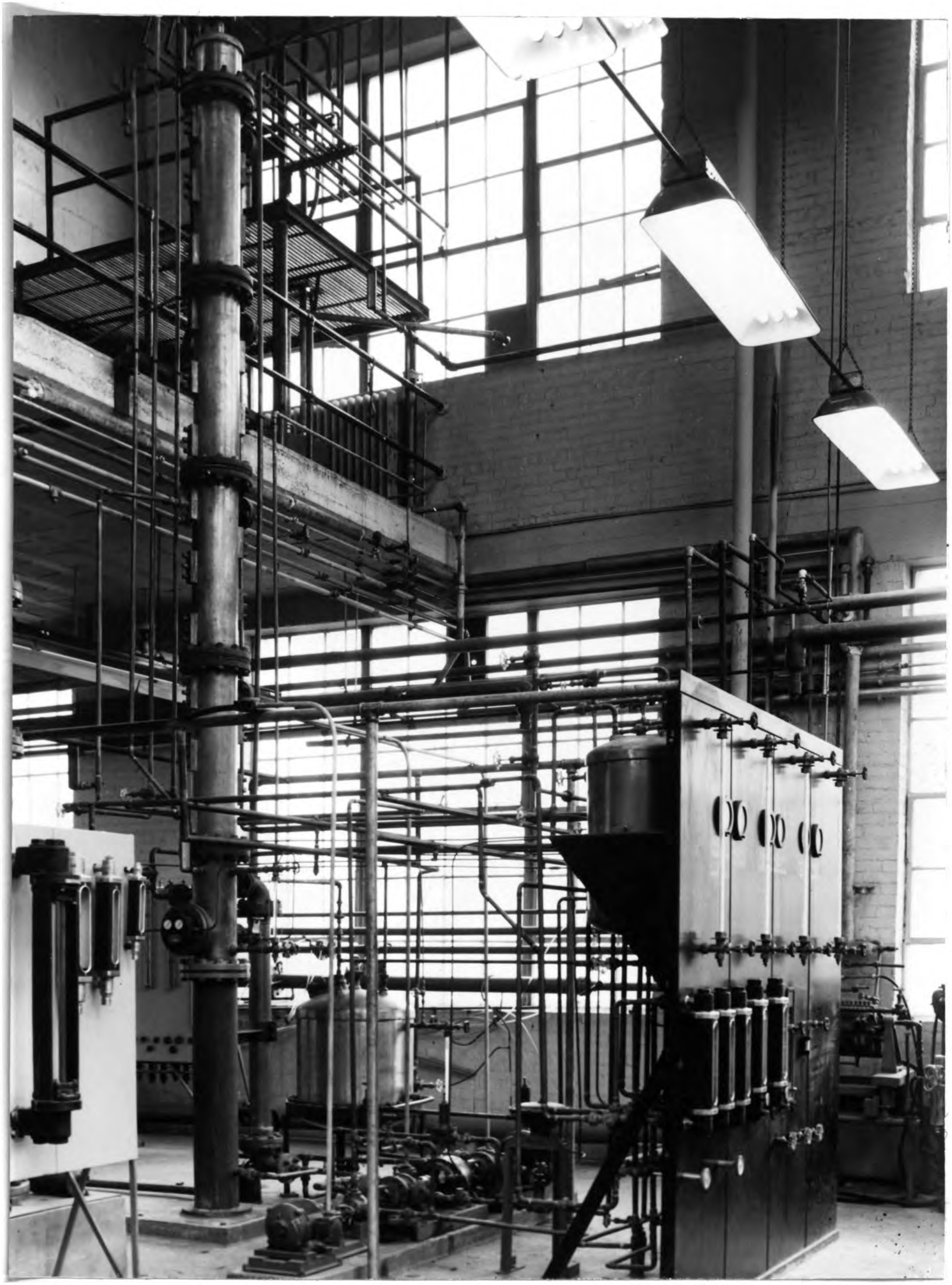
The densities of the samples were determined at room temperature using a chainomatic Westphal balance.

The viscosities of the liquid samples and bottom products were determined by using a glass Kimble C-200 viscosimeter of the Ostwald type. The temperatures were maintained to plus or minus one-half a degree centigrade in a constant temperature water bath. The viscosimeter and bath are shown in Figure 8. The bath was heated by two 150 watt knife heaters controlled by a Cenco DeKhotinsky Thermoregulator. A variable speed stirrer assured a uniform temperature through out the bath.

The distillation components were distilled water and 95% ethyl alcohol. The viscosity of the liquid in the tower was varied using solutions of Hercules CMC, or Cellulose Gum, type CMC-70-H.(2)

Figure 3.

Model A-2 Experimental Distillation Unit previous to the installation of the sampling valves and insulation.



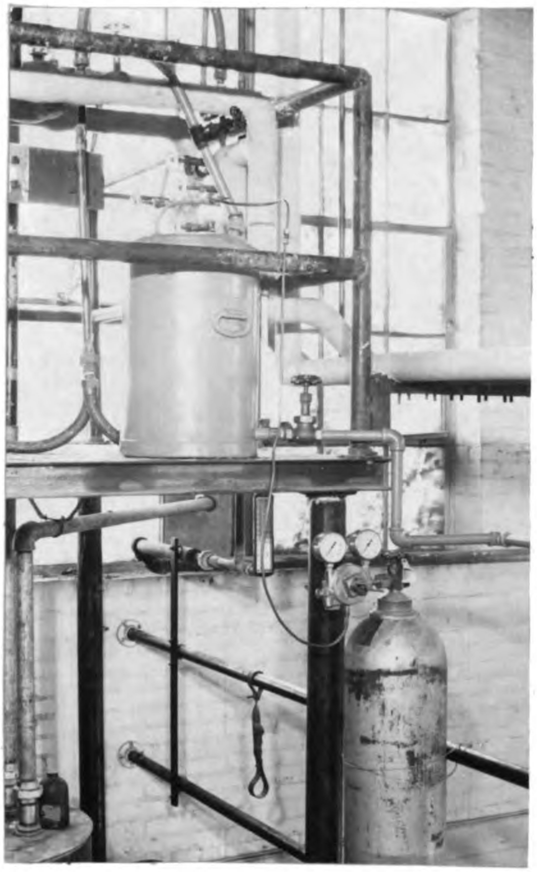


Figure 6. CMC feeding system, showing the storage tank and pressure source.

Figure 7. Sampling apparatus, showing the valves, unions and cooling coil.

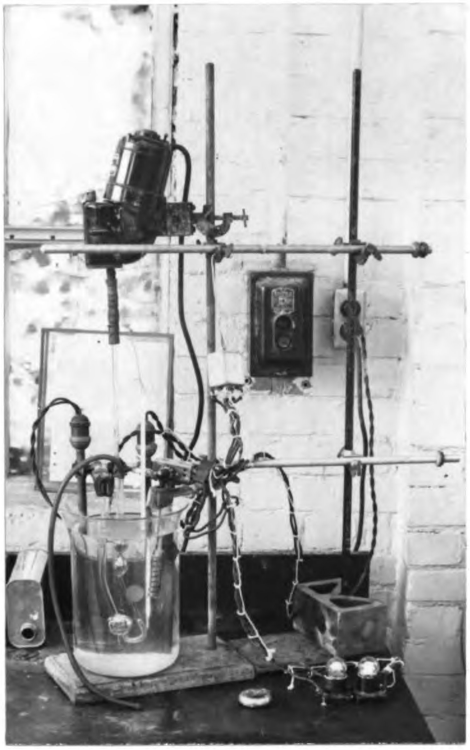


Figure 8. Viscosimeter, showing the stirrer, heaters and controller.

Photography by Huby,
Kaiser and Author.

PROCEDURE

It was previously stated that the system necessary to feed the CMC solutions into the top of the tower was not a regular part of the tower unit, but was added especially for this purpose. The CMC solutions were fed into the tower through what was formerly a thermometer well. This well was in the vapor space above the top (24th.) tray and directly below the reflux inlet. It was felt that the effect of the reflux liquid flowing down over the CMC solution into the pool of liquid behind the weir would cause essentially perfect mixing.

A bottle of gas, such as N_2 or CO_2, was used as a pressure source for the feeding system. The pressure in the feeding tank was kept between 5 and 7 psig.

The alcohol-water feed stock was mixed in the kettle to a concentration of approximately 5% ethanol, by weight. The solutions were thoroughly mixed by recirculation to assure uniformity of the feed.

A problem that initially caused some trouble, was that of dissolving the powered CMC. It was desired to use solutions of 0.75% and 0.375% CMC as feed. Solutions of these concentrations have viscosities of approximately 20 and 6 centipoise respectively. When the CMC powder was added to water, a very gelatinous film immediately formed around clumps of the powder, very greatly decreasing the rate of solution. The problem was solved by slowly adding the correct amount of CMC to 80 pounds of water while the solution was being agitated with a C-4 Lightnin' Mixer. Forty-five minutes of mixing resulted in a clear uniform solution.

The column was brought to operating equilibrium by allowing it to operate under a fixed set of conditions for at least 70 minutes. During this period, feed rate and product rate were fixed, and all the other conditions were allowed to adjust themselves accordingly. The distillate and bottom products were recycled during this portion of the run. Equilibrium operating conditions were said to exist in the tower when in-coming and out-going streams remained essentially constant in quanity and quality over a period of time. The visible effects of equilibrium were indicated by constant values of steam pressure, feed temperature, feed, reflux, and product meter readings, and a constant alcohol concentration in the product streams.

When the tower reached the condition where it was operating at equilibrium, the CMC solution was metered into the top plate. It should be emphasized at this point that from that time forward a minimum amount of operating time remained. All of the samples had to be taken before the supply of CMC and feed stock was gone, or the receiver tanks were filled.

As the [redacted] solution was started into the top of the column, the receiver tanks were isolated from the kettle so

that the system was no longer recirculating. The flow of CMC solution was regulated to the desired rate and held at a constant value. The sampling was begun when the tower again came to equilibrium from the effects of the CMC, usually about 20 minutes.

Samples of 50 ml. were drawn off from each tray into seven inch test tubes using the cooled sampling coil. For the last three runs a slight vacuum was used to speed the drawing of samples. The samples were taken in the order y_{21}, x_{22}, y_{22}, x_{23}, y_{23}, T, B, and F. Gauge, meter, and condensate readings were taken and the CMC flow stopped. The tower was left in operation for a short period of time to clear it somewhat of viscous solutions.

Before the tower could be used for another run it had to be cleared of all the viscous material. This was accomplished by draining the viscous bottoms product from the receivers into the kettle. Here it was heated with closed steam so that the alcohol and water was boiled off leaving a viscous water solution. This was discarded and the alcohol and water reused.

The sample concentrations and viscosities were determined in the manner described on page 36 of Daniels, Mathews and Williams. (3) Data for the alcohol-water density-temperature-concentration determination was taken from 439 of the <u>Chemical Engineers' Handbook</u> by Perry. (6)

DATA

The following section is composed of the laboratory data taken in the process of the experiment. The data may be roughly divided into two parts. One consists of special observations and the other is normal tower operational data.

