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THE ABSORPTION OF HYDROGEN CHLORIDE FROM DILUTE AIR MIXTURES

BY

EDGAR L. DEMAREST

A THESIS

PRESENTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE

OF

MASTER OF SCIENCE IN CHEMICAL ENGINEERING

AT

NEWARK COLLEGE OF ENGINEERING

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Newark, New Jersey

1970

ABSTRACT

A study was made of the absorption of hydrogen chloride from air mixtures containing from 1 to 40 mgm. HCl/liter (1000 to 40000 mgm./m.^{3}), using a 4" diameter tower packed with $\frac{1}{2}$" Intalox saddles, irrigated with water or with sodium hydroxide solutions of 0.3% to 3.8% concentration. Gas flow rates of 177 to 752 lbs./(hr.)(ft.^{2}) were investigated at three liquid rates: 2960, 4260, and 5700 lbs./(hr/)(ft.^{2}). All data were collected below the flooding point.

Correlations of the height of a transfer unit with the superficial gas velocity were prepared for water and for sodium hydroxide irrigation, and a relationship was presented for the over-all coefficient of mass transfer to the ratio of sodium hydroxide normality and pressure. Height of a transfer unit is approximately 0.5 foot for a superficial gas velocity of 500 lbs./(hr.)(ft.^{2}) for both water and sodium hydroxide as absorbing liquid.

APPROVAL OF THESIS

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FROM DILUTE AIR MIXTURES

BY

EDGAR L. DEMAREST

FOR

DEPARTMENT OF CHEMICAL ENGINEERING

NEWARK COLLEGE OF ENGINEERING

BY

FACULTY COMMITTEE

APPROVED: _____

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NEWARK, NEW JERSEY

JUNE, 1970

PREFACE

A great deal of information has been published on the absorption of various gases from air, but there seems to have been only one article dealing with the absorption of hydrogen chloride from dilute air mixtures. This one paper (8) reports the performance of various types of scrubbing equipment handling air streams containing 20 mgm./m.^{3} of hydrogen chloride, using non-recirculated water as scrubbing agent. The data collected for this thesis cover concentrations of 1 to 40 mgm./liter (1000 to 40000 mgm./m.^{3}), which is a useful range for processes involving the evaporation of hydrochloric acid into a moving air stream. Although there are at present no air pollution regulations on chloride levels in force in the United States, Great Britain and Canada limit emissions to 290 ppm. (1) Proposed limits for New Jersey are very much less than this.

The correlations presented here will be of assistance in the design of equipment to produce industrial effluents of acceptable levels, and will permit evaluation of the economics of water versus caustic soda as irrigating liquid.

ACKNOWLEDGEMENTS

The advice and encouragement of Dr. J.J. Salamone in the preparation of this thesis is gratefully acknowledged.

Acknowledgement is also made to Catalyst Development Corporation for the use of their laboratory facilities and equipment in collecting the data presented here.

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I - INTRODUCTION

Hydrogen chloride in the gaseous state, or in solution in non-polar solvents such as chloroform or benzene, is a covalent compound. The solution of hydrogen chloride in water causes the covalent bond to break, transferring proton to the water and creating hydrochloric acid: (4)

$$H_2O + HCl \longrightarrow \underset{\text{oxonium ion}}{H_3O^+} + Cl^-$$

Absorption of hydrogen chloride in water is, therefore, absorption accompanied by chemical reaction. When alkaline solutions are used as absorbents, there is the second reaction of neutralization and salt formation taking place. This second reaction seems to exert only slight influence on the rate of absorption.

Absorption with simultaneous chemical reaction has been studied by many investigators, among the first of whom were Hatta (6) and Davis and Crandall (3). Hatta's work was based on the two-film concept of Whitman, and showed that, if a rapid irreversible reaction takes place in the liquid phase, the rate of absorption may be controlled only by the resistance to diffusion in the gas phase. He studied the absorption of carbon dioxide in potassium hydroxide and potassium carbonate solutions, which follows Henry's Law reasonably well. The results

were expressed as:

$$\frac{dW}{A\,d\theta} = \frac{(S/2 + HP_g)}{(1/k_l + H/k_g)} \qquad \text{(Equation 1-1)}$$

The earlier work of Whitman had defined film coefficients thus: (9)

$$K_G = K_L/H = \frac{1}{1/k_g + H/k_l} \qquad \text{(Equation 1-2)}$$

The value of H, which is the slope of the partial pressure versus concentration curve, is virtually zero for HCl in the concentration range under investigation, as shown in Figure 1-1.

Davis and Crandall showed diagramatically the concentration gradients existing in the liquid film for cases of no reaction, irreversible mol for mol reaction in one stage, and instantaneous irreversible reaction in two stages. These diagrams are shown in Figure 1-2. The absorption of hydrogen chloride in water is represented by diagram B, and if alkaline absorbing agents are used, by diagram C. This work was revised by Sherwood and Pigford (15). They assumed Henry's Law to apply in the first section of the reaction zone, and further assumed that the molal rates of diffusion for reactant and product were equal. These assumptions give the equation:

$$N_A = \frac{(P/H) + (D_B/D_A)q}{(x_L/D_A) + (1/HK_g)} \qquad \text{(Equation 1-3)}$$

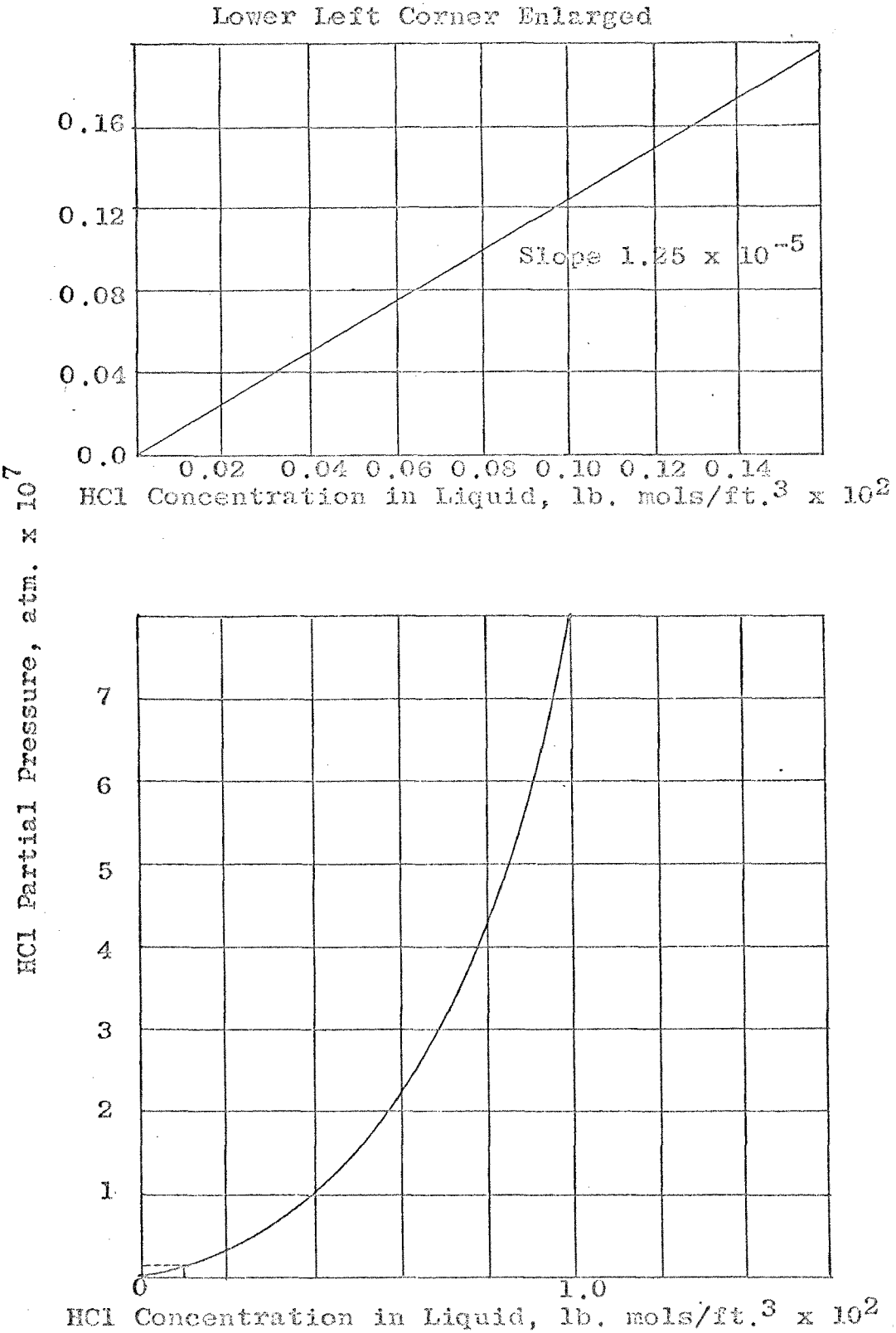


FIGURE 1-1 PARTIAL PRESSURE OF HYDROGEN CHLORIDE

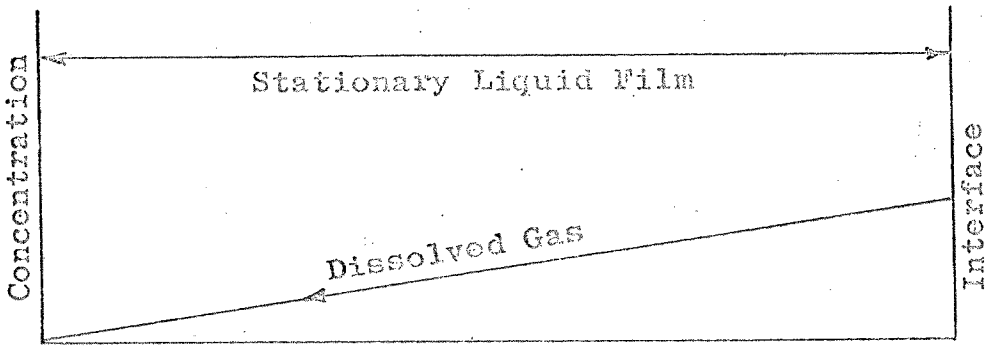


FIGURE 1-2A SCHEMATIC DIAGRAM OF
GAS & LIQUID FILM - PHYSICAL ABSORPTION

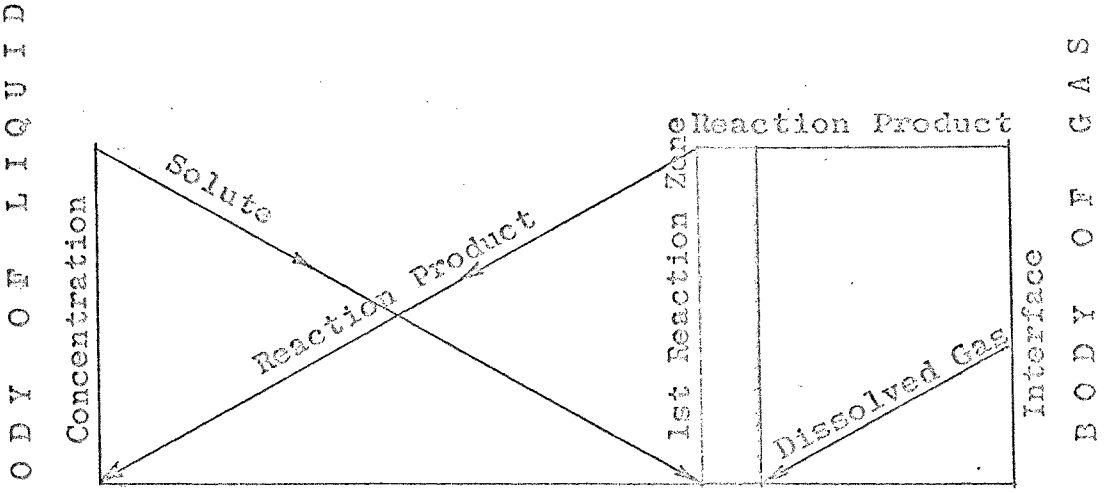


FIGURE 1-2B SCHEMATIC DIAGRAM OF
GAS & LIQUID FILM - ONE STAGE REACTION

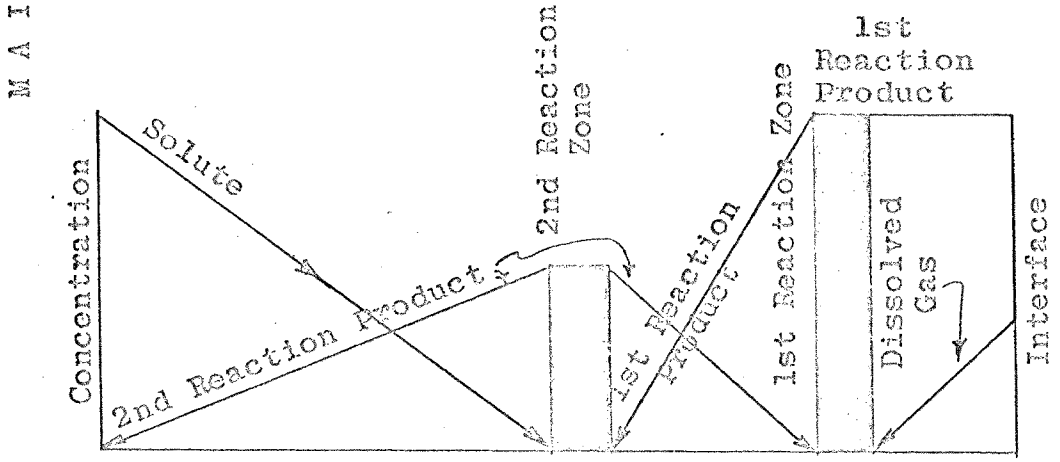


FIGURE 1 -2C SCHEMATIC DIAGRAM OF
GAS & LIQUID FILM - TWO STAGE REACTION

Eliminating gas concentrations gives:

$$N_A = (D_A/x_L)(1 + D_B q/D_A c_{Ai}) \quad \text{(Equation 1-4)}$$

Where no chemical reaction takes place, the coefficient is equal to D_A/x_L. The expression in the second parentheses in Equation 1-4 shows the effect of concentration of the substance reacting with the solute.