The first part of the data is for the standardization of the Ostwald type viscosimeter and the equation for its use, and an investigation of the effect of CMC concentration upon the liquid density and viscosity.

The second part, or normal tower operational data, lists several things. These include: concentration of CMC feed solution, rate of CMC feed into the tower, tower rotameter readings, and liquid and vapor sample properties.

Standardization of Ostwald viscosimeter using distilled water at 25.0 deg. C. (Kimble Viscosimeter size C-200)

10 cc. water sample

time	9.82	
	9.83	
	9.82	
	9.86	average time 9.85 sec.

The viscosity of water at 25.0 deg. C. is .8937 centipoise. The density is .9971.

The equation for use with the viscosimeter was developed as follows:

$$\frac{u_1}{u_2} = \frac{d_1 t_1}{d_2 t_2} \; ; \; \frac{u}{.8937} = \frac{dt}{(.9971)(9.85)}$$

$$u = \frac{.8937\ dt}{(.9971)(9.85)}$$

$$u = .09105\ dt$$

where

u is viscosity in centipoise

d is the density of the fluid

t is the time of efflux in seconds.

Investigation of effect of CMC concentration upon density and viscosity.

9/15/49

	Weight Fract. CMC	Density	Temperature deg. C.	Density Corr. to 21° C	Pure Water at 21 deg. C.
1	.00375	.9996	22.5	1.000	.9982
2	.001875	.9982	21.3	.9988	.9982
3	.000937	.9988	21.3	.9989	.9982
4	.000468	.9987	20.9	.9987	.9982
5	.000234	.9987	21.1	.9987	.9982
6	.000117	.9977	21.2	.9978	.9982
7	.000059	.9980	21.2	.9981	.9982

9/19/49

	Weight Fract. CMC	Density	Temperature deg. C.	Density Corr. to 21° C	Pure Water at 21 deg. C.
8	.00400	1.0006	23.9	1.0015	.9982
9	.00300	.9992	25.2	.9998	.9982
10	.00200	.9987	23.6	.9993	.9982
11	.00100	.9984	23.0	.9989	.9982
12	.00050	.9980	22.7	.9983	.9982
13	.00025	.9981	22.7	.9984	.9982
14	.00000	.9982	21.2	.9982	.9982

All of the viscosities were determined at a bath temperature of 85 deg. C. The viscosities are in centipoise and time in seconds.

Sample 1	Sample 2	Sample 3
time 93.0	time 40.4	time 25.98
89.5	40.8	25.94
87.0	39.8	26.15
85.5	40.2	
84.0		
value used 84.0	value used 40.3	value used 25.96
Viscosity 7.4	Viscosity 3.56	Viscosity 2.28

Sample 4	Sample 5	Sample 6
time 13.89	time 9.45	time 6.63
13.40	9.29	6.60
13.00	9.36	6.62
12.68	9.33	
12.76	9.35	
12.65		
value used 12.70	value used 9.35	value used 6.62
Viscosity 1.12	Viscosity .82	Viscosity .58

Sample 7	Sample 8	Sample 9
time 6.80	time 74.2	time 53.2
6.84	74.0	52.6
6.85	74.0	53.5
6.82		53.5
6.80		
value used 6.82	value used 74.0	value used 53.1
Viscosity .60	Viscosity 6.53	Viscosity 4.68

	Sample 10	Sample 11	Sample 12
time	40.5	21.84	9.12
	40.7	21.84	9.00
	40.3	21.86	9.13
			9.18
			9.18
value used	40.5	21.85	9.12
Viscosity	3.57	1.93	.80

	Sample 13	Sample 14
time	7.42	6.02
	7.42	5.97
	7.42	6.06
		6.01
value used		6.01
Viscosity	.65	.53

Run Number 1 8/1/49

0.75% CMC solution

Rate of CMC feed

time	fall
6:32	0"
6:48	6¾"

Diameter of CMC feed tank is 12½".

Steam condensate

242# at 7:12
123# at 6:18

119# in 54 min.

Rotameter readings

Feed	11.3
Reflux	3.8
Product	2.7

Sample Properties

Sample	Density	Temperature deg. C.	Wt. Fract. Alc.	Mol. Fract. Alc.	Mol. Fract. Alc.*
y_{21}	.9648	26.5	.205	.092	
x_{22}	.9664	26.5	.195	.087	
y_{22}	.9393	26.5	.356	.1775	.417
x_{23}	.9584	26.5	.248	.114	
y_{23}	.9029	26.5	.525	.302	.460
T	.8890	26.5	.587	.358	
B	.9971	26.5	.000	.000	

Viscosity Determinations

Sample	x_{22}	x_{23}
B.P. deg. C.	86.0	84.5
Bath temp.	85.0	83.5
Time of efflux seconds	15:25	10.08
	15.15	10.12
	15.31	10.05
	15.25	10.04
	15.28	
	15.21	
Value used	15.24	10.07
Viscosity centipoise	1.30	0.85

Run Number 2 8/8/49

0.75% CMC solution
steam to column at 77 psig.
Feed liquid to column at 78 deg. C.

Rate of CMC feed

time	fall
5:43	0"
6:05	7.5"

Diameter of CMC feed tank
is 12.5"

Steam condensate

258# at 6:14
101# at 5:12
157# in 1:02 hrs.

Rotameter readings

Feed	11.4
Reflux	4.3
Product	2.85

Sample Properties

Sample	Density	Temperature deg. C.	Wt. Fract. Alc.	Mol. Fract. Alc.	Mol. Fract. Alc.*
y_{21}	.9574	33.0	.231	.105	
x_{22}	.9840	33.0	.061	.025	
y_{22}	.9520	33.0	.264	.123	.213
x_{23}	.9768	33.0	.106	.043	
y_{23}	.9248	33.0	.402	.208	.302
T	.9196	33.0	.421	.221	
B	.9945	33.0	.003	.002	
F	.9836	33.0	.063	.026	

Viscosity Determinations

Sample	x_{22}	x_{23}	B
B.P. deg. C.	93.0	89.5	100.0
Bath temp.	92.0	88.5	98.0
Time of efflux seconds	101.86	21.08	25.97
	101.48	20.95	25.70
		20.84	25.38
			25.33
			25.18
			25.15
Value used	101.67	20.96	25.16
Viscosity centipoise	8.82	1.81	2.19

Run Number 3 8/11/49

0.75% CMC solution
steam to column at 55 psig.
Feed liquid to column at 80 deg. C.

Rate of CMC feed

time	fall
4:30	0"
5:04	5"

Diameter of CMC feed tank is 12.5"

Steam condensate

224# at 5:08.5
92# at 4:02.5
132# in 1:06 hrs.

Rotameter readings

Feed	9.5
Reflux	3.5
Product	2.6

Sample Properties

Sample	Density	Temperature deg. C	Wt. Fract. Alc.	Mol. Fract. Alc.	Mol. Fract Alc.*
y_{21}	.9713	27.5	.157	.068	
x_{22}	.9888	27.5	.042	.017	
y_{22}	.9663	27	.192	.084	.150
x_{23}	.9694	27.5	.170	.074	
y_{23}	.9575	27.5	.250	.116	.392
T	.9298	27.5	.398	.206	
B	.9978	27.5	.000	.000	
F	.9897	27.5	.037	.0145	

Viscosity Determinations

Sample	x_{22}	x_{23}	B
B.P. deg. C.	95.0	87.0	100.0
Bath temp.	94.0	86.0	99.0
Time of efflux in seconds	82.58	23.22	28.00
	77.02	23.24	27.92
	74.82	23.05	27.63
	74.38	22.82	27.57
		23.20	27.12
			26.90
Value used	74.61	23.11	26.90
Viscosity centipoise	6.47	1.95	2.35

Run Number 4 — 8/17/49

0.75% CMC solution
Feed liquid to column at 81° C.

Rate of CMC Feed

time	fall
4:14	0"
4:52.5	8.5"

Diameter of CMC feed tank is 12.5"

Steam condensate

241# at 4:51
94# at 3:58

147# in 1:13 hrs.

Rotameter readings

Feed	9.9
Reflux	3.3
Product	2.5

Sample Properties

Sample	Density	Temperature deg. C.	Wt. Fract. Alc.	Mol. Fract. Alc.	Mol. Fract. Alc.*
y_{21}	.9687	26.0	.181	.079	
x_{22}	.9692	26.0	.176	.077	
y_{22}	.9682	26.0	.184	.0815	.392
x_{23}	.9869	26.0	.057	.023	
y_{23}	.9558	26.0	.266	.134	.220
T	.9343	26.0	.382	.194	
F	.9904	26.0	.035	.014	
B	.9980	26.5	.000	.000	

Remark: Sample y_{23} taken before x_{23}

Viscosity Determinations

Sample	x_{22}	x_{23}	B
B. P. deg. C.	86.5	93.5	100
Bath temp.	85.5	92.5	98.5
Time of efflux in seconds	12.62	74.30	33.90
	12.74	70.30	33.54
	12.72	71.80	33.02
	12.65	69.04	32.88
		68.45	32.72
			32.46
Value used	12.68	68.45	32.46
Viscosity centipoise	1.09	5.70	2.84

Run Number 5 8/19/49

0.75% CMC solution
Steam to column at 70 psig.
Feed to column at 80° C.

Rate of CMC feed

time	fall
4:36	0"
5:17	8¾"

Diameter of CMC feed tank is 12.5"

Steam condensate

190# at 5:20
112# at 4:41
78# in 39 min.

Rotameter readings

Feed	10.3
Reflux	3.2
Product	2.9

Sample Properties

Sample	Density	Temperature deg. C.	Wt.Fract. Alc.	Mol.Fract. Alc.	Mol.Fract. Alc.*
y_{21}	.9702	23.0	.169	.074	
x_{22}	.9897	26.0	.039	.016	
y_{22}	.9644	23.0	.220	.099	.142
x_{23}	.9612	26.5	.229	.104	
y_{23}	.9551	23.0	.282	.133	.448
T	.9882	26.5	.361	.181	
B	.9976	26.0	.000	.000	
F	.9885	23.5	.051	.205	

Viscosity Determinations

Sample	x_{22}	x_{23}	B
B. P. deg. C.	95.5	85.0	100
Bath temp.	94.5	84.0	98
Time of efflux in seconds	43.22	9.81	15.57
	41.73	9.65	15.22
	41.14	9.68	15.00
	40.56	9.63	14.70
	40.26		14.71
	40.02		14.65
Value used	40.02	9.65	14.69
Viscosity in centipoise	3.48	0.82	1.28

Run Number 6 8/23/49

0.75% CMC solution
Steam to column at 70 psig.
Feed liquid to column at 78° C.

Rate of CMC feed

time	fall
3:48	0"
4:04	7"

Diameter of CMC feed tank is 12.5"

Steam Condensate

156# at 4:11
109# at 3:47
47# in :24

Rotameter readings

Feed	10.4
Reflux	3.3
Product	3.9

Sample Properties

Sample	Density	Temperature deg. C.	Wt.Fract. Alc.	Mol.Fract. Alc.	Mol.Fract. Alc.*
y_{21}	.9393	24.5			
y_{22}	.9429	25.0			
T	.9237	25.0	.436	.232	
B	.9986	25.0	.000	.000	
F	.9878	25.0	.052	.021	

Remarks: Run only partially completed. Ran out of CMC at 4:04.

Viscosity Determinations

Sample	B
B.P. deg. C.	100.0
Bath temp.	98.0
Time of efflux in seconds	14.80
	14.80
	14.57
	14.50
Value used	14.50
Viscosity in centipoise	1.266

Run Number 7 8/25/49

0.375% CMC solution
Steam to column at 70 psig.
Feed liquid to column at 72° C.

Rate of CMC feed

time	fall
12:14	0"
1:12	9.62"

Diameter of CMC feed tank is 12.5"

Steam condensate

242# at 1:15
130# at 12:17
112# in :58 min.

Rotameter Readings

Feed	10.1
Reflux	3.8
Product	0.1

Sample Properties

Sample	Density	Temperature deg. C.	Wt.Fract. Alc.	Mol.Fract. Alc.	Mol.Fract. Alc.*
y_{21}	.9194	28.5	.443	.238	
x_{22}	.9602	30.0	.224	.102	
y_{22}	.9069	28.5	.500	.282	.443
x_{23}	.9445	29.5	.317	.153	
y_{23}	.8764	28.5	.633	.403	.408
T	.9033	29.0	.514	.293	
B	.9966	30.0	.000	.000	
F	.9855	30.0	.057	.023	

Viscosity Determinations

Sample	x_{22}	x_{23}	B
B.P. deg. C.	85.0	83.0	100.0
Bath temp.	84.0	82.0	98.5
Time of efflux in seconds	34.42	33.73	15.94
	34.33	33.60	15.75
	34.05	33.68	15.33
	34.04	33.62	15.30
	34.04		14.10
			14.06
			14.10
			14.10
Value used	34.04	33.63	14.10
Viscosity in centipoise	2.89	2.81	1.26

Run Number 8 — 8/26/49

0.375% CMC solution
steam to column at 80 psig.
Feed liquid to column at 77° C.

Rate of CMC feed

time	fall
4:49	0"
5:17	10"

Diameter of CMC feed tank is 12.5"

Steam condensate

185# at 5:28
109# at 4:52
76# in :36 min.

Rotameter readings

Feed	10.4
Reflux	3.6
Product	2.3

Sample Properties

Sample	Density	Temperature deg. C.	Wt.Fract. Alc.	Mol.Fract. Alc.	Mol.Fract. Alc.*
y_{21}	.9549	24.0	.279	.133	
x_{22}	.9812	25.0	.095	.042	
y_{22}	.9433	24.0	.333	.164	.297
x_{23}	.9748	25.2	.139	.059	
y_{23}	.9250	24.0	.434	.231	.355
T	.8939	23.8	.575	.347	
B	.9982	25.0	.000	.000	
F	.9907	24.6	.036	.0145	

Viscosity Determinations

Sample	x_{22}	x_{23}	B
B.P. deg. C.	91.0	88.5	100.0
Bath temp.	90.0	87.5	98.0
Time of efflux in seconds	43.20	41.33	18.32
	43.32	41.28	18.38
	43.22	41.22	18.28
	43.10	41.36	18.38
		41.20	18.28
Value used	43.21	41.28	18.33
Viscosity in centipoise	3.73	3.55	1.60

Run Number 9 8/30/49

0.37% CMC solution
steam to column at 90 psig.
Feed liquid to column at 78° C.

Rate of CMC feed

time	fall
4:20.5	0"
5:11	7"

Diameter of CMC feed tank is 12.5"

Steam condensate

199# at 5:12.5
95# at 4:20
104# in :52.5 min.

Rotameter readings

Feed	10.0
Reflux	3.7
Product	2.8

Sample Properties

Sample	Density	Temperature deg. C.	Wt. Fract. Alc.	Mol. Fract. Alc.	Mol. Fract. Alc.*
y_{21}	.9658	19.0	.222	.100	
x_{22}	.9604	21.5	.253	.123	
y_{22}	.9620	20.0	.248	.114	.470
x_{23}	.9850	21.4	.077	.031	
y_{23}	.9515	20.0	.313	.153	.248
T	.9097	20.6	.517	.295	
B	.9988	21.3	.000	.000	
F	.9895	21.5	.047	.019	

Viscosity Determinations

Sample	x_{22}	x_{23}	B
B.P. deg. C.	84.5	92.5	100.0
Bath temp.	83.5	91.5	98.5
Time of efflux in seconds	7.90	23.76	13.77
	7.96	23.10	13.68
	8.00	22.97	13.47
	8.08	22.80	13.37
	7.91	22.96	13.39
	7.91	22.98	13.34
	8.00		13.37
Value used	7.97	22.93	13.37
Viscosity in centipoise	.676	1.98	1.17

Run Number 10 9/2/49

0.00% CMC solution
Steam to column at 85 psig.
Feed to column at 80 deg. C.

Rate of CMC feed

time	fall
4:28	0"
5:04	7.5"

Diameter of CMC feed tank is 12.5"

Steam condensate

194# at 5:07
115# at 4:29
79# in :38 min.

Rotameter readings

Feed	10.65
Reflux	3.20
Product	3.35

<u>Sample Properties</u>

Sample	Density	Temperature deg. C.	Wt.Fract. Alc.	Mol.Fract. Alc.	Mol.Fract. Alc.*
y_{21}	.9475	21.8	.329	.161	
x_{22}	.9374	24.0	.374	.189	
y_{22}	.9380	22.2	.378	.1925	.521
x_{23}	.9549	24.5	.277	.130	
y_{23}	.9274	22.1	.430	.288	.542
T	.9276	22.1	.429	.228	
B	.9979	24.1	.000	.000	
F	.9880	24.3	.046	.018	

Viscosity Determinations

Sample	x_{22}	x_{23}	B
B.P. deg. C.	82.5	84.0	100.0
Bath temp.	81.5	83.0	98.5
Time of efflux in seconds	8.22	8.38	8.82
	8.08	8.40	4.77
	8.02	8.50	5.90
	8.00	8.38	3.82
	8.04	8.45	8.83
Value used	8.04	8.42	8.83
Viscosity in centipoise	.666	.711	.770

Run Number 11 — 9/5/49

No CMC solution used
Steam to column at 80 psig.
Feed liquid to column at 78° C.

Rotameter readings

Feed	10.7
Reflux	3.55
Product	2.80

Sample Properties

Sample	Density	Temperature deg. C.	Wt.Fract. Alc.	Mol.Fract. Alc.	Mol.Fract. Alc.*
y_{21}	.8930	21.5	.587	.357	
x_{22}	.8958	21.8	.572	.343	
y_{22}	.9102	21.0	.513	.293	.5[illegible]0
x_{23}	.9333	22.0	.401	.207	
y_{23}	.9020	21.2	.548	.322	.531
T	.9017	21.5	.549	.323	
B	.9973	22.1	.004	.001	
F	.9894	22.4	.047	.019	

Viscosity Determinations

Sample	x_{22}	x_{23}	B
B. P. deg. C.	80.6	82.0	99.0
Bath temp.	79.5	81.0	98.0
Time of efflux in seconds	8.60	8.28	7.01
	8.71	8.13	7.10
	8.55	8.16	6.96
	8.55	8.10	7.05
Value used	8.55	8.13	7.02
Viscosity in centipoise	.677	.671	.613

Run Number 12 9/9/49

0.75% CMC solution
Steam to column at 100 psig.
Feed liquid to column at 80° C.

Rate of CMC feed

time	fall
5:26.5	0"
5:51	6.87"

Diameter of CMC feed tank is 12.5"

Steam condensate

222# at 5:53
82# at 4:50
140# in 1:03

Rotameter readings

Feed	10.6
Reflux	3.6
Product	2.75

Sample Properties

Sample	Density	Temperature deg. C.	Wt.Fract. Alc.	Mol.Fract. Alc.	Mol.Fract. Alc.*
y_{21}	.9690	23.0	.188	.083	
x_{22}	.9870	25.0	.060	.024	
y_{22}	.9638	23.0	.224	.102	.205
x_{23}	.9859	25.2	.064	.026	.218
y_{23}	.9543	23.0	.287	.136	
T	.9078	23.6	.511	.290	
B	.9976	24.3	.000	.000	
F	.9892	24.0	.046	.018	

Viscosity Determinations

Sample	x_{22}	x_{23}	B
B. P. deg. C.	93.5	93.5	100
Bath temp.	92.5	92.5	98.0
Time of efflux in seconds	12.12 12.12 12.16 12.03	80.4 79.1 76.7 72.6 70.8 71.4	9.03 9.06 9.00 9.02
Value used	12.11	71.6	9.03
Viscosity in centipoise	1.05	6.20	.789

Run Number 13 — 9/13/49

0.375% CMC solution
Steam to column at 80 psig.
Feed liquid to column at 72° C.

Rate of CMC feed

time	fall
2:58	0"
3:26	11.5"

Diameter of CMC feed tank is 12.5"

Steam Condensate

190" at 3:44
118" at 3:02
72" in :42 min.

Rotameter readings

Feed	10.7
Reflux	3.1
Product	0.1

Sample Properties

Sample	Density	Temperature deg. C.	Wt. Fract. Alc.	Mol. Fract. Alc.	Mol. Fract. Alc.*
y_{21}	.8732	21.7	.650	.422	
x_{22}	.8764	22.0	.657	.427	
y_{22}	.8698	21.3	.690	.465	.614
x_{23}	.8687	22.3	.687	.462	
y_{23}	.8621	21.7	.7175	.4985	.62[illegible]
T	.8765	27.5	.625	.406	
B	.9971	23.3	.000	.000	
F	.9911	23.0	.028	.012	

Remarks: Steam supply dropped to 35 psig. during run.