Hydrogen chloride does not follow Henry's Law, since dissociation into ions occurs when solution takes place. Denbigh (5) shows that, for hydrogen chloride in dilute solutions, the partial pressure of the gas varies as the square of the HCl concentration rather than as the first power. If this relationship is used in the calculations which follow, the values of $K_G a$ become enormous (in the 10,000 to 50,000 range) and H_{OG} correspondingly small. When Henry's Law is assumed to hold over the narrow range of concentration explored here, the values of $K_G a$ and H_{OG} agree much more closely with the published data, as shown in Figure 4-4.

The dividing line between pure physical absorption and absorption accompanied by chemical reaction is frequently difficult to draw. Teller (18) lists 24 common industrial absorption systems which involve chemical reaction in a comprehensive review of the subject. Norman (10) points out that, if a physical absorption is largely gas-film

controlled, the addition of a reactant to the liquid should not affect the overall coefficient of mass transfer. In the case of hydrogen chloride absorption, the coefficient appears not to be greatly influenced by the addition of sodium hydroxide. The absorption process, although gas-film controlled, is certainly not a purely physical one.

Higbie (7) in 1935 presented the penetration theory of absorption, based on the mathematical work done by von Wroblewski (19) in 1878 and on Fick's Law of Diffusion. (7) This theory derives its name from the proposed mechanism of penetration of a quiescent liquid film by the dissolved gas. Danckwerts (2) modified Higbie's idea to produce the surface renewal theory, providing for the internal turbulence of the liquid film which occurs under industrial conditions.

The following is a comparison of liquid film coefficients calculated in accordance with the three theories:

Two film Theory	$k_L = D/B$
Penetration Theory	$k_L = 2\sqrt{D/\pi\theta}$
Surface Renewal Theory	$k_L = \sqrt{Ds}$

Sherwood and Holloway(14) found that the liquid film coefficient was proportional to $D^{\frac{1}{2}}$, which agrees with the penetration and surface renewal theories.

II - PROCEDURE

The apparatus used to collect the data presented here is shown schematically in Figure 2-1.

Hydrogen chloride was injected into a measured air stream by bubbling a small amount of air through warmed concentrated hydrochloric acid. The mixed gases were sampled and fed to the bottom of the experimental tower, made from 4" diameter Pyrex pipe and filled to a depth of 2 feet with $\frac{1}{2}$" Intalox saddles made of porcelain. The absorbing liquid, either water or dilute caustic soda, was recirculated through a rotameter. A sample was also taken from the exit gas stream.

Samples were taken by aspirating the gas slowly, about 200 ml./minute, into calibrated 4 liter bottles, passing the gas through two gas absorbing bottles filled with distilled water. After completion of sampling, the hydrochloric acid present was determined by titrating to a bromcresol green endpoint using N/50 sodium hydroxide. Sample collection periods were synchronized so that the inlet and exit samples were collected over approximately the same time interval. In the case of caustic scrubbing, samples of the recirculated liquid were taken at intervals and the alkali content determined by titration with N/50 sulfuric acid using bromcresol green indicator.

Air flow and rate of liquid recirculation were measured by rotameter. Inlet and exit gas temperatures were read from mercury thermometers and column pressure drop was indicated by water manometer.

One hundred runs were made, but the results of the first 34 were not reported. In these runs, N/50 sodium hydroxide was used as absorbent in the sample bubblers, and the solution back-titrated with N/50 sulfuric acid to a phenolphthalein endpoint. This procedure proved unsatisfactory, since ambient carbon dioxide was also absorbed and included in the titration. Changing to water as absorbing liquid and bromcresol green as indicator eliminated this interference.

Readings were taken at various gas flow rates and at three liquid recirculation rates. The data collected are presented in tabular form in the appendix. The wide scattering of the data points is believed due to difficulties in analysis, which was confirmed by Kemper, Seiler and Bowman. (8) They were able to obtain reproducible results only by measuring electrical conductivity of the solution in the sample collecting bubblers, and they comment that the customarily used wet test methods are neither simple nor reproducible.

The air rotameter (2) measures only the air passing

directly into the column, and does not include the side stream which passes through the hydrochloric acid reservoir. The error introduced by this is negligible, being about 0.1%.

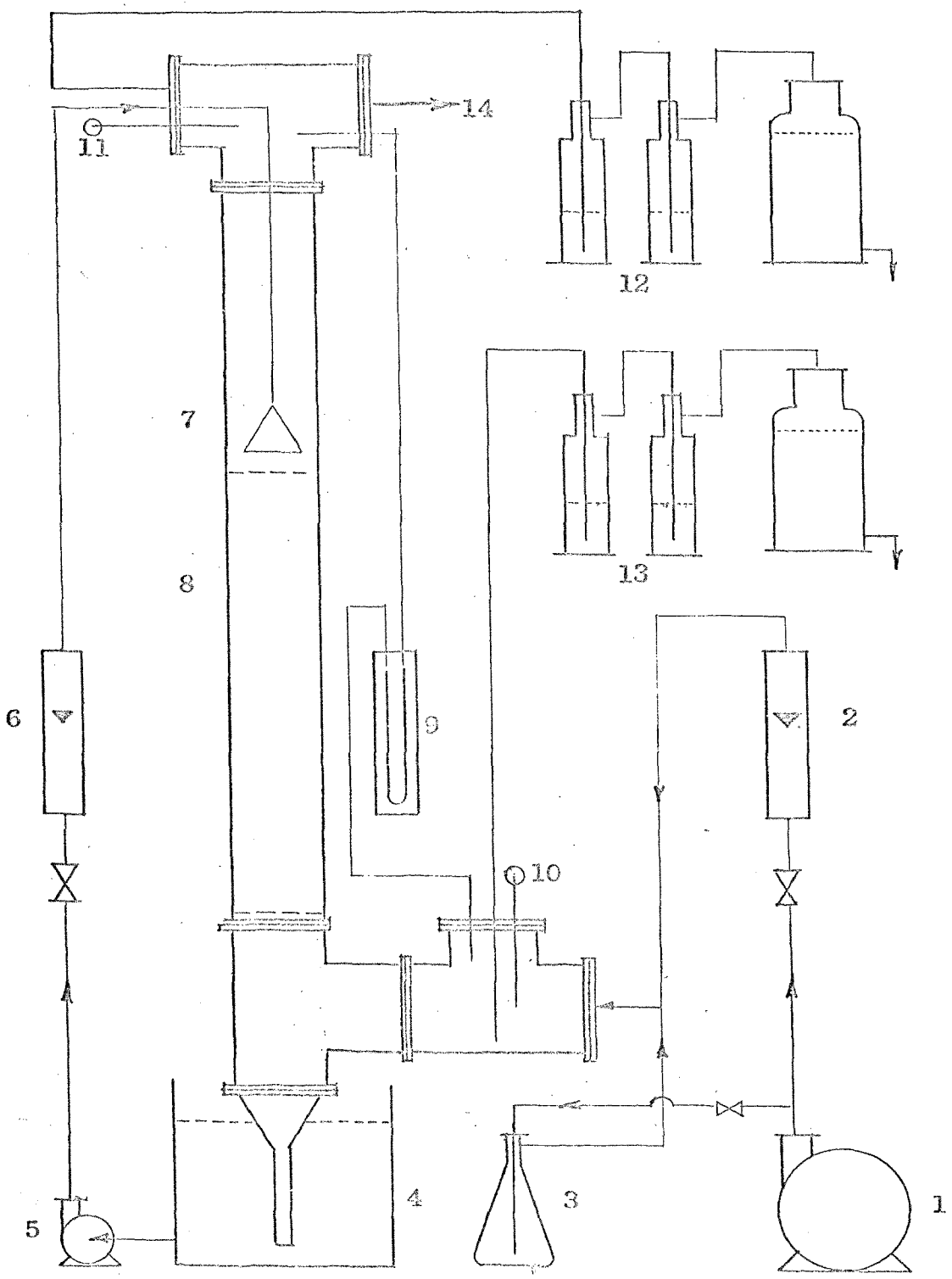


FIGURE 2-1 EQUIPMENT FLOW SHEET

KEY TO FIGURE 2-1

1	Air Blower
2	Air Rotameter
3	Hydrochloric Acid Flask
4	Recirculation Tank
5	Recirculation Pump
6	Liquid Rotameter
7	Liquid Distributor
8	Packed Column
9	Water Manometer
10	Inlet Gas Thermometer
11	Outlet Gas Thermometer
12	Outlet Gas Sample Train
13	Inlet Gas Sample Train
14	Outlet to Atmosphere

III - DISCUSSION OF RESULTS

The results of the investigation are presented as a series of graphs. Figure 4-1 is a plot of pressure drop across the packed section of the column versus G. Since the column was Pyrex glass, it was possible to confirm visually that all observations were made below the flooding point.

Figures 4-2, 4-3 and 4-4 show the effect of G on H_{OG} for water as the irrigating liquid at L = 5700, L = 4260 and L = 2960, respectively. The curves are drawn by the method of least squares, and are represented by the following equations:

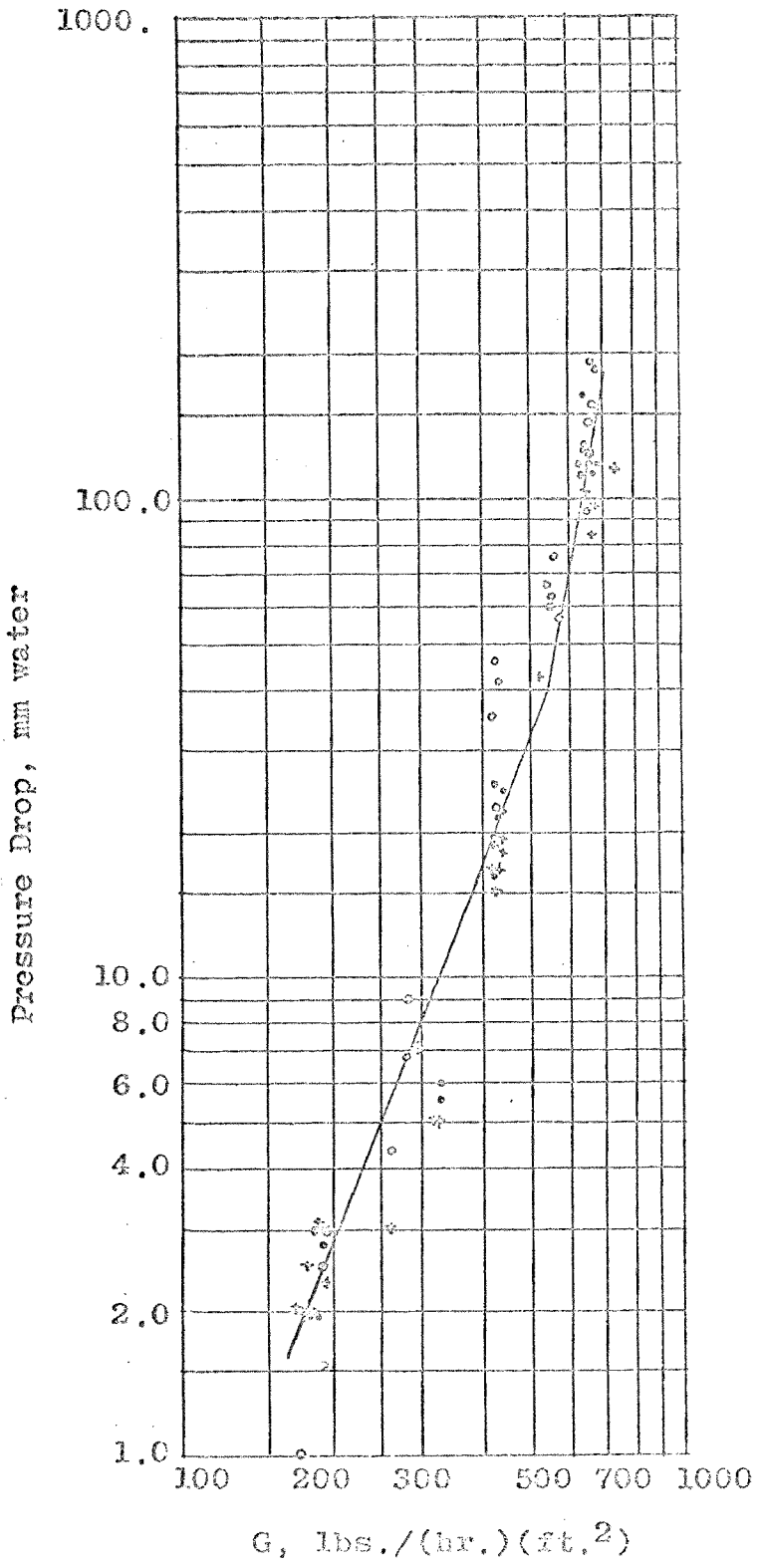
$$L = 5700 \qquad H_{OG} = 0.070\ G^{0.32}$$

$$L = 4260 \qquad H_{OG} = 0.006\ G^{0.74}$$

$$L = 2960 \qquad H_{OG} = 0.024\ G^{0.49}$$

At G = 500, H_{OG} values calculate to be 0.51, 0.59, and 0.51, respectively, for the three liquid flow rates. As G increases, H_{OG} increases for a given L, which is in agreement with the observations of Sherwood (16) on ammonia absorption in water. There are a great many data available on the ammonia-water system, and Perry (11) gives a factor $\left[(\mu/\rho D)/0.78\right]^{\frac{1}{2}}$ for converting H_{OG} values for ammonia to other gases. This conversion was made for L = 2960, and the curve is drawn as a broken line on Figure