Viscosity Determinations

Sample	x_{22}	x_{23}	B
B. P. deg. C.	80.4	80.0	100
Bath temp.	79.0	79.0	93.0
Time of efflux in seconds	8.51	8.72	15.67
	8.72	8.70	15.65
	8.72	8.75	15.69
	8.72	8.72	15.64
Value used	8.72	8.72	15.66
Viscosity in centipoise	.674	.669	1.37

Run Number 14 9/26/49

.075% CMC solution
Steam to column at 100 psig.
Feed liquid to column at 60° C.
Rate of CMC feed

time	fall
3:02	0"
3:06	1"
3:07	2"
3:10	3"
3:22	4"
3:30	5"
3:34	6"
3:38	7"
3:51	8"

Steam condensate

height	time
2.9"	at 3:10
17.5"	at 4:05

Diameter of condensate tank is 18.75"

Diameter of CMC feed tank is 12.5"

Rotameter readings

Feed	10.4
Reflux	3.8
Product	.05

Sample Properties

Sample	Density	Temperature deg. C.	Wt.Fract. Alc.	Mol.Fract. Alc.	Mol.Fract. Alc.*
y_{21}	.9001	25.0	.542	.317	
x_{22}	.9375	26.2	.305	.103	
y_{22}	.8701	24.8	.672	.444	.518
x_{23}	.9343	27.8	.376	.191	
y_{23}	.8630	25.1	.701	.4775	.521
T	.9019	26.9	.529	.305	
B	.9979	27.6	.000	.000	
F	.9867	27.2	.055	.0225	

Viscosity Determinations

Sample	x_{22}	x_{23}	B
B.P. deg. C.	82.5	82.5	100.0
Bath temp.	81.5	81.5	99.0
Time of efflux in seconds	144.	168	30.31
	144.5	177	29.57
		172.5	22.73
			29.18
			28.32
			28.12
			27.82
			27.90
			27.72
Value used	144	172	27.81
Viscosity in centipoise	11.93	14.16	2.43

Run Number 15

0.75% CMC solution
Steam to column at 90 psig.
Feed liquid to column at 82° C.
Rate of CMC feed

time	fall
11:02	0
11:11	1.0
11:14	2.1
11:25	3.0
11:27.5	4.0
11:33	5.3
11:38	6.4
11:39.5	7.0
11:40	8.1
11:43.5	9.0
11:48	10.0

Steam condensate

3.9" at 11:09
19.5" at 12:08

Diameter of condensate tank is 18.75"
Diameter of CMC feed tank is 12.5"

Rotameter readings

Feed	9.7
Reflux	3.1
Product	2.85

Sample Properties

Sample	Density	Temperature deg. C.	Wt.Fract. Alc.	Mol.Fract. Alc.	Mol.Fract. Alc.*
y_{21}	.9792	22.3	.114	.047	
x_{22}	.9875	23.0	.058	.023	
y_{22}	.9654	22.8	.213	.096	.205
x_{23}	.9764	22.9	.132	.056	
y_{23}	.9585	23.0	.260	.121	.345
T	.9482	23.0	.321	.156	
B	.9992	22.9	.000	.000	
F	.9846	23.0	.076	.031	

Viscosity Determinations

Sample	x_{22}	x_{23}	B
B. P. deg. C.	93.5	88.5	100.0
Bath temp.	92.5	87.5	98.5
Time of efflux in seconds	24.92	27.22	23.85
	24.68	27.30	23.94
	24.64	27.40	23.93
	24.78	27.40	33.80
Value used	24.70	27.40	23.88
Viscosity in centipoise	2.14	2.36	2.09

Run Number 16 9/29/49

0.75% CMC solution
Steam to column at 85 psig.
Feed liquid to column at 83 deg. C.
Rate of CMC feed

time	fall
3:13.5	.5
3:14.5	1.0
3:16	2.0
3:17.5	3.0
3:20.5	4.0
3:27	5.0
3:33	6.0
3:38	7.5

Rotameter readings

Feed	10.5
Reflux	3.3
Product	3.7

Diameter of CMC feed tank is 12.5"

Sample Properties

Sample	Density	Temperature deg. C.	Wt.Fract. Alc.	Mol.Fract. Alc.	Mol.Fract. Alc.*
y_{21}	.9779	24.0	.120	.050	
x_{22}	.9844	29.1	.066	.027	
y_{22}	.9758	26.8	.127	.053	.225
x_{23}	.9702	29.1	.160	.069	
y_{23}	.9698	26.5	.171	.074	.330
T	.9502	27.2	.295	.1505	
B	.9979	27.8	.038	.015	
F	.9896	27.1	.038	.015	

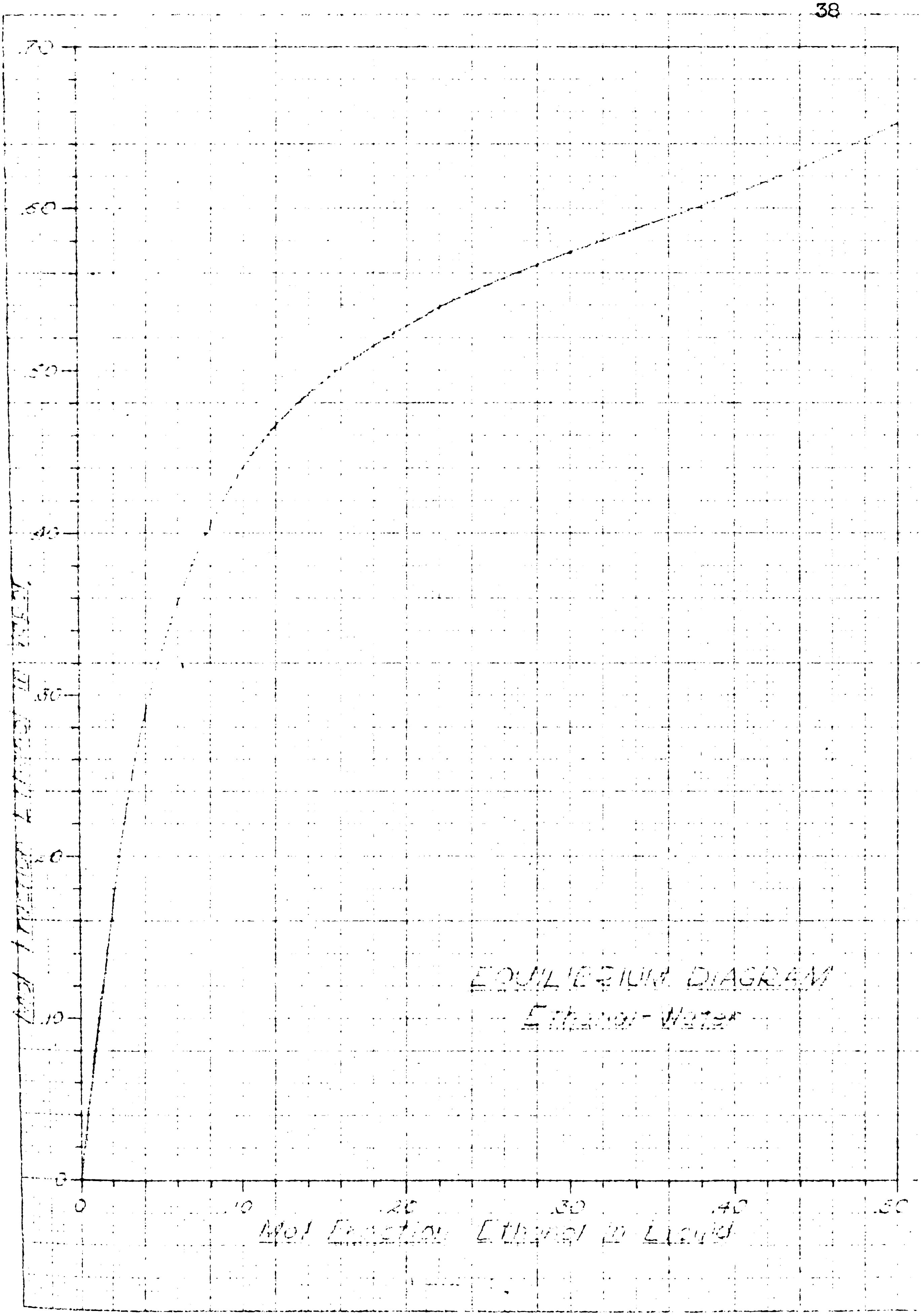
Viscosity Determinations

Sample	x_{22}	x_{23}	B
B. P. deg. C.	93.0	87.5	100.0
Bath temp.	92.0	86.5	98.5
Time of efflux in seconds	31.20	18.73	28.04
	31.13	18.47	27.98
	31.30	18.39	27.95
		18.48	27.75
		18.44	27.81
Value used	31.21	18.45	27.84
Viscosity	2.65	1.58	2.42

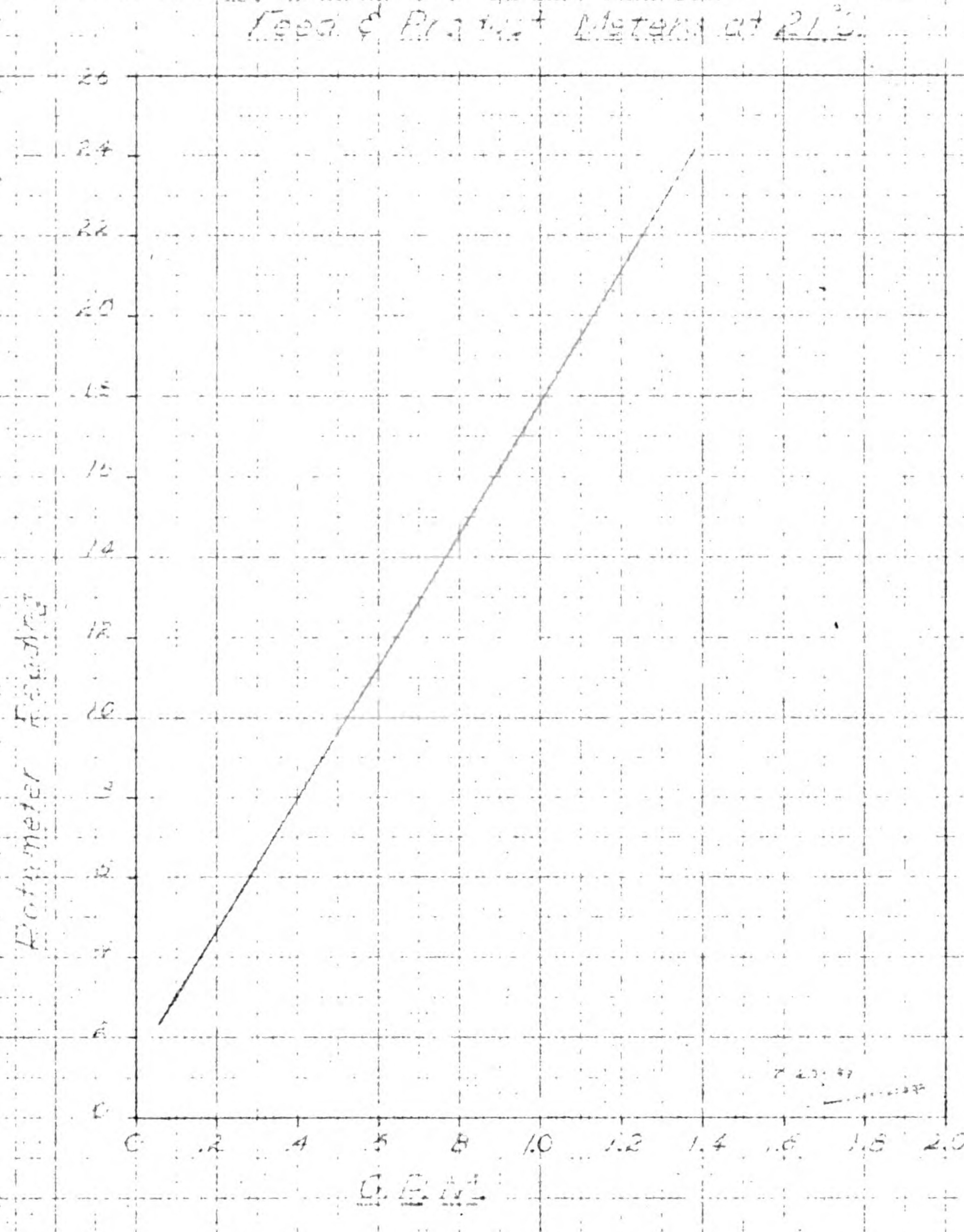
TABLE I

SUMMARY OF DATA

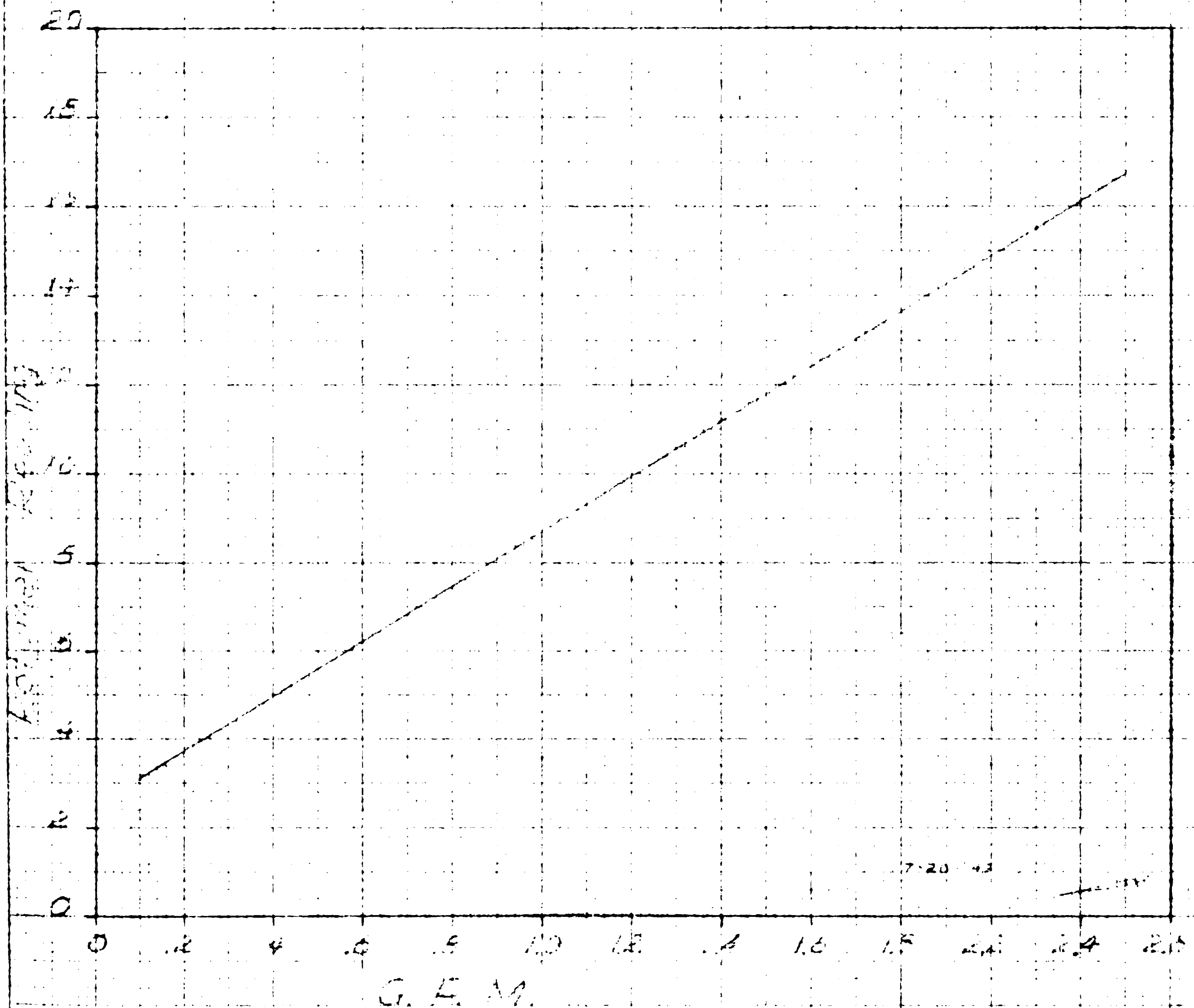
Run	22nd tray Efficiency	22nd tray Viscosity	23rd tray Efficiency	23rd tray Viscosity	Over-all Efficiency	Bottoms Viscosity
1	0.26	1.30	0.44	0.85	0.292	
2	0.17	8.82	0.47	1.81	0.208	2.20
3	0.20	6.47	0.10	1.95	0.250	2.35
4	0.01	1.09	0.38	5.70	0.208	2.84
5	0.37	3.48	0.10	0.82	0.208	1.28
6					0.292	1.27
7	0.22	2.89	0.56	2.81	0.292	1.26
8	0.19	3.73	0.35	3.55	0.375	1.60
9	0.04	0.68	0.29	1.99	0.208	1.17
10	0.09	0.67	0.10	0.71	0.208	0.77
11	-0.28	0.68	0.22	0.67	0.208	0.61
12	0.16	1.05	0.29	6.20	0.208	0.78
13	0.23	0.67	0.20	0.67	0.624	1.37
14	0.63	11.93	0.44	14.16	0.292	2.43
15	0.36	2.14	0.10	2.36	0.292	2.09
16	0.017	2.65	0.076	1.58	0.208	2.42


EQUILIBRIUM DIAGRAM
Ethanol-Water
.70
.60
.50
.40
.30
.20
.10
0
0
.10
.20
.30
.40
.50
Mol Fraction Ethanol in Liquid

ROTAMETER CALIBRATION
Feed & Product Meters at 21°C.



ROTAMETER CALIBRATION



DISCUSSION

It is important to note that the efficiency of this tower is unusually low, while it is often possible to easily reach 95% efficiency with commercial towers of this and other systems. With this tower the average over-all efficiency was approximately 25%. Similar results have been shown by other persons using the tower in the past.

Naturally one can only postulate upon the reasons for these low efficiencies, for there may be many. The seemingly most obvious reason is the small amount of vapor space between plates. The individual trays in the column are spaced on six inch centers. Such a distance is recognized as being very near the minimum. At such a distance a very significant amount of entrainment may result at the higher vapor velocities, reducing the over-all efficiency.

The high ratio of tower wall surface area to the tray area and vapor space may also add some explanation to the efficiency figures. A column of small diameter such as this one may have the coefficient of heat transfer between liquid and vapor reduced because of the liquid collection upon the wall. It is understood that the transfer occurs, not only between vapor bubbles and liquid on the tray, but also between the vapor and liquid droplets in the vapor space. A lengthy discussion might result over which is controlling. If a portion of the liquid droplets collect upon the tower wall in the form of a film, the transfer surface area is reduced, resulting in a decrease in the transfer coefficient and over-all efficiency.

Other conditions, such as the small number of bubble-caps per tray, may also contribute to the trend of efficiency figures.

It must be understood, therefore, that any conclusions drawn from this experimental data of this problem should be taken in a relative sense with regard to other towers and systems, rather than in the absolute.

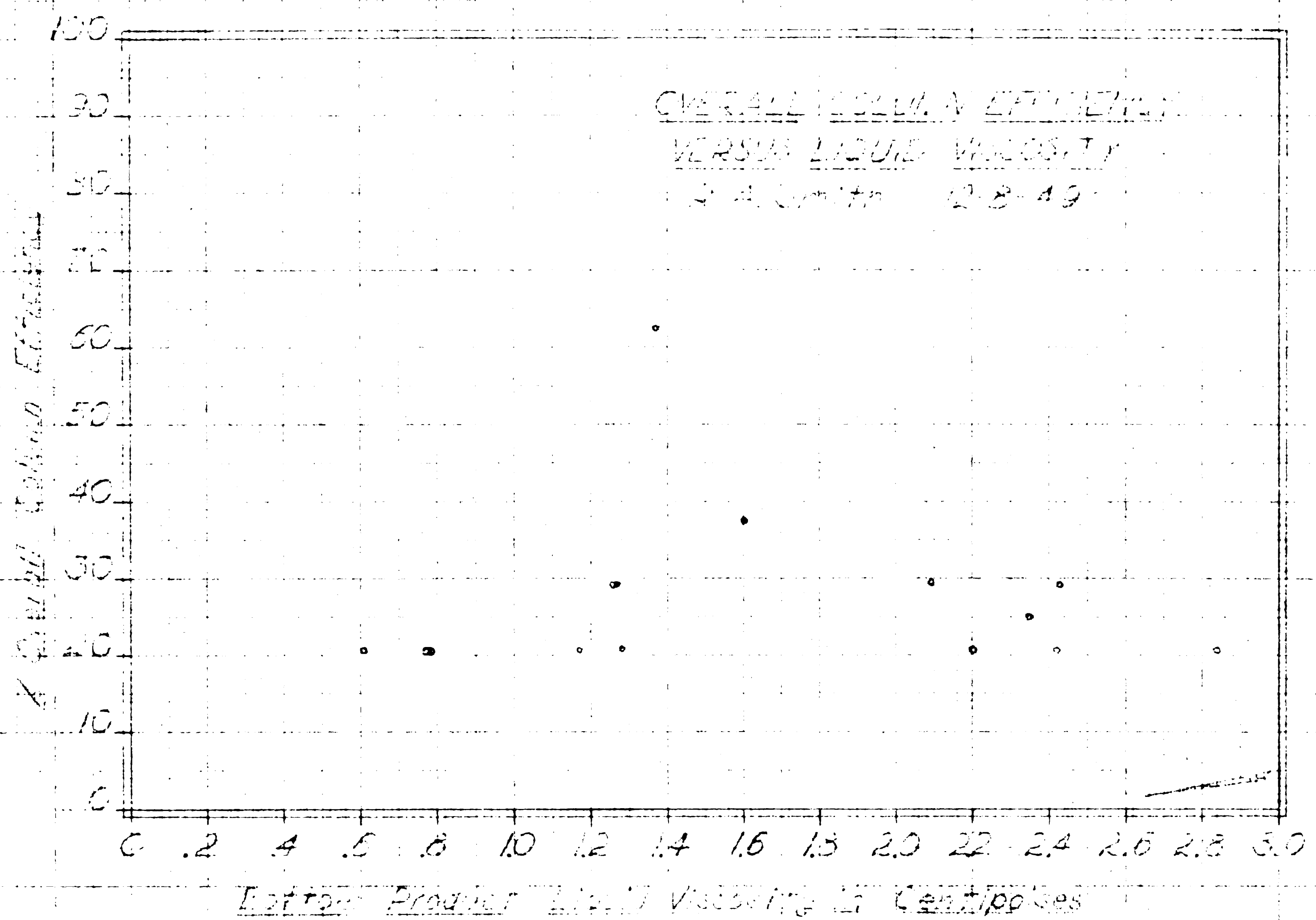
Figure 4 is a drawing of one of the bubble-trays copied from the company prints. It illustrates the lay-out of the bubble-caps, weirs, down spout, and sampling ports. It is difficult to explain the variation in individual tray efficiencies except perhaps by the close location of the sampling ports to the bubble-caps. It might conceivably cause a local concentration change if the liquid is depleted near one side of a cap. A change in concentration of the sample can cause an error in the calculation of the theoretical enrichment and the resulting plate efficiency.