FIGURE 4-1 EFFECT OF GAS RATE ON PRESSURE DROP



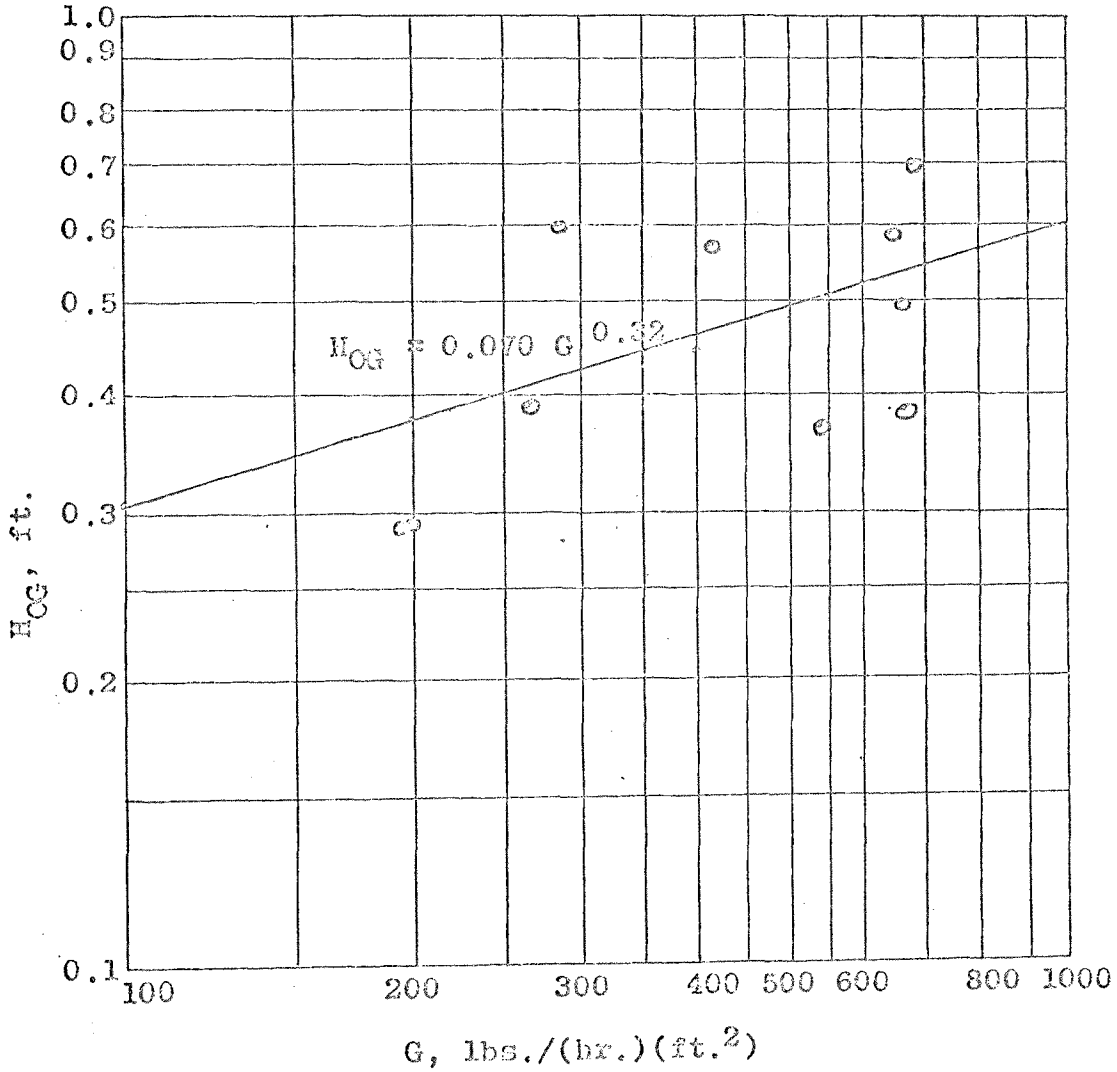


FIGURE 4-2
EFFECT OF GAS RATE
ON H_{OG} L = 5700
(Water)

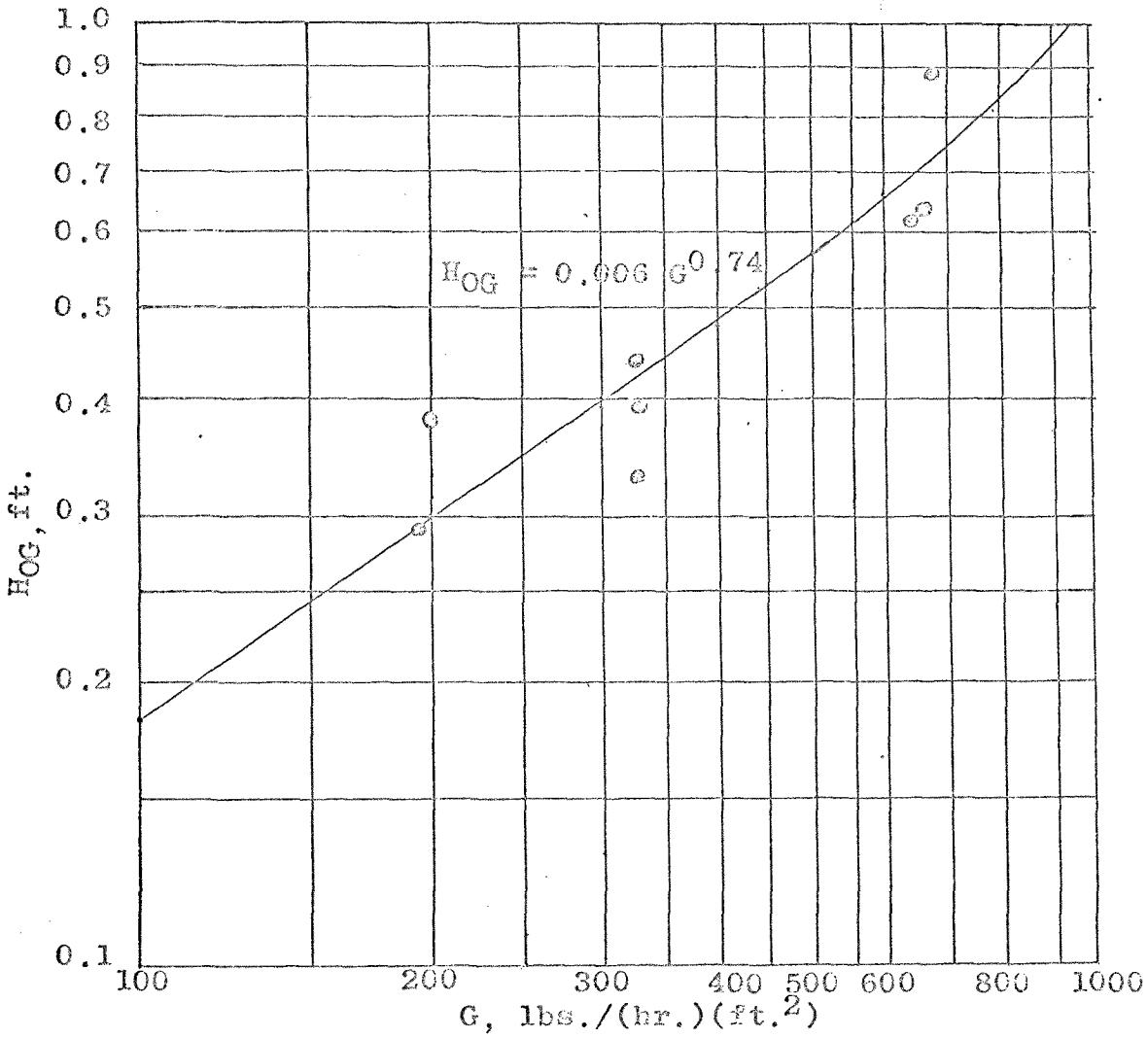


FIGURE 4-3
EFFECT OF GAS RATE
ON H_{OG} L = 4260
(Water)

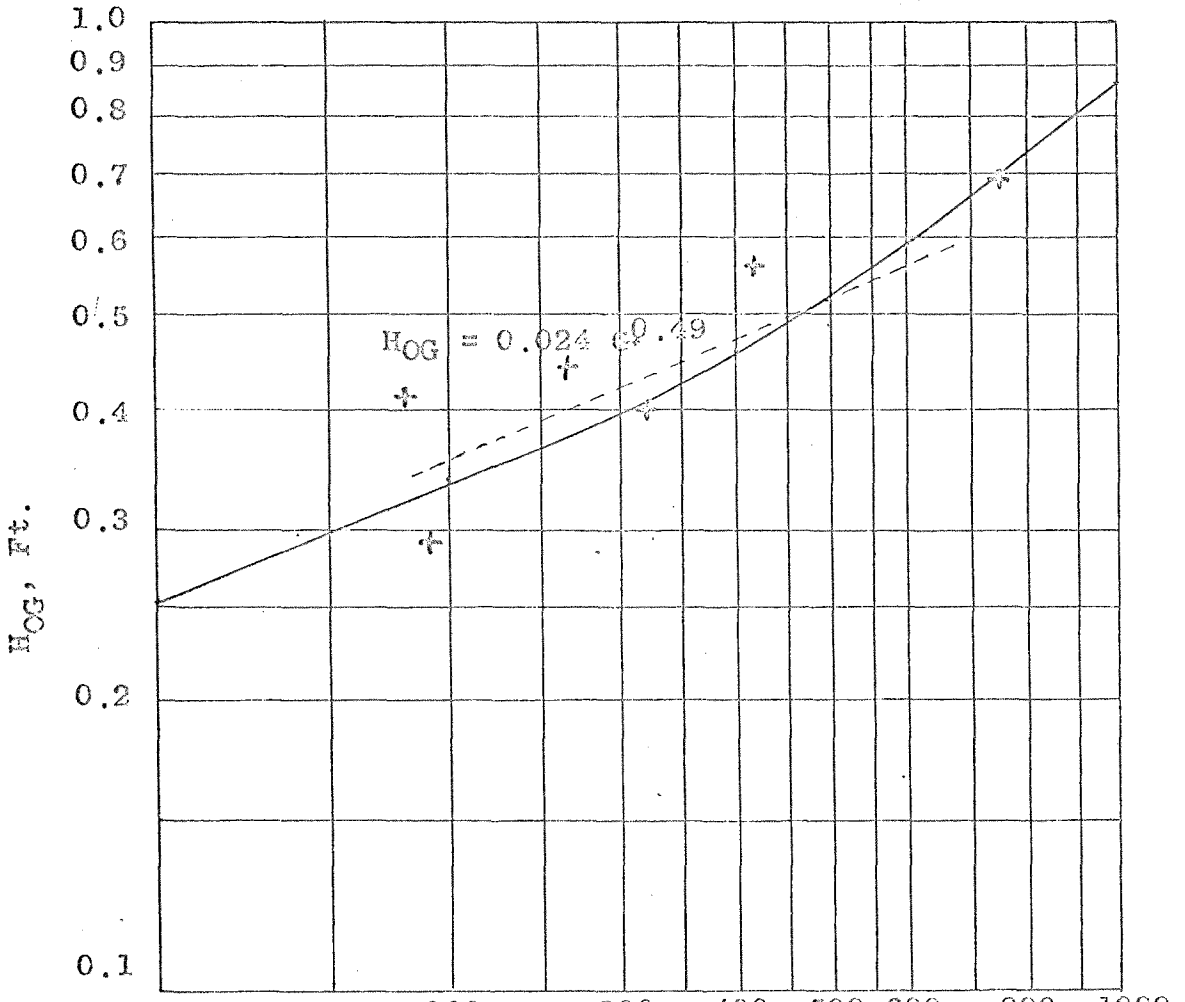


FIGURE 4-4
EFFECT OF GAS RATE
ON H_{OG} L = 2960
(Water)

4-4, showing reasonable agreement with the observed data.

Similar curves, Figures 4-5, 4-6, and 4-7 show the change in H_{OG} with G for irrigation with solutions of caustic soda at liquid rates of L = 5700, L = 4260 and L = 2960, respectively. The equations of these curves are:

$$L = 5700 \qquad H_{OG} = 0.027\ G^{0.49}$$

$$L = 4260 \qquad H_{OG} = 0.065\ G^{0.30}$$

$$L = 2960 \qquad H_{OG} = 0.44\ G^{0.049}$$

For G = 500, H_{OG} values calculated from these equations are 0.56, 0.42, and 0.60 respectively for the three liquid flow rates. The data from which these curves were plotted show wider variation than for those of water as absorbing liquid.

Sherwood and Holloway (12) produced a correlation of gas film resistance to mass transfer by plotting $H_{OG}L^{1/3}$ against G. Figure 4-8 shows this correlation for water as the absorbing liquid, and Figure 4-9 is the graph for irrigation with caustic soda solutions. The curves for these equations are:

$$\underline{\text{Water}} \qquad H_{OG} = 0.194\ \frac{G^{0.63}}{L^{1/3}}$$

$$\underline{\text{Caustic Soda}} \qquad H_{OG} = 2.68\ \frac{G^{0.173}}{L^{1/3}}$$

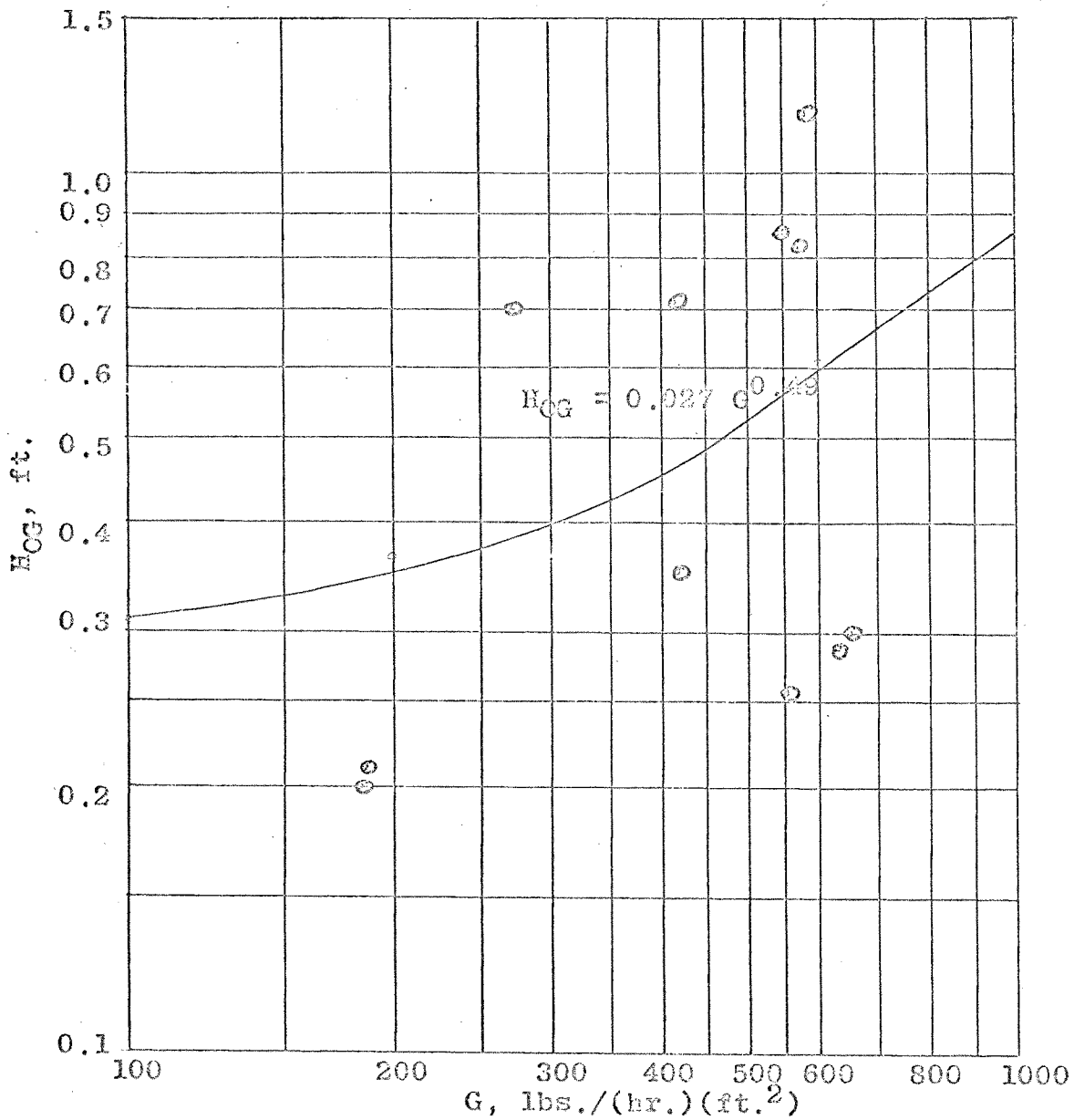


FIGURE 4-5
EFFECT OF GAS RATE
ON H_{OG} L = 5700
(Sodium Hydroxide)

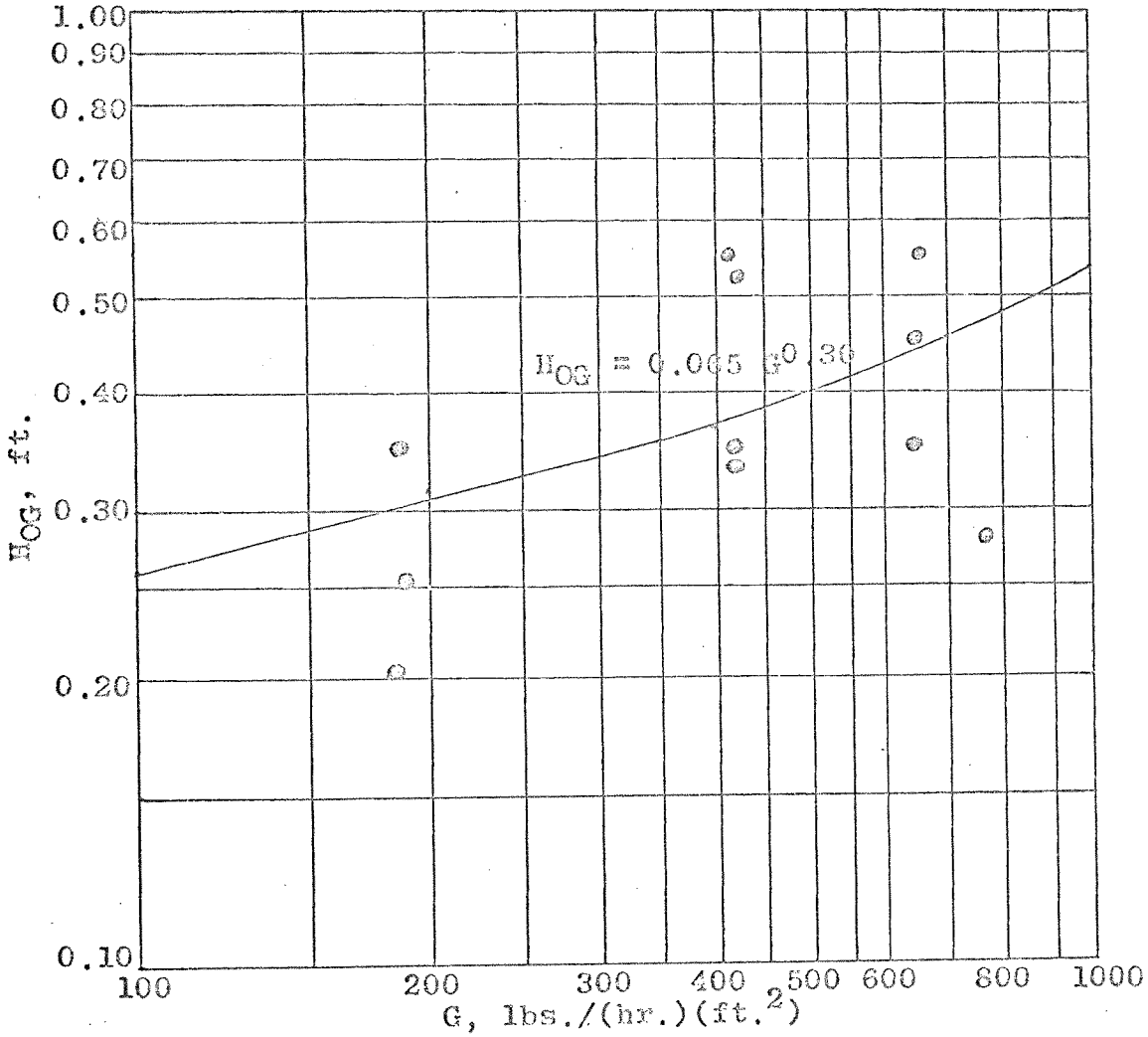


FIGURE 4-6
EFFECT OF GAS RATE
ON H_{OG} L = 4260
(Sodium Hydroxide)

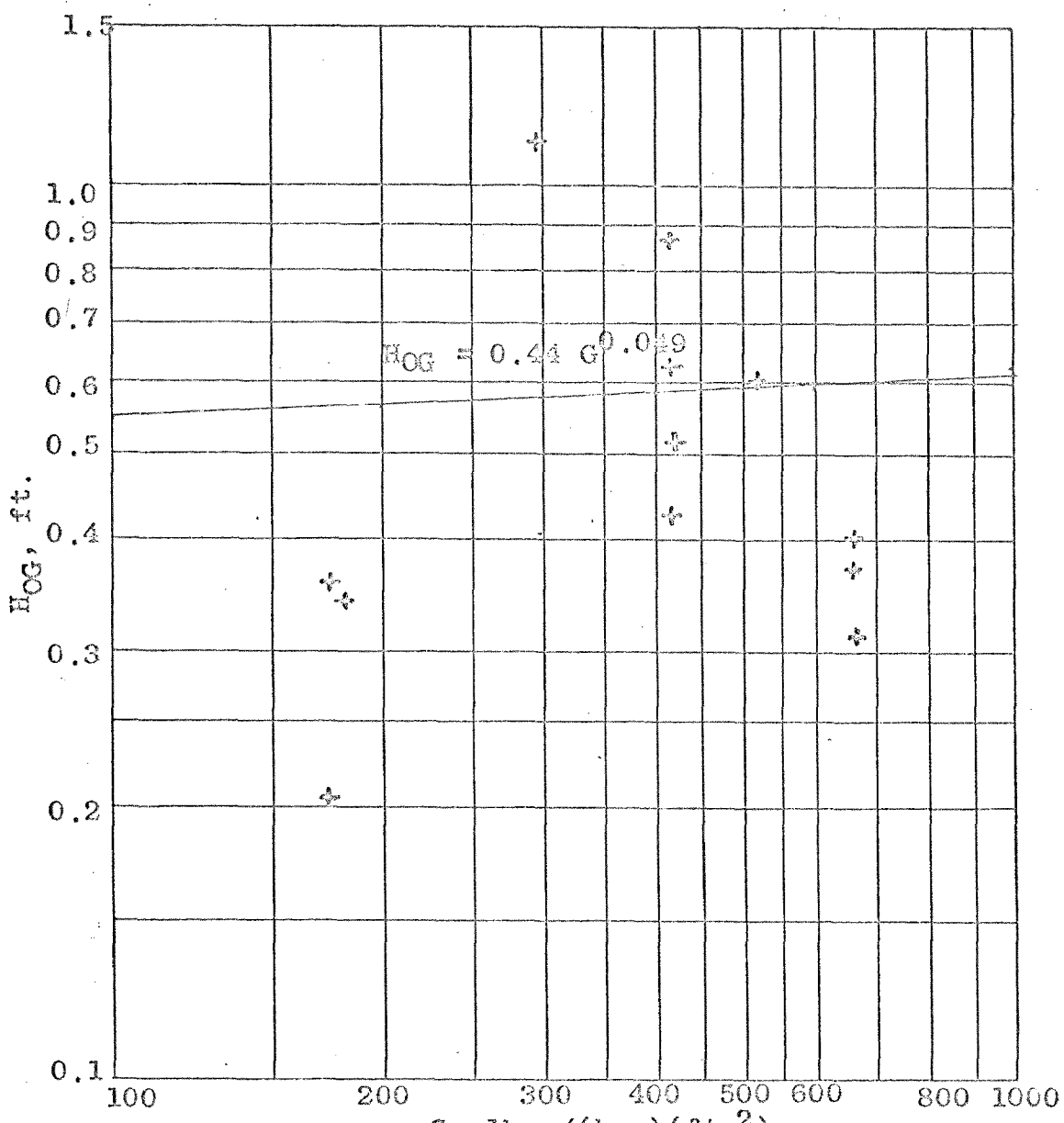
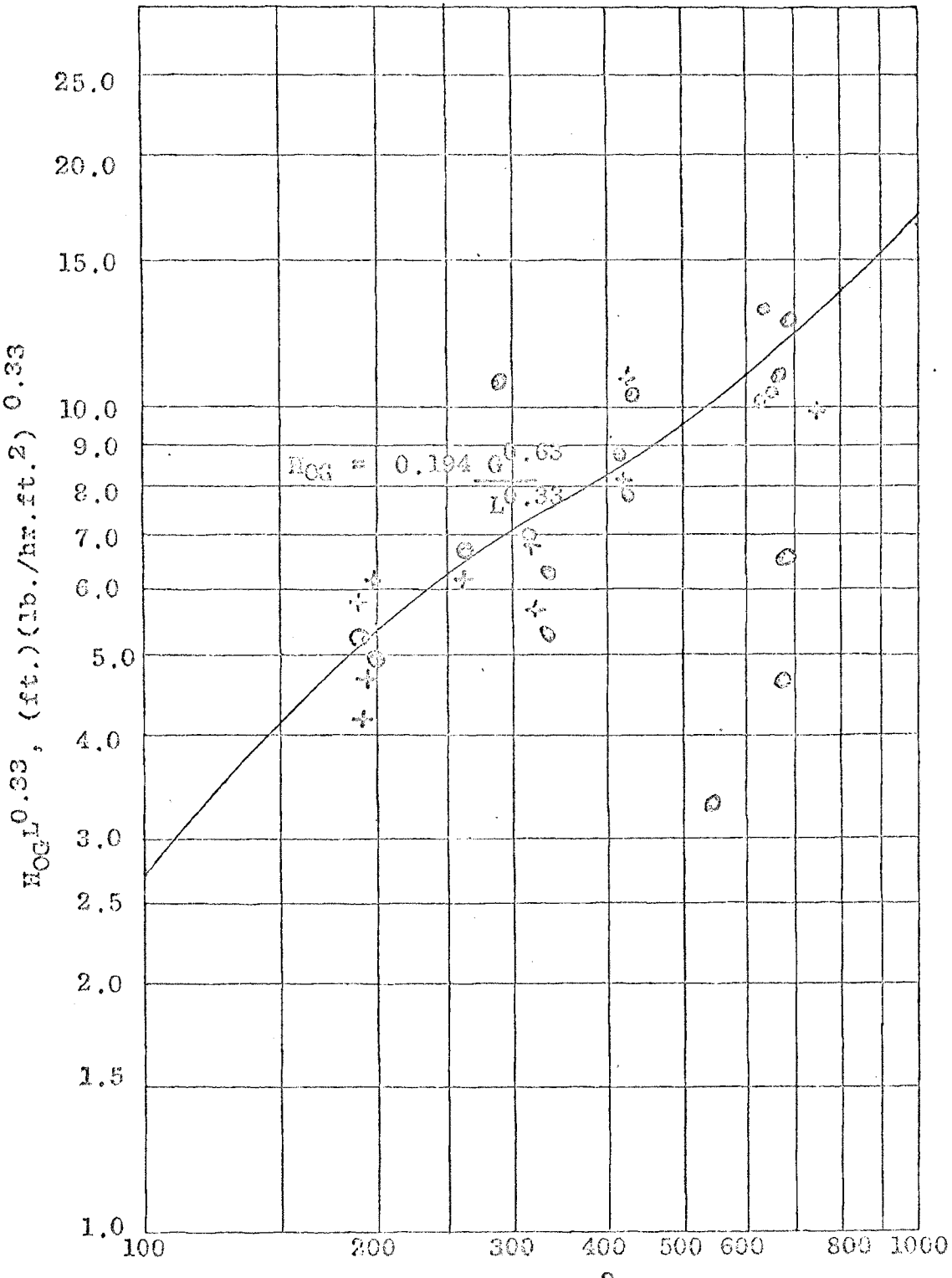