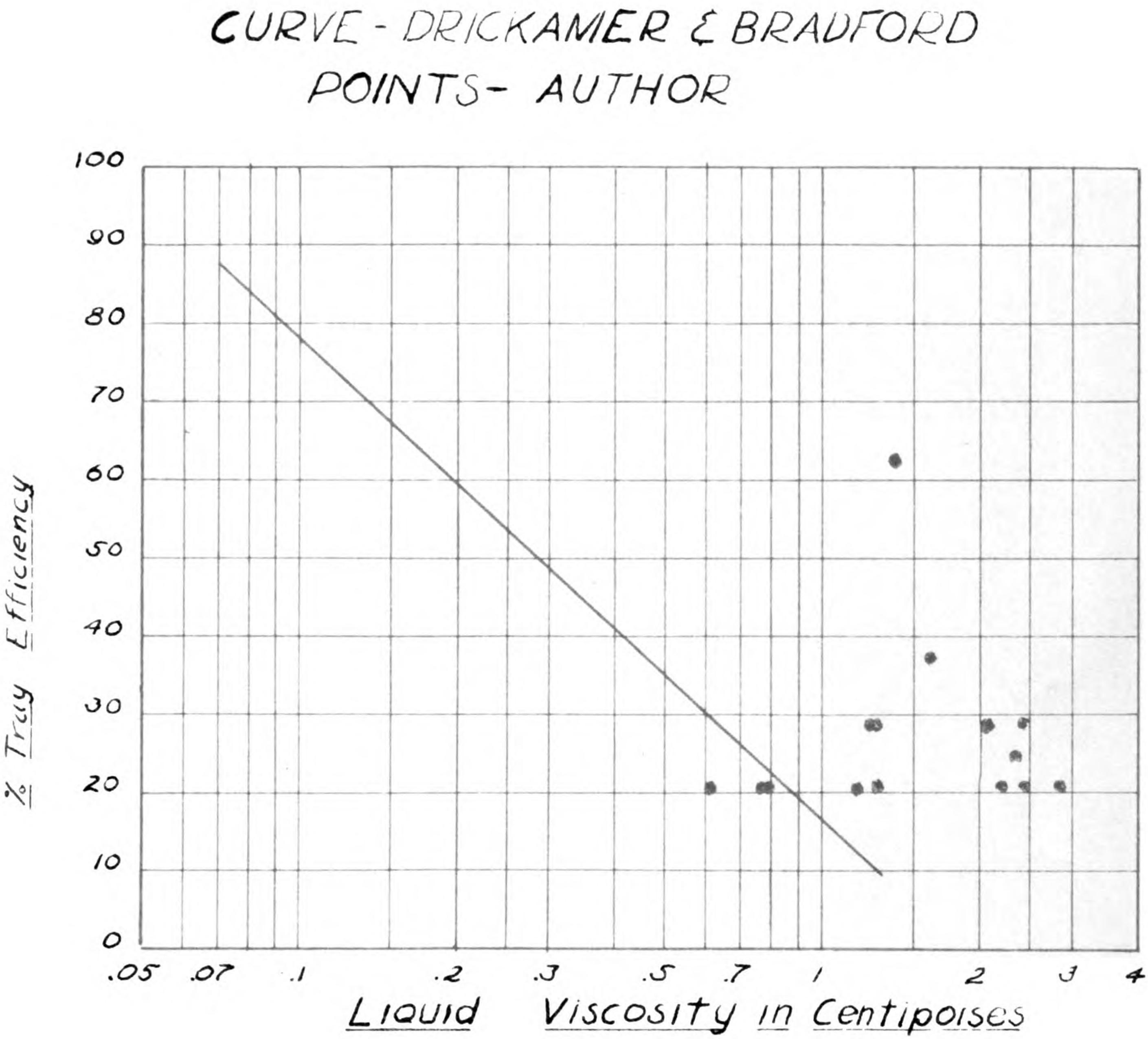
The results of the problem are shown in Table I. Figure 12 illustrates in graphic form the over-all tray efficiency versus liquid viscosity. Over the range of viscosity studied here, there is no apparent correlation between liquid viscosity and bubble tray efficiency.

The data observed here is plotted over the curve of Drickamer and Bradford in figure 13. The two do not agree. Drickamer and Bradford include in their original data only one point at a viscosity of greater than 0.5 centipoise. It is logical to have some doubt of the validity of the correlation in the region from 0.5 to 1.5 centipoise. Their correlation would indicate an efficiency of near 30% for towers with a liquid viscosity near that of water, and correspondingly lower for higher viscosities. While not true for this particular tower, it is known that many commercial alcohol-water towers operate at much higher efficiencies, and the results of the present work indicate that the efficiency does not necessarily decrease with increasing viscosity over the range observed.

Figures 15 and 16 illustrate the effect of CMC concentration upon the solution density and viscosity. It was discovered after extensive duplicate calculations that correcting the solution concentrations for any change in density due to the slight amounts of CMC had a negligible effect upon the resulting efficiency figures.

It was necessary to determine the liquid viscosity at a temperature slightly below the actual boiling point. If any boiling had actually occurred during the determination it would have caused considerable error. For simplicity, the boiling point was determined from the concentration, and


OVERALL COLUMN EFFICIENCY
VERSUS LIQUID VISCOSITY
% Overall Column Efficiency
Bottom Product Liquid Viscosity in Centipoises


CURVE - DRICKAMER & BRADFORD
POINTS- AUTHOR
100
90
80
70
60
50
40
30
20
10
0
.05
.07
.1
.2
.3
.5
.7
1
2
3
4
Liquid Viscosity in Centipoises
% Tray Efficiency

a temperature of one degree Centigrade less used. Figure 17, taken from the Hercules pamphlet, indicates that at higher temperatures then is little change in viscosity with temperature, so the author feels the action justified. (2)

The method used in calculating the efficiency was a modification of the Sorel method. (9) This method was chosen because of its greater accuracy over the McCabe-Thiele, for the effect of the added CMC and the changes in latent heat may be included. In the modified Sorel method the effect of the difference between actual and theoretical feed compositions may also be corrected. The basic equations of the modified Sorel method are shown below. (See Figure 14).

A material balance around the top of the column and the n+1 plate yields

$$V_n = O_{n+1} + D - C \qquad (1)$$

and

$$Y_n V_n = X_{n+1} O_{n+1} + X_V D \qquad (2)$$

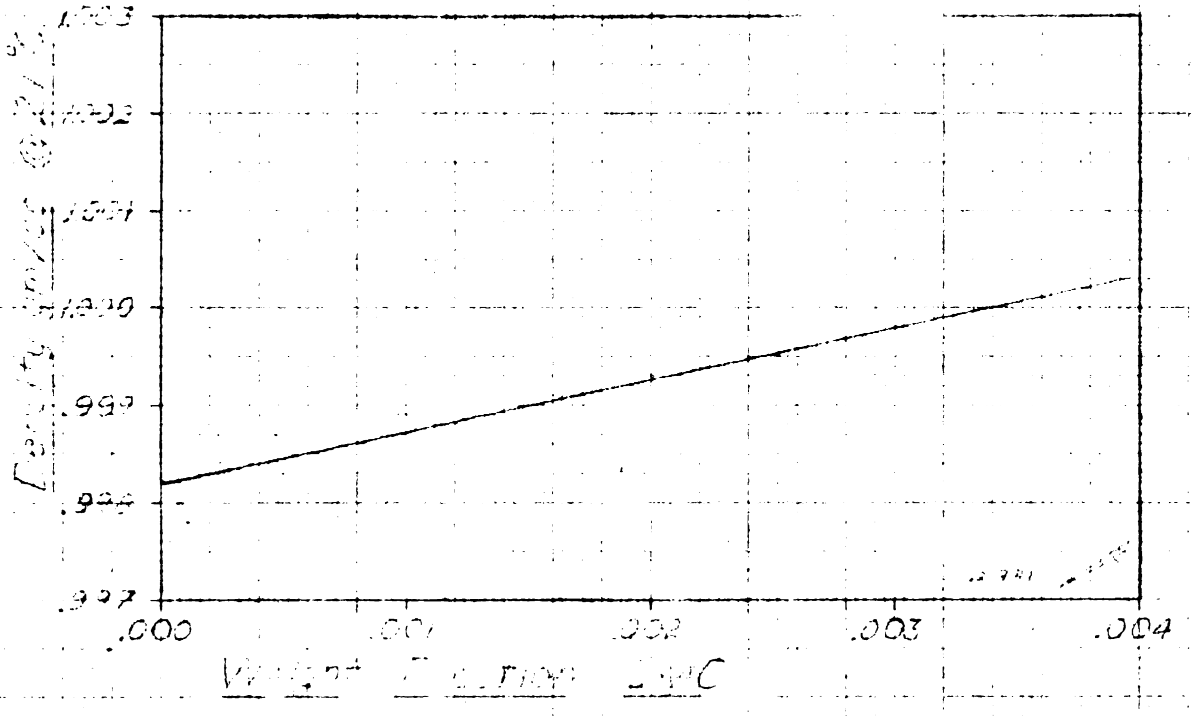
then

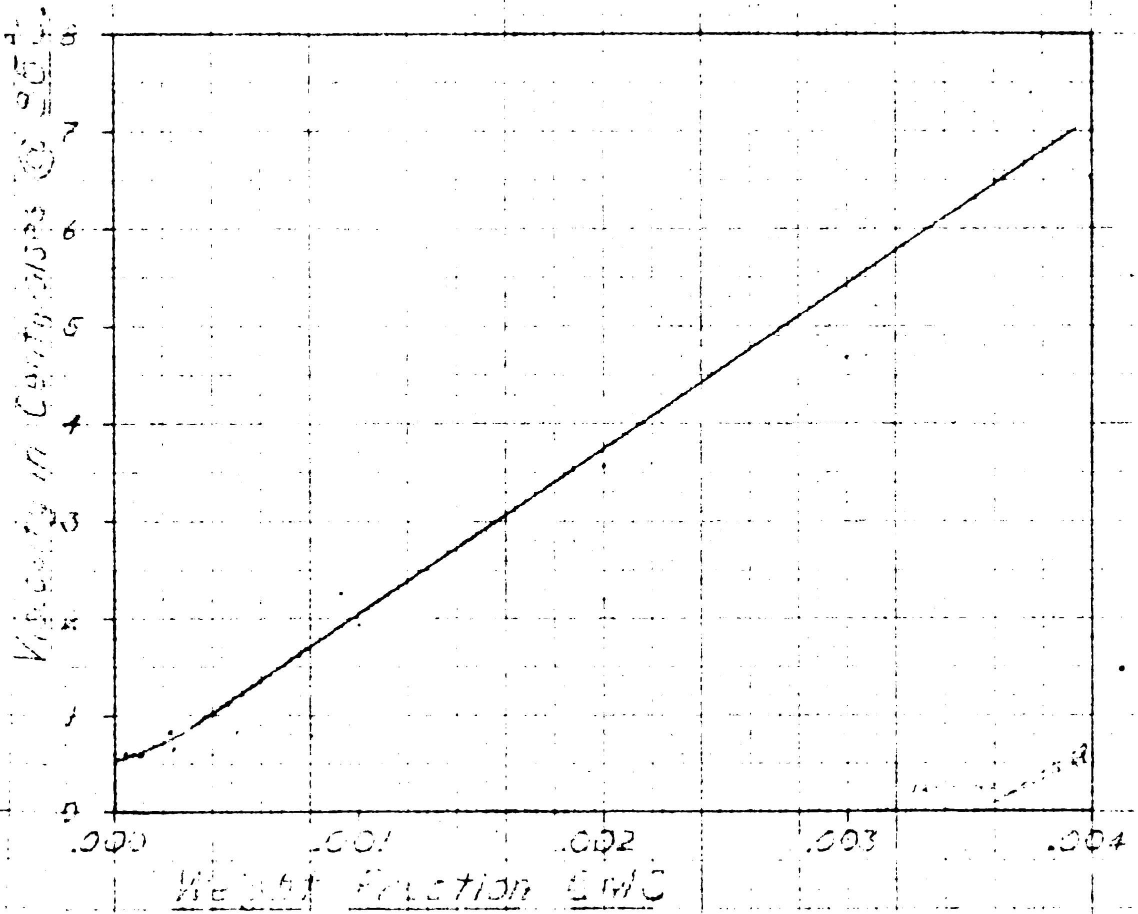
$$Y_n = \frac{X_{n+1} O_{n+1}}{O_{n+1} + D-C} + \frac{X_d D}{O_{n+1} + D-C} \qquad (3)$$

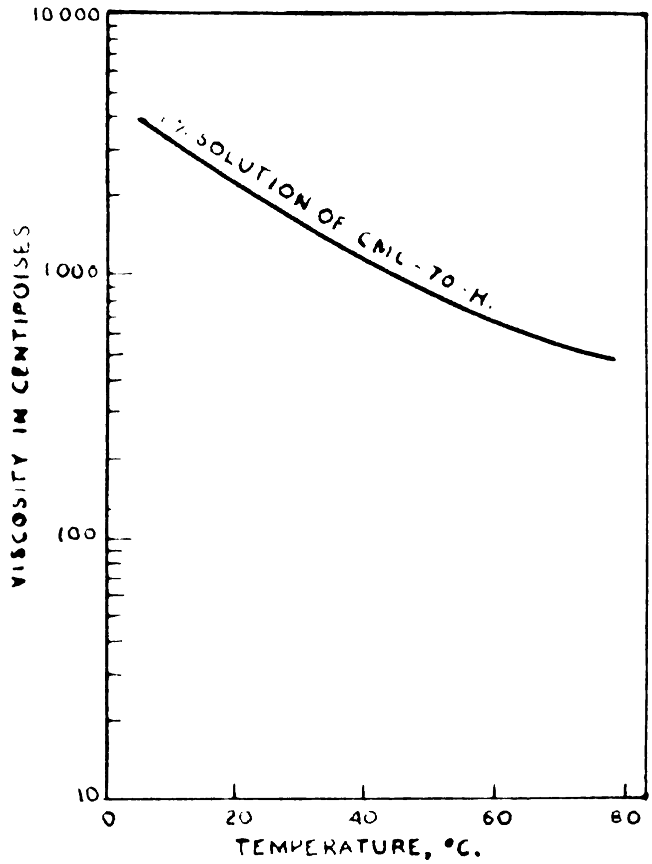
$$Y_n = \frac{X_{n+1} O_{n+1}}{V_n} + \frac{X_D D}{V_n} \qquad (3)$$

A material balance around the bottom of the column and the mth plate yields

$$O_{m+1} = V_m + W \qquad (4)$$


Weight Fraction CMC
.000
.001
.002
.003
.004


Weight Fraction CMC
.000
.001
.002
.003
.004
1
4
5
6
7


10 000
1000
100
10
0
20
40
60
80
VISCOSITY IN CENTIPOISES
TEMPERATURE, °C.

By the same reasoning as in (3)

$$Y_m = \frac{X_{m+1}\ O_{m+1}}{O_{m+1} - W} - \frac{X_w W}{O_{m+1} - W} \qquad (5)$$

$$Y_m = \frac{X_{m+1}\ O_{m+1}}{V_m} - \frac{X_w W}{V_m} \qquad (5)$$

Making a heat balance around the top plate

$$V_{t-1}\ H_{t-1} + O_r h_r + Ch_c = V_t\ H_t + O_t\ h_t \qquad (6)$$

Equation (1) may be written for the top of the column

$$V_t = O_r + D - C \qquad (7)$$

and for the top plate

$$V_{t-1} = O_t + D - C \qquad (8)$$

Also for the top plate

$$Y_{t-1} = \frac{X_t\ O_t}{V_{t-1}} + \frac{X_d D}{V_{t-1}} \qquad (9)$$

Another important equation around the complete tower is

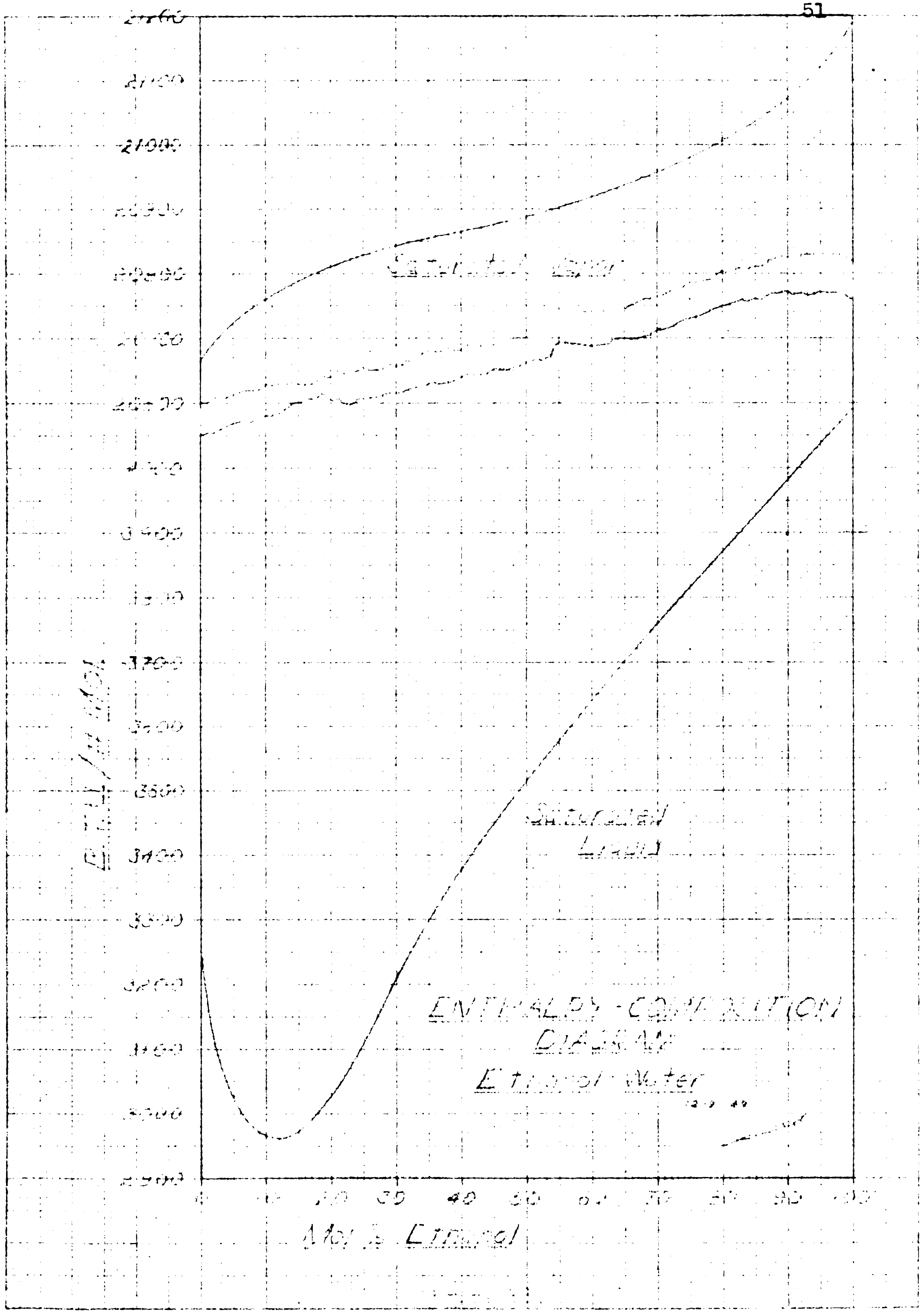
$$W = F + C - D \qquad (10)$$

and around the condenser

$$V_t = O_r + D \qquad (11)$$

It was necessary to modify equation (5) for use on the f-1 tray when the actual feed composition differed from the theoretical.

$$Y_m = \frac{X_{m+1}\ O_{m+2}}{V_m} + \frac{X_f F}{V_m} - \frac{X_w W}{V_m} \qquad (12)$$


ENTHALPY-COMPOSITION
DIAGRAM
Ethanol-Water
Saturated
Liquid
Mol % Ethanol
30
40

CONCLUSIONS

On the basis of the experimental and theoretical work done, the author believes the following conclusions may be drawn:

1. There is no definite correlation between the efficiency and liquid viscosity of a bubble-tray tower in the viscosity range from 0.6 to 3.0 centipoise.
2. The correlation of Drickamer and Bradford is in error in their higher viscosity range if it is to be used as a general correlation covering all types of systems.
3. There are many things which have a far greater effect upon the tray efficiency than the liquid viscosity. Some of these are, slot area, bubble-cap design, weir design, downspout design, tray diameter, and vapor and liquid rates.
4. There are several improvements which would lessen the difficulty and increase the accuracy of future work with this tower. Some of these improvements include: thermometers in the feed, reflux, and product rotameters, and condensers, a large diameter vapor connection between the kettle and column, and rotameter calibration in the lower flow ranges.