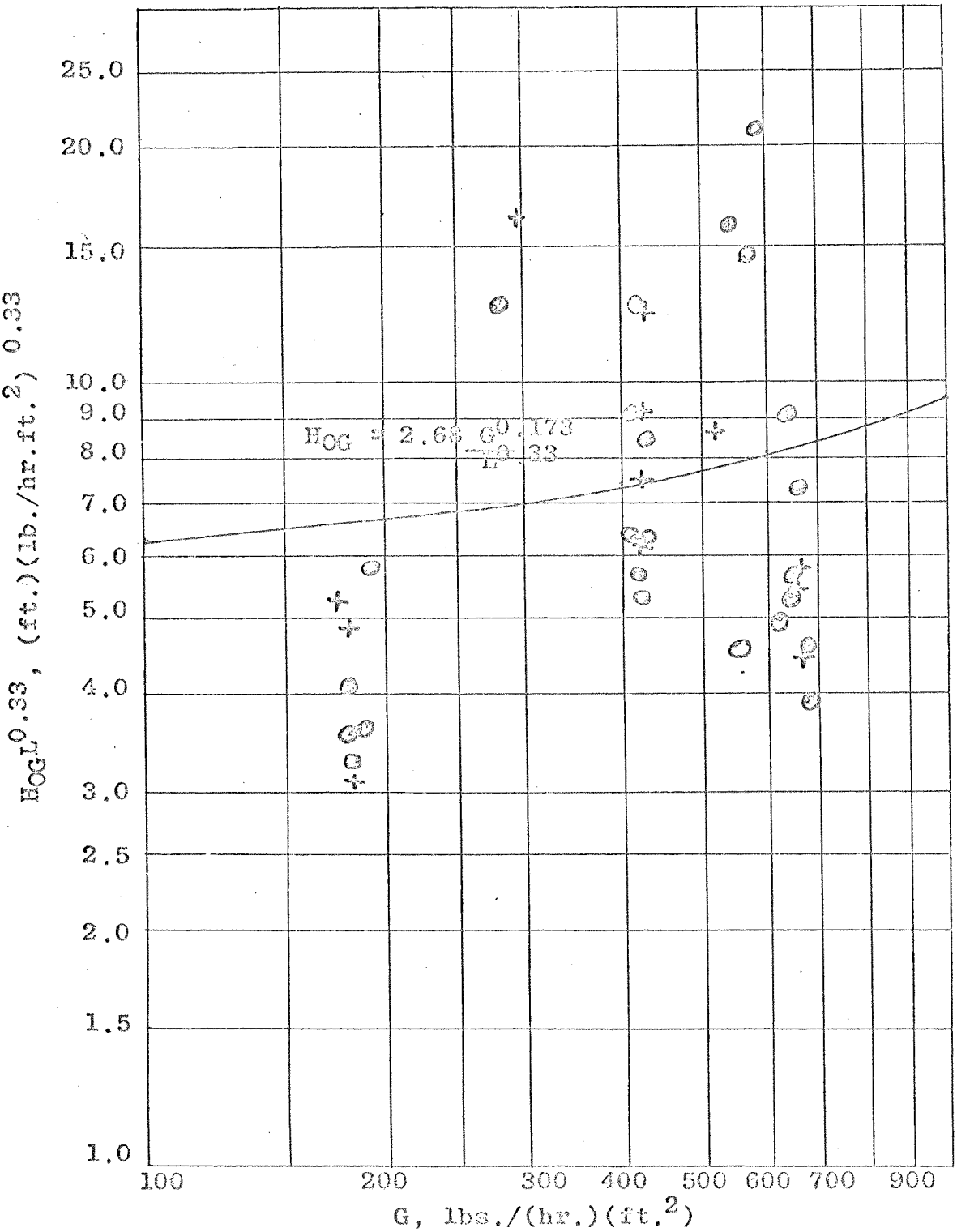
FIGURE 4-7
EFFECT OF GAS RATE
ON H_{OG} L = 2960
(Sodium Hydroxide)

FIGURE 4-8



CORRELATION OF DATA ON GAS FILM RESISTANCE,
IRRIGATION WITH WATER

FIGURE 4-9



CORRELATION OF DATA ON GAS FILM RESISTANCE,
IRRIGATION WITH
SODIUM HYDROXIDE SOLUTION

From these equations, for G = 500, the following values are found for the various liquid rates:

	Water	Caustic Soda
L = 5700	0.55	0.45
L = 4260	0.62	0.50
L = 2960	0.70	0.56

In each case, the H_{OG} value found for caustic soda irrigation is approximately 80% of the value for the same liquid and gas rate for water. Therefore the packed height of a tower to scrub hydrogen chloride with caustic soda solutions could be 80% of that of a column using water as absorbent. For the concentration under study, the saving in height of the packed section would be about 1 foot, which would make virtually no difference in the cost of the equipment required. The additional expense of providing alkaline scrubbing liquid would more than offset any saving. Sherwood (17), in discussing absorption accompanied by a rapid chemical reaction, presents a correlation of K_G, lb. mols/(hr.)(ft.^{2}) atm, and q/p, normality/partial pressure. A similar plot, using $K_G a$ instead of K_G, was prepared from the data collected in all runs using alkaline irrigating liquid. The data points are scattered, probably because the present investigation deals with absorption in which the gas film is controlling, rather than the liquid film. However, it

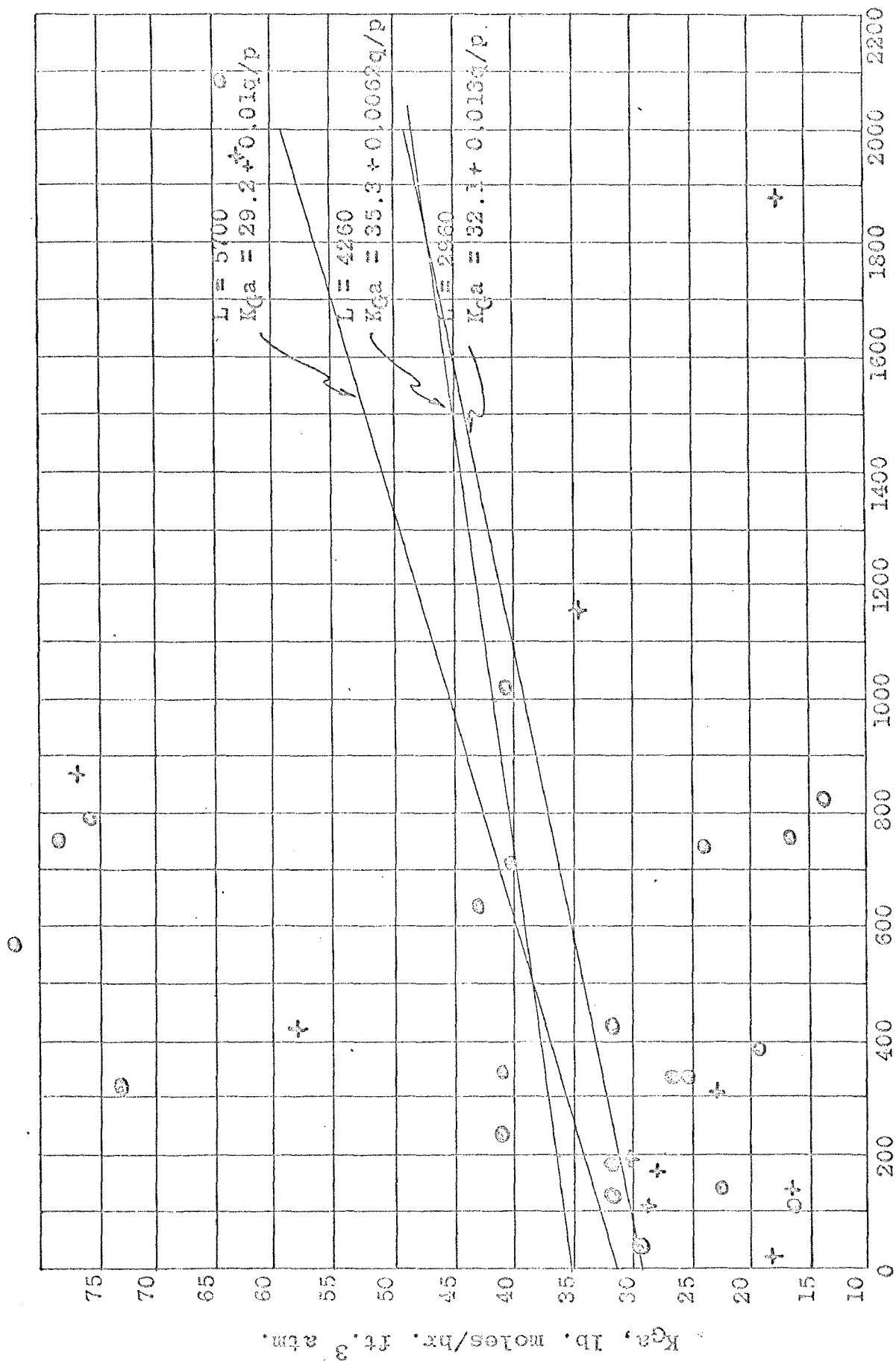


FIGURE 4-10 EFFECT OF CAUSTIC NORMALITY ON K_Ga

appears that $K_G a$ increases with increase in alkalinity of the absorbing liquid, which would be expected from Hatta's theory (Equation 1- 1). For the various liquid flow rates, the equations are:

$L = 5700 \qquad K_G a = 29.2 + 0.01\ q/p$

$L = 4260 \qquad K_G a = 35.3 + 0.0062\ q/p$

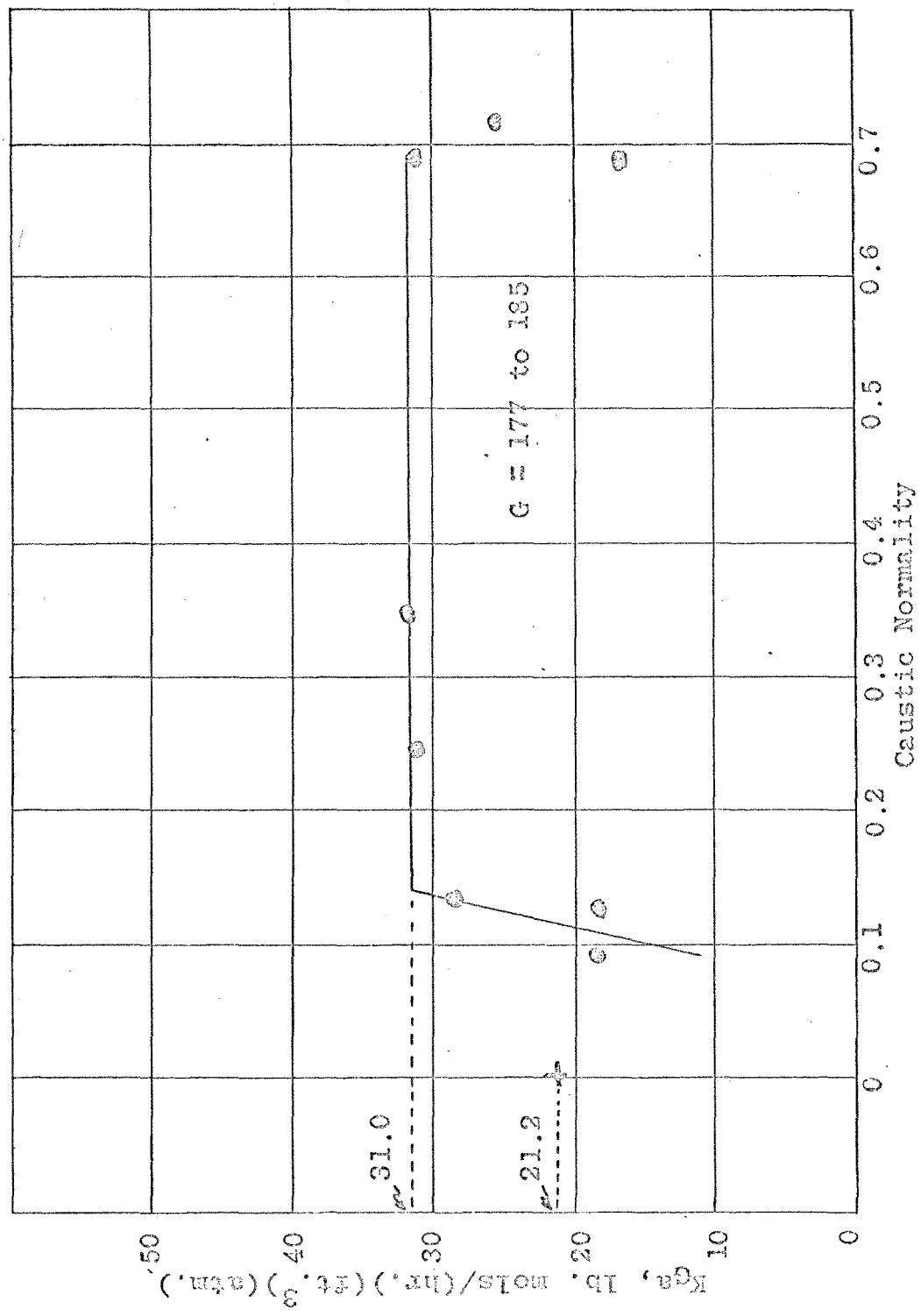
$L = 2960 \qquad K_G a = 32.1 + 0.013\ q/p$

When $q = 0$, the first term of the above equations gives the value of $K_G a$, and the values should agree with the values observed for water at the various L rates. The following interesting comparison can be made:

L	$K_G a$ when $q = 0$	$1/K_G a = R_1$	$K_G a$ from Water Data	$1/K_G a = R_2$	R_1/R_2
5700	29.2	0.0342	25.3	0.0395	0.866
4260	35.3	0.0283	28.4	0.0352	0.805
2960	32.1	0.0312	29.1	0.0343	0.907

Sherwood and Holloway (13) used a plot of $K_G a$ versus acid normality to evaluate relative gas film and liquid film resistance for ammonia absorption in acid. They found that $K_G a$ reached a constant value above a critical solute concentration, which constant value they extrapolated to zero normality to provide a true for the gas film coefficient. Applying the same technic gives the above figures, which show that the resistance of the gas film accounts for 80%

FIGURE 4-11 EFFECT OF CAUSTIC NORMALITY ON $K_G a$



to 90% of the total resistance to mass transfer. This is, however, not rigorous since the value of $K_G a$ did not remain constant for any of the alkalinity values covered by these data, but the figures so obtained indicate that the bulk of the resistance to mass transfer occurs in the gas film, which was expected.

The height of an over-all transfer unit is related to the individual film resistances by the equation:

$$H_{OG} = H_G + mG/L\ H_L$$

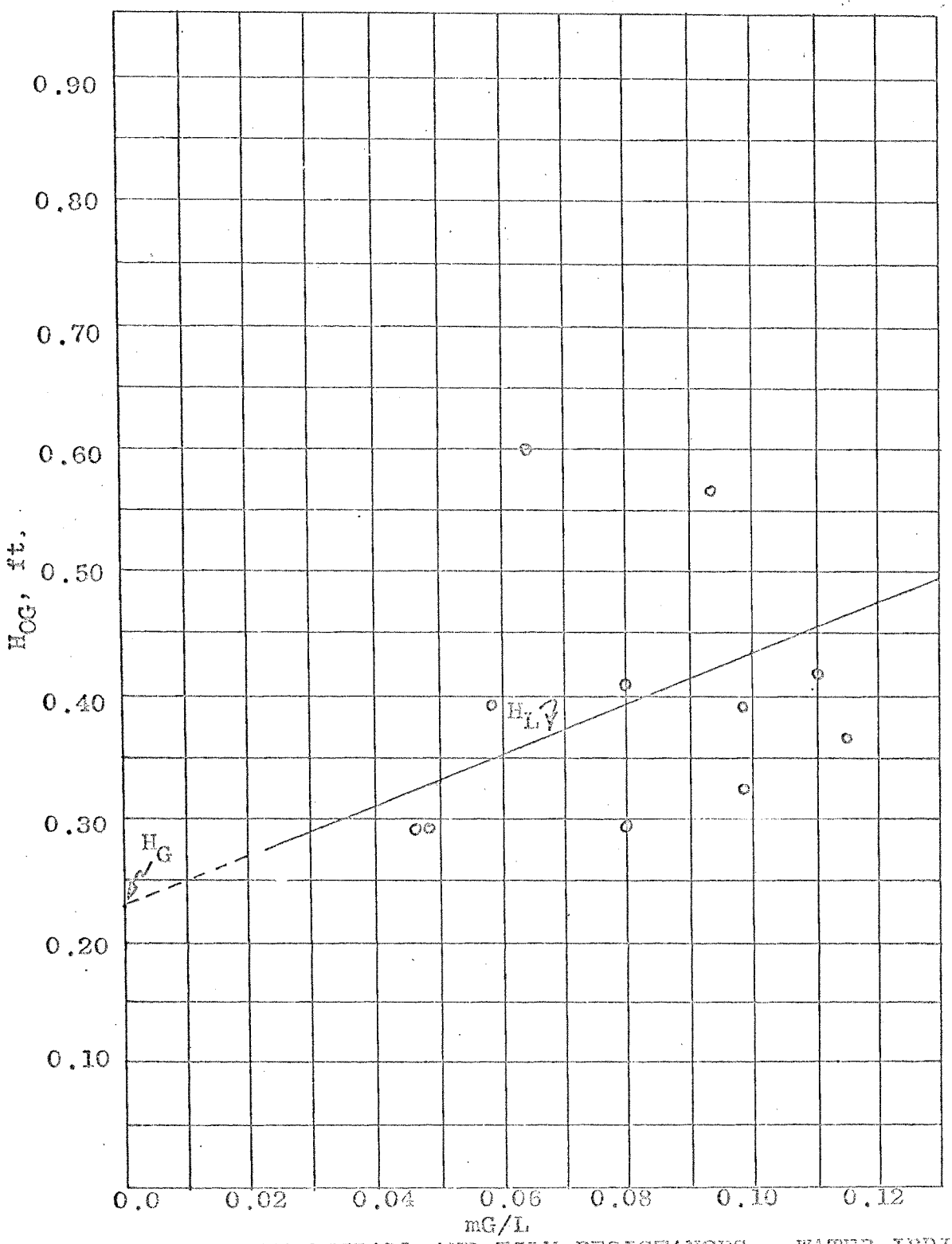
In cases where Henry's Law applies, m is a constant, and individual H_G and H_L values can be found for the gas and liquid films, respectively, provided that slow chemical reaction does not occur. (15) Using the value of m found from Figure 1-1, Figures 4-12 and 4-13 were prepared to show the relationship between H_G and H_L as derived from the above equation, for both water and sodium hydroxide irrigation.

Evaluation of the equations for both water and caustic soda solution at L = 2960, G = 500, gives the following:

Water	$H_{OG} = 0.47$	$H_G = 0.23$	$H_L = 0.12$
Caustic Soda	$H_{OG} = 0.47$	$H_G = 0.31$	$H_L = 0.11$

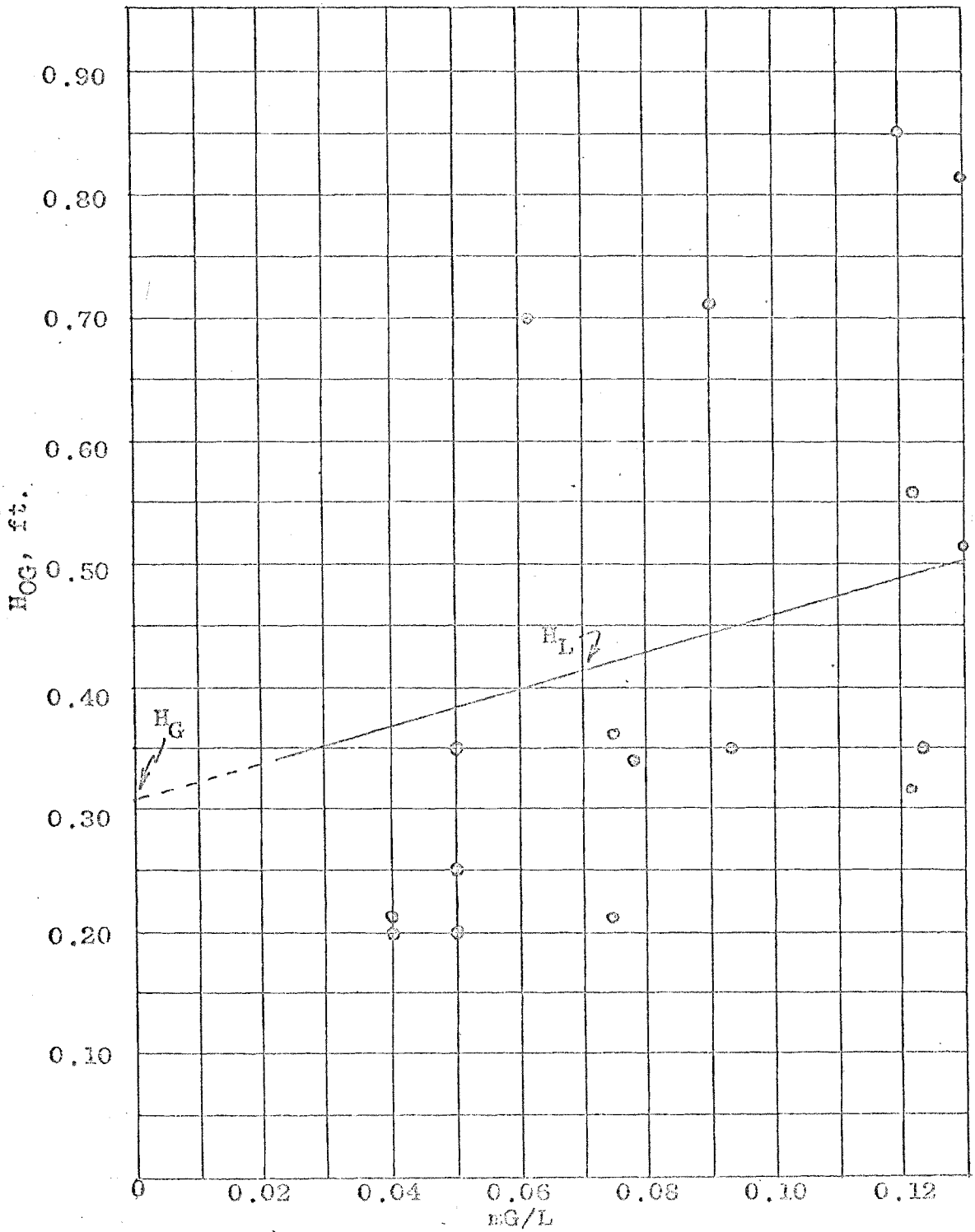
These values do not agree with those predicted by the equations of Figures 4-5 through 4-10, since the slope

FIGURE 4-12



RELATIONSHIP OF OVERALL AND FILM RESISTANCES - WATER IRRIGATION

FIGURE 4-13



RELATIONSHIP OF OVERALL AND FILM RESISTANCES - CAUSTIC IRRIGATION

m of the solubility curve is not a constant, and since the value of H_L is influenced by the chemical reaction taking place in the liquid film. However, the conclusion that there is no economic advantage in using an alkaline scrubbing agent remains valid.

IV - CONCLUSIONS

The purpose of this investigation was to provide information to permit the evaluation of an industrial scrubber system handling a hydrogen chloride - air mixture. Based on the manufacturer's recommendation, the scrubbing liquid used has been a 4% solution of caustic soda. Operating conditions (approximate) have been G = 315 and L = 4000 for 6 feet of packing.

The data presented here indicate that the use of an alkaline scrubbing agent does not substantially increase the number of transfer units available for absorption. In 5 of 30 runs (16.7%) using water as absorbent, no hydrogen chloride was found in the effluent gas. In 15 of 35 runs (42.9%) using various strengths of caustic soda solution as irrigant, the exit gas from the scrubber contained no hydrogen chloride.

It is apparent that the use of caustic soda beyond the amount necessary to produce a neutral liquid effluent is not economically justified.

V - RECOMMENDATIONS

Further work should be done to find a method of analysis which will give reproducible results at the relatively low concentrations of acid gases used in this investigation. Kemper (8) has reported an analytical method based on electrical conductivity of the solution in the sample bubbler, but this requires rather expensive instrumentation which is not readily portable.

The use of thermal conductivity cells for gas samples should be examined, although it is possible that the dilute mixtures used here are below the useful range of such devices.