CALCULATIONS

Sample calculation of run number 3.

Basis - 1 minute

Murphree Efficiencies -

$$E_{22} = \frac{y_{22} - y_{21}}{y^*_{22} - y_{21}} = \frac{.084 - .0675}{.150 - .0675} = 0.200$$

$$E_{23} = \frac{y_{23} - y_{22}}{y^*_{23} - y_{22}} = \frac{.116 - .084}{.392 - .084} = 0.104$$

The following calculations, along with all the others, were completed in tabular form. Since the actual calculations are very lengthy, the complete calculations from only Run No. 3 will be given. A condensation of the more important figures of the rest of the runs will be given at the end of the calculations.

Run No. 3

Mol fract. EtOH in feed		0.0145
Mol fract. EtOH in distillate		0.206
Reflux - O_r (Corrected) (See ref. 8)		0.281 gal.
Product - D	" "	0.073 gal.
Feed - F	" "	0.49 gal.
Spec. Gravity of O_R		0.905
" " " F		0.990
" " " D		0.930
Weight of O_R		2.11 #
Weight of F		4.04 #
Weight of D		0.565#
Wt. fract. EtOH in O_R		0.398
Wt. EtOH in O_R		0.840#

Wt. water in O_R	1.27 #
Mols EtOH in O_R	0.182 mols
Mols water in O_R	0.0705 mols
Total mols of O_R	0.0887 mols of O_R
Wt. fract. EtOH in F	0.037
Wt. EtOH in F	0.149 #
Wt. water in F	3.89 #
Mols EtOH in F	0.00325 mols
Mols water in F	0.216 mols
Total mols of F	0.2193 mols of F
Wt. EtOH in D	0.225 #
Wt. water in D	0.340 #
Mols EtOH in D	0.00489 mols
Mols water in D	0.01888 mols
Total mols of D	0.02377 mols of D
Wt. water in C	0.641 #
Mols water in C	0.0362 mols of C
F plus C	0.2555 mols
$W = F + C - D$	0.2317 mols of W
$V_t = O_R + D$	0.1125 mols of V_t
Total heat of vapor - H	20816 Btu
Total heat of liquid - h	3040 Btu
Net heat of vapor - N_H	17776 Btu in N_H
$H_t = (V_t)(N_H)$	2000 Btu in H_t

Tabular form of Sorel calculations

$y_t = x_D = 0.206$

$x_t = 0.0248$

$x_F = 0.0145$

For purposes of calculation X_W was arbitrarily taken as 0.001

Estimates	H	h	N_H	H_t	V_n or V_m
1st est. y_{t-1} = .10	20758	2963	17795	2000	0.1123
2nd est. y_{t-1} = .071	20738	2986	17752	2000	0.1127
1st est. y_{t-2} = .05	20715	3028	17690	2000	0.1131

	H	h	N_H	H_t	V_m
1st est. y_{f-1} = .035	20705	3072	17633	2000	0.1134

	H	h	N_H	H_t	V_m
1st est. y_{f-2} = .020	20688	3135	17553	2000	0.1140
1st est. y_{f-3} = .007	20674	3201	17473	2000	0.1145
1st est. y_{f-4} = .005	20670	3210	17460	2000	0.1146

$$J = \frac{x_{n+1} + O_{n+1}}{V_n}$$

$$K = \frac{(x_D)\ (D)}{V_n}$$

$$M = \frac{x_{m+1} + O_{m+2}}{V_m}$$

$$Q = \frac{(x_F)\ (F)}{V_m}$$

$$Z = \frac{x_{m+1} + O_{m+1}}{V_m}$$

$$S = \frac{(x_W)\ (W)}{V_m}$$

C	$V_n + C$	D	$O_{n+1} = V_n + C - D$	J	K	y_n	x_n^*
0.0362	0.1458	0.0238	0.1247	0.0275	0.0436	0.0711	0.0083
0.0362	0.1489	0.0238	0.1251	0.0275	0.0436	0.0711	0.0083
0.0362	0.1493	0.0238	0.1255	0.0092	0.0434	0.0526	0.0064

W	$O_{m+1} = V_m + W$	M	Q	S	y_n	x_n^*
0.2317	0.3541	0.0071	0.0280	0.0020	0.033	0.0041

W	O_{m+1}	Z	S	y_n	x_n^*
0.2317	0.3457	0.0243	0.00203	0.0223	0.0030
0.2317	0.3462	0.0110	0.00202	0.0090	0.0014
0.2317	0.3463	0.00423	0.00202	0.0020	0.0003 less than 0.001

Therefore, in the third run, the Sorel method requires seven theoretical trays. These trays are t, t-1, t-2 = f, f-1, f-2 and f-4. Since the reboiler of the tower acts as one theoretical tray, tray f-4 is not counted in the efficiency calculations. The theoretical number of trays used in the efficiency calculations is six.

$E_{over\text{-}all} = 6/24 = 0.250$

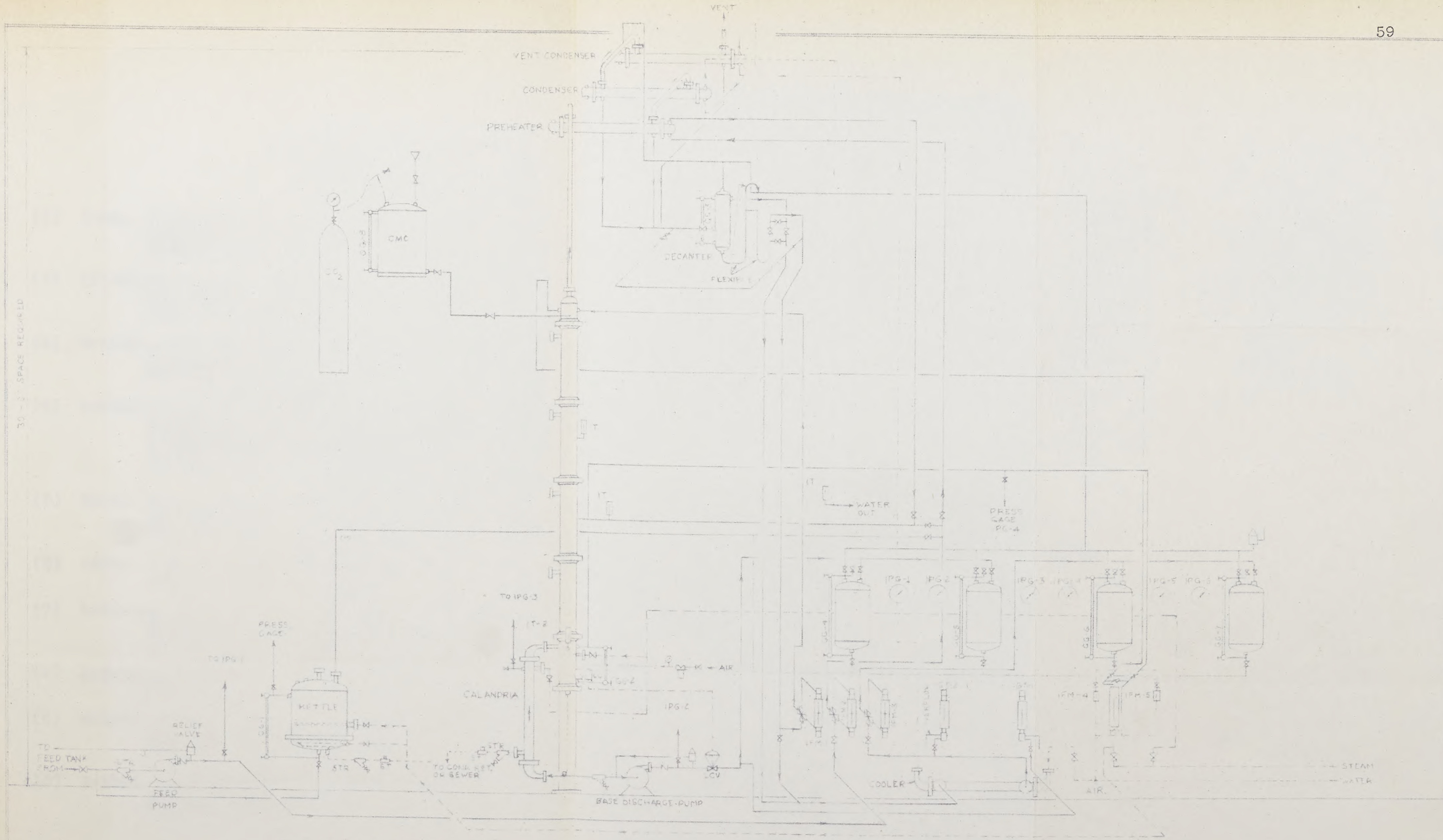
Viscosity of bottoms = 2.35 centipoise

x_{t-3}	$x_{[illegible]}$
0.0103	0.[illegible]
	0.[illegible]
	0.[illegible]
	0.[illegible]
	0.[illegible]
0.0128	0.[illegible]
0.0003	0.[illegible]
0.0120	0.[illegible]
	0.[illegible]
	0.[illegible]
	0.[illegible]
	0.[illegible]
0.0048	0.[illegible]
0.0004	0.[illegible]
0.0070	0.[illegible]
	0.[illegible]

1

NOMENCLATURE

B	bottoms product
C	mols of CMC solution
d	liquid density, gm/cc
D	mols of distillate
E	efficiency
E_{MV}	murphree point vapor efficiency
f	feed tray
F	mols of feed
h	molal heat content of liquid
h_1	effective liquid depth, inches
H	molal heat content of vapor
H_c	Henry's law coefficient, #mols/ft.^{3} atm.
N_h	net heat of vapor above liquid at its boiling point
O_n	mols of overflow from the nth tray
P	total pressure, atmospheres
t	time of efflux through the viscosimeter, seconds
T	distillate sample
u	viscosity, centipoise
V	mols of vapor
w	bubble-cap slot width, inches
W	mols of bottoms product
x_n	composition of liquid from the nth tray, mol fraction
y_n	composition of vapor from the nth tray, mol fraction
y_n^*	theoretical composition of vapor in equilibrium with the liquid on the nth tray, mol fraction



INSTRUMENTS & ACCESSORIES	
	DESCRIPTION
T	INDICATING THERMOMETER
IP	" PRESSURE GAGE
[illegible]	" FLOWMETER
[illegible]	SPECIFIC GRAVITY TESTER
M	MANOMETER
[illegible]	STEAM TRAP
STR	STRAINER
GG	GAGE GLASS
LC	LEVEL CONTROL
LCV	" " VALVE
SG	SIGHT GLASS

THE VULCAN COPPER & SUPPLY CO.

FIGURE-19

DIAGRAMMATIC ARRANGEMENT
MODEL A-2
EXPERIMENTAL DISTILLATION UNIT

2-7-49 | DWG 15180

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