VI APPENDIX

SAMPLE CALCULATION

Run # 73

Inlet Concentration

Inlet titration 11.2 ml N/50 NaOH

Normality = 0.0208 = 0.76 mgm HCl

Inlet sample - 4.2 liters

$$\frac{(11.2)(0.76)}{4.2} = 2.03 \text{ mgm./liter}$$

$$= 5.56 \times 10^{-5} \text{ gm. mols/liter}$$

Outlet Concentration

Outlet titration 0.3 ml N/50 NaOH

Outlet sample 3.5 liters

$$\frac{(0.3)(0.76)}{3.5} = 0.06 \text{ mgm./liter}$$

$$= 0.016 \times 10^{-5} \text{ gm. mols/liter}$$

Circulating Liquid Concentration

Titration 4.6 ml N/50 H_2SO_4 for 1 ml sample

Normality = 0.0177 = 0.0709 % NaOH

(4.6)(0.0709) = 0.32% NaOH

HCl Absorbed

2.03 - 0.06 = 1.97 mgm./liter

Gas Flow - Rotameter reading 40

(0.40)(20.8) = 8.32 SCFM

$$\frac{(8.32)(28.32)(60)(1.97)}{1000} = 27.85 \text{ gm./hr.}$$

$$\frac{27.85}{(36.5)(454)} = 1.68 \times 10^{-3} \text{ lb.mols}$$

SAMPLE CALCULATION

Packing Volume

Packing depth 24 inches

Column diameter 4 inches

$$\frac{(24)(4^2)(0.7854)}{1728} = 0.174 \text{ ft}^3$$

N

$$\frac{1.68 \times 10^{-3}}{1.74 \times 10^{-1}} = 96.6 \times 10^{-4} \text{ lb. mols/(hr)(ft}^3\text{)}$$

Driving Force

Average air temperature in 27.5°C

Average air temperature out 16.6°C

Air density in (from graph) 0.04060 gm. mols/liter

Air density out 0.04208 gm. mols/liter

Gas mixture in

0.040600 gm. mols air
0.000056 gm. mols HCl
0.040656 gm. mols total

Mol fraction in

0.99862 mol fraction air
0.00138 mol fraction HCl
1.00000

Gas mixture out

0.04208000 gm. mols air
0.00000016 gm mols HCl
0.04208016 gm. mols total

Mol fraction out

0.999996 mol fraction air
0.000004 mol fraction HCl
1.000000

Log mean mol fraction $\frac{138.0 - 0.4}{\ln \frac{138.0}{0.4}}$

SAMPLE CALCULATION

$$= \frac{137.6}{\ln 345} = 23.5 \times 10^{-5}$$

G

Air density (from graph) 0.0732 lbs/ $(ft.^3)$

$$G = \frac{(60)(8.32)(0.0732)}{0.0873}$$

$$= 419 \text{ lbs./(hr.)}(ft.^2)$$

$$G_m = \frac{419}{29} = 14.4 \text{ lb. mols/(hr.)}(ft.^2)$$

K_Ga = N/log mean y = $\frac{96.6 \times 10^{-4}}{23.5 \times 10^{-5}}$ = 41.1 lb. mols/ $(hr.)(ft.^3)(atm.)$

H_{OG} = G_m/K_Ga = $\frac{14.4}{41.1}$ = 0.35 ft

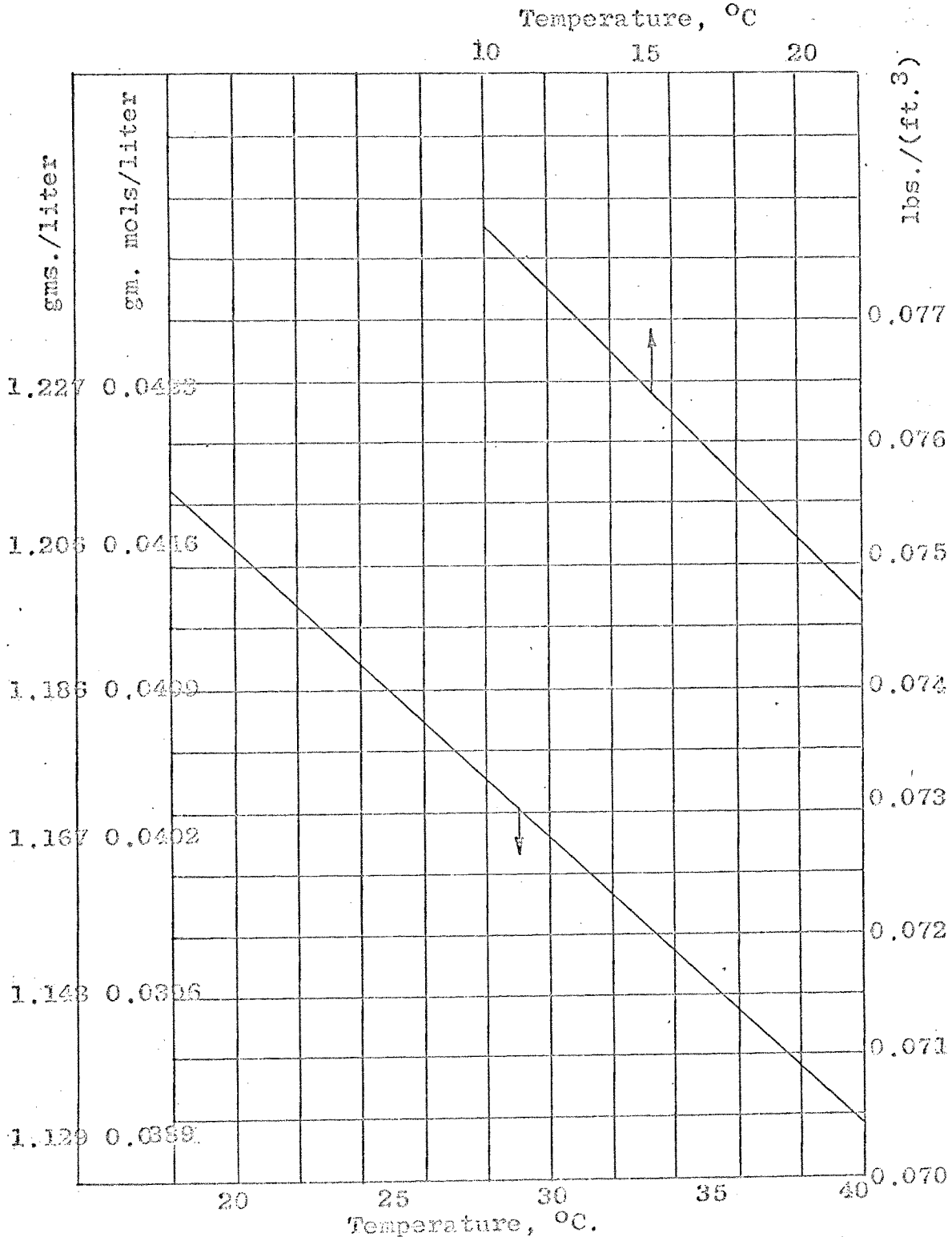


FIGURE 2-2 AIR DENSITY VARIATION WITH TEMPERATURE

TABLE 2-1

DATA

Run #	Duration, minutes	Gas Inlet Temp., ^{o}C	P Drop mm water	Liquid Rotameter	Air Rotameter
35	35	14.0	56	94	
36	35	24.9	75.8	93	
37	35	19.0	9.0	92	
38	30	22.7	7.0	50	
39	25	29.5	112.5	50	
40	30	25.0	60.0	93	
41	20	23.6	124.0	92	
42	25	29.3	159.8	93	
43	25	23.8	93.5	94	
44	25	17.8	60.0	93	
45	15	27.3	66.5	94	
46	25	25.8	41.8	50	
47	No good				
48	30	24.5	140.0	93	62
49	25	24.5	122.7	93	62
50	25	25.2	22.3	92	40
51	40	24.5	4.2	93	25
52	40	27.2	3.0	50	25
53	30	29.0	60	94	64
54	35	19.6	3.0	93	19
55	35	26.0	2.6	93	19
56	35	30.1	3.0	50	18
57	25	16.8	2.3	50	18

TABLE-2-2
DATA

Run #	Duration, minutes	Gas Inlet Temp., °C	P Drop mm water	Liquid Rotameter	Air Rotameter
58	30	21.3	5	50	30
59	40	23.3	5	50	30
60	35	21.8	6	70	31
61	40	23.3	6	70	31
62	35	28.1	115.2	70	62
63	40	33.3	119.9	70	62
64	35	21.3	2.8	70	18
65	40	26.6	3	70	19
66	45	22.3	5.5	70	31
67	25	29.1	116.6	70	63
68	45	26.5	16.1	50	40
69	30	23.2	15.9	50	40
70	35	25.1	15.8	70	40
71	30	28.8	16.0	70	40
72	40	25.0	40.0	93	40
73	30	27.5	19.0	70	40
74	40	26.8	19.0	50	40
75	40	26.7	18.0	50	40
76	30	23.0	30.0	70	40
77	20	31.4	35.0	93	40
78	40	24.3	15.0	50	40
79	35	21.4	2.5	50	17

TABLE 2-3

DATA

Run #	Duration, minutes	Gas Inlet Temp., °C	P Drop mm water	Liquid Rotameter	Air Rotameter
80	40	29.3	103	50	64
81	40	28.5	116	70	63
82	40	28.2	24	70	41
83	30	27.0	2	70	17
84	25	31.4	97	50	64
85	40	26.2	19	50	40
86	35	32.3	2	50	17
87	50	27.1	1	93	18
88	40	27.2	46	93	40
89	40	32.4	163	70	62
90	45	30.8	125	70	63
91	40	25.9	2	70	18
92	30	30.2	23	70	40
93	40	28.1	2	93	18
94	30	31.9	183	90	60
95	50	29.3	2	50	17
96	55	32.5	2	70	18
97	35	30.1	3	93	18
98	40	28.5	82	50	65
99	35	25.0	118	70	65
100	45	25.8	181	92	63

TABLE 2-4
DATA

Run #	Sample Volume, liters		Gas Outlet Temp., °C.	Titrations, ml N/50 NaOH		
	In	Out		Gas In	Gas Out	Liquid
35	3.0	2.5	15.0	15.3	2.6	
36	3.0	4.1	14.9	18.2	1.9	
37	4.0	3.5	14.7	25.0	1.2	
38	2.6	3.0	17.0	3.9	1.4	
39	4.0	2.0	13.9	11.7	1.1	
40	4.0	2.0	13.7	17.4	0.8	
41	4.0	2.5	14.6	20.0	0.8	
42	4.0	2.0	15.8	18.6	1.4	
43	4.0	3.5	17.8	18.3	1.3	
44	4.0	2.5	15.5	20.5	0.5	7.8
45	4.0	2.0	15.5	20.7	0.4	5.8
46	4.0	1.5	17.3	7.4	0.5	8.1
47		No good				
48	4.0	3.0	12.1	1.8	0.5	
49	4.0	3.5	14.3	8.1	0.0	
50	4.0	4.0	15.3	10.6	0.3	
51	4.0	4.0	16.7	15.2	0.0	
52	3.0	3.0	18.7	9.3	0.0	
53	4.0	3.0	20.3	26.1	0.0	
54	3.8	3.0	15.1	59.2	0.2	
55	3.5	3.0	20.5	74.9	0.2	
56	4.0	3.5	22.1	14.2	0.1	
57	4.0	4.0	16.5	105.2	0.1	

TABLE 2-5
DATA

Run #	Sample Volume, liters		Gas Outlet Temp., °C.	Titrations, ml N/50 NaOH		
	In	Out		Gas In	Gas Out	Liquid
58	4.0	3.5	16.9	19.1	0.1	
59	4.0	4.0	18.6	26.5	0.4	
60	3.5	4.0	18.5	28.4	0.2	
61	4.0	3.5	14.6	45.6	0.1	
62	4.0	3.5	16.9	9.3	0.2	
63	4.0	4.0	17.9	8.3	0.3	
64	4.0	4.3	18.6	83.0	0.1	
65	3.5	4.0	19.9	14.3	0.1	
66	4.0	3.8	19.1	29.4	0.3	
67	4.0	3.5	20.2	8.9	0.3	
68	4.0	3.0	19.0	24.4	0.5	
69	4.0	3.1	18.3	14.2	0.7	
70	4.0	3.5	18.2	19.5	0.3	
71	4.0	3.0	19.0	11.4	0.2	
72	4.0	3.5	13.7	22.4	0.1	6.6
73	4.2	3.5	16.6	11.2	0.3	4.6
74	4.0	3.5	18.7	17.4	0.3	5.7
75	4.0	4.0	19.7	6.5	0.3	4.4
76	4.0	2.5	20.9	16.0	0.3	11.0
77	4.0	3.1	21.8	10.3	0.5	10.6
78	4.0	4.0	17.4	21.7	2.2	8.3
79	4.0	4.0	17.6	158.6	1.6	6.5

TABLE 2-6
DATA

Run #	Sample Volume, liters		Gas Outlet Temp., °C.	Titrations, ml N/50 NaOH		
	In	Out		Gas In	Gas Out	Liquid
80	4.0	4.1	18.5	14.6	0.1	9.2
81	4.0	3.0	18.4	10.4	0.2	41.5
82	4.0	3.5	19.5	9.3	0.2	40.7
83	4.0	3.5	20.3	127.1	0.1	37.5
84	4.3	3.0	21.0	15.8	0.2	36.4
85	4.0	4.0	17.5	23.3	0.2	39.3
86	4.0	2.5	19.5	15.3	0.1	37.0
87	3.5	3.5	19.7	110.5	0.0	37.2
88	4.1	4.2	20.8	25.8	0.1	33.6
89	4.0	3.5	21.2	12.1	0.0	30.8
90	4.0	3.5	15.7	15.7	0.3	21.2
91	4.1	4.0	21.2	139.7	0.0	18.1
92	4.0	3.0	21.4	21.0	0.4	15.2
93	4.0	4.1	20.6	132.9	0.0	12.8
94	3.5	4.0	21.6	25.6	0.0	7.6
95	4.1	3.8	16.1	90.1	0.0	7.1
96	4.0	3.5	18.3	35.6	0.0	5.0
97	4.0	4.0	20.1	99.5	0.0	2.9
98	4.1	4.0	15.6	8.6	0.0	7.7
99	4.0	3.0	14.4	8.8	0.0	4.6
100	4.1	2.5	15.3	5.3	0.0	4.3

TABLE 2-7
CALCULATION SUMMARY

Run #	HCl Content, mgm./liter In	Out	Absorbed	Log Mean Mol Fraction x 10^4	N Lb.mols/(hr.)(ft^2) x 10^4
35	3.88	0.79	3.09	12.5	212.2
36	4.61	0.35	4.26	11.5	276.3
37	4.75	0.26	4.49	10.3	140.3
38	0.88	0.15	0.73	2.7	24.2
39	2.07	0.11	1.96	7.4	168.3
40	3.15	0.00	3.15	3.9	194.3
41	3.65	0.00	3.65	3.1	277.5
42	3.38	0.23	3.15	7.3	248.3
43	3.33	0.11	3.22	6.4	103.7
44	3.70	0.03	3.67	10.3	229.8
45	3.81	0.00	3.81	3.3	239.4
46	1.31	0.05	1.26	2.5	75.4
47					
48	0.34	0.12	0.22	1.4	16.4
49	1.52	0.11	1.41	2.8	107.2
50	1.99	0.06	1.93	3.7	94.7
51	2.74	0.00	2.74	3.4	84.0
52	2.23	0.00	2.23	2.3	69.0
53	4.70	0.00	4.70	5.8	374.6
54	11.2	0.05	11.15	10.7	259.7
55	16.3	0.05	16.25	16.0	366.9
56	2.7	0.02	2.68	3.8	59.7
57	19.98	0.02	19.96	18.9	433.4

TABLE 2 - 8
CALCULATION SUMMARY

Run #	HCl Content, mgm./liter In	Out	Absorbed	Log Mean Mol Fraction x 10^4	N lb. mols/(hr.)(ft.^{2})
58	3.63	0.02	3.61	4.8	132.8
59	5.04	0.08	4.96	7.8	182.5
60	6.20	0.04	6.16	8.0	234.2
61	8.66	0.02	8.64	9.4	328.5
62	4.85	0.12	4.73	5.2	130.8
63	1.58	0.06	1.52	3.4	119.4
64	15.77	0.02	15.75	15,3	352.9
65	3.10	0.02	3.08	4.0	71.7
66	5.59	0.06	5.53	8.0	210.3
67	1.69	0.07	1.62	3.5	125.1
68	4.64	0.13	4.51	8.8	221.2
69	2.70	0.17	2.53	6.3	124.1
70	3.71	0.07	3.64	6.0	178.5
71	2.17	0.05	2.12	3.9	104.0
72	4.26	0.02	4.24	5.1	208.0
73	2.03	0.06	1.97	2.4	96.6
74	3.31	0.07	3.24	5.7	158.9
75	1.27	0.06	1.21	2.7	59.3
76	3.12	0.09	3.03	5.8	148.6
77	2.01	0.13	1.88	4.9	92.2
78	4.12	0.42	3.70	10.8	181.5
79	40.71	0.35	40.36	46.4	842.3
80	2.81	0.02	2.79	3.8	218.9

TABLE 2-9
CALCULATION SUMMARY

Run #	HCl Content, mgm./liter In	Out	Absorbed	Log Mean Mol Fraction $x10^4$	N Lb.mols/(hr.)(ft.^{2}) $\times 10^4$
81	2.00	0.05	1.95	3.0	150.6
82	1.79	0.04	1.75	3.1	87.6
83	24.47	0.02	24.45	20.5	518.9
84	2.82	0.05	2.77	3.5	217.4
85	4.49	0.04	4.45	6.4	218.3
86	2.95	0.03	2.92	3.7	61.8
87	24.30	0.00	24.30	16.6	521.7
88	4.85	0.02	4.83	5.8	236.9
89	2.33	0.00	2.33	2.3	178.0
90	3.02	0.07	2.95	5.7	227.8
91	26.23	0.00	26.23	17.8	562.9
92	4.04	0.01	4.03	4.6	197.7
93	25.58	0.00	25.58	17.7	549.0
94	1.97	0.00	1.97	1.9	146.7
95	17.13	0.00	17.13	12.9	368.2
96	6.85	0.00	6.85	8.3	151.1
97	19.15	0.00	19.15	14.4	416.8
98	1.64	0.00	1.64	1.7	130.7
99	1.69	0.00	1.69	1.6	134.0
100	1.00	0.00	1.00	1.0	76.7

TABLE 2-10

CALCULATION SUMMARY

Run #	K_Ga lb. mols/(hr.)(ft.^{3})(atm.)	G lbs./(hr.)(ft.^{2})	L	H_{OG} ft.
35	17.0	580	5700	1.18
36	24.0	569	5700	0.82
37	13.6	277	5700	0.70
38	9.0	295	2960	1.13
39	37.4	752	2960	0.69
40	101.0	540	5700	0.18
41	89.2	673	5700	0.26
42	34.0	687	5700	0.70
43	16.2	284	5700	0.60
44	22.3	547	5700	0.85
45	73.6	550	5700	0.26
46	30.1	523	2960	0.60
47				
48	11.7	656	5700	1.93
49	38.2	656	5700	0.59
50	25.6	423	5700	0.57
51	24.7	265	5700	0.38
52	29.8	262	2960	0.43
53	64.3	677	5700	0.36
54	24.3	199	5700	0.28
55	22.9	195	5700	0.29
56	15.7	188	2960	0.41
57	23.0	192	2960	0.29

TABLE 2-11
CALCULATION SUMMARY

Run #	$K_G a$ lb. mols/(hr.)(ft.^{3})(atm.)	G lbs./(hr.)(ft.^{2})	L	H_{OG} ft.
58	27.7	320	2960	0.40
59	23.4	318	2960	0.47
60	29.3	330	4260	0.39
61	34.9	330	4260	0.33
62	25.1	647	4260	0.81
63	35.1	637	4260	0.62
64	23.1	195	4260	0.29
65	17.9	199	4260	0.38
66	26.3	330	4260	0.43
67	35.8	654	4260	0.63
68	25.7	420	2960	0.56
69	19.7	424	2960	0.74
70	29.8	421	4260	0.49
71	26.7	416	4260	0.54
72	40.9	422	5700	0.35
73	41.1	419	4260	0.35
74	27.9	420	2960	0.52
75	22.8	420	2960	0.63
76	25.6	415	4260	0.56
77	19.6	413	5700	0.72
78	16.8	423	2960	0.87
79	18.2	182	2960	0.34
80	57.6	665	2960	0.40

TABLE 2-12
CALCULATION SUMMARY

Run #	K_Ga lb. mols/(hr.)(ft.^{3})(atm.)	G lbs./(hr.)(ft.^{2})	L	H_{OG} ft.
81	50.2	656	4260	0.45
82	28.3	426	4260	0.52
83	25.3	181	4260	0.25
84	62.3	660	2960	0.37
85	34.1	420	2960	0.43
86	16.9	177	2960	0.36
87	31.4	180	5700	0.20
88	41.0	412	5700	0.35
89	64.0	641	4260	0.35
90	40.0	652	4260	0.56
91	31.6	184	4260	0.20
92	43.1	415	4260	0.33
93	31.1	183	5700	0.20
94	78.4	626	5577	0.28
95	28.6	178	2960	0.21
96	18.2	185	4260	0.35
97	29.0	184	5700	0.22
98	76.8	678	2960	0.31
99	83.2	684	4260	0.28
100	76.0	657	5700	0.30

TABLE 2-13
CALCULATION SUMMARY

Run #	% NaOH in Liquid	Normality, q	q/p, normality/atm.
35	3.79	0.95	760
36	3.39	0.85	739
37	3.30	0.83	805
38	3.27	0.82	3037
44	0.55	0.14	135
45	0.41	0.10	308
46	0.57	0.14	195
72	0.47	0.12	235
73	0.32	0.08	340
74	0.40	0.10	175
75	0.31	0.08	301
76	0.78	0.20	346
77	0.75	0.19	385
78	0.59	0.15	139
79	0.46	0.12	26
80	0.65	0.16	421
81	2.94	0.74	2470
82	2.88	0.72	2320
83	2.85	0.71	346
84	2.72	0.68	1950
85	2.94	0.74	1160
86	2.76	0.69	1890
87	2.78	0.70	422

TABLE 2-14

CALCULATION SUMMARY

Run #	% NaOH in Liquid	Normality, q	q/p, normality/atm.
88	2.51	0.63	1090
89	2.30	0.58	2086
90	1.58	0.40	702
91	1.36	0.34	191
92	1.14	0.29	632
93	0.96	0.24	136
94	0.57	0.14	749
95	0.53	0.13	101
96	0.37	0.09	109
97	0.22	0.06	42
98	0.58	0.15	882
99	0.34	0.09	559
100	0.32	0.08	792

TABLE 4-5

L = 5700 lbs./(hr.)($ft.^2$)

Run #	G	$K_G a$	H_{OG}	q	$H_{OG} L^{\frac{1}{3}}$
100	657	76.0	0.30	0.08	5.35
45	550	73.6	0.26	0.10	4.64
72	422	40.9	0.35	0.12	6.25
94	626	78.4	0.28	0.14	5.00
44	547	22.3	0.85	0.14	15.18
97	678	76.8	0.22	0.15	3.93
77	413	19.6	0.72	0.19	12.86
93	183	31.1	0.20	0.24	3.57
88	412	37.0	0.35	0.63	6.25
87	180	31.4	0.20	0.69	3.57
37	277	13.6	0.70	0.83	12.50
36	569	24.0	0.82	0.85	14.65
35	580	17.0	1.18	0.95	21.08

TABLE 4-6

L = 4260 lbs./(hr.)(ft.^{2})

Run #	G	$K_G a$	H_{OG}	q	$H_{OG}L^{1}_{3}$
73	419	41.1	0.35	0.08	5.67
96	185	18.2	0.35	0.09	5.67
99	684	83.2	0.28	0.09	4.54
76	415	25.6	0.56	0.19	9.08
92	415	43.1	0.33	0.29	5.35
91	184	31.6	0.20	0.34	3.24
90	652	40.0	0.56	0.40	9.08
89	641	64.0	0.35	0.58	5.67
83	181	25.3	0.25	0.71	4.05
82	426	28.3	0.52	0.72	8.43
81	656	50.2	0.45	0.74	7.30

TABLE 4-7

$L = 2960$ lbs./(hr.)(ft.^{2})

Run #	G	$K_G a$	H_{OG}	q	$H_{OG}L^{\frac{1}{3}}$
98	678	76.8	0.31	0.05	4.45
75	420	22.8	0.63	0.07	9.05
74	420	27.9	0.52	0.10	7.47
79	182	18.2	0.34	0.12	4.88
95	178	28.6	0.21	0.13	3.02
46	523	30.1	0.60	0.14	8.62
78	423	16.8	0.87	0.15	12.49
80	665	54.7	0.40	0.16	5.74
84	660	62.3	0.37	0.68	5.31
86	177	16.9	0.36	0.69	5.17
85	420	34.1	0.43	0.74	6.18
38	295	8.96	1.13	0.82	16.23

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VIII NOMENCLATURE

A	Contact area, $dm.^2$
B	Effective film thickness, ft.
C_{Ai}	Concentration of solute at interface, lb. mols/$ft.^3$
D_A	Liquid diffusivity for component A, $ft.^2$/hr.
D_B	Liquid diffusivity for component B, $ft.^2$/hr.
G	Superficial mass velocity of gas, lbs./(hr.)($ft.^2$)
H	Henry's Law constant, mols/atm.
H_{OG}	Height of an over-all gas phase transfer unit, ft.
K_G	Over-all gas film coefficient of mass transfer, lb. mols/(hr.)($ft.^2$)(atm.)
K_L	Over-all liquid film coefficient of mass transfer, lb. mols/(hr.)($ft.^2$)(lb. mols/$ft.^3$)
k_g	Gas film coefficient of mass transfer, lb. mols/(hr.)($ft.^2$)(atm.)
k_l	Liquid film coefficient of mass transfer, lb. mols/(hr.)($ft.^2$)(lb. mols/$ft.^3$)
K_Ga	Over-all mass transfer coefficient, lb. mols/(hr.)($ft.^3$)(atm.)
L	Superficial mass velocity of liquid, lbs./(hr.)($ft.^2$)
m^3	Cubic meter
N_A	Diffusion rate of component A, lb. mols/(hr.)($ft.^2$)
P_g	Partial pressure of carbon dioxide, atm.
p	Partial pressure, atm.
q	Concentration in bulk of solution of substance reacting with solute, lb. mols/$ft.^3$
R	Resistance to mass transfer, = $1/K_Ga$
S	Ratio of diffusion coefficients of carbonate to carbon dioxide in absorbing liquid

NOMENCLATURE

s	Fractional rate of surface renewal
W	Weight of carbon dioxide absorbed, mols
x_1	Effective thickness of liquid film, ft.
ρ	Density, lb./ft.^{3}
θ	Time, hrs.
μ	Viscosity, lb./(hr.)(ft.)

IX VITA

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Laboratory Work -	299 hours
Thesis Preparation -	114 hours
Total	491 hours

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