ABSORPTION OF AMMONIA IN A RING-PACKED TOWER

by

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Signature of Chairman of
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The Graduate House
Massachusetts Institute of Technology
Cambridge, Massachusetts
May 15, 1937

Professor George W. Swett
Secretary of the Faculty
Mass. Inst. of Technology
Cambridge, Mass.

Dear Sir:

Submitted herewith is a copy of the thesis entitled, "Absorption of Ammonia in a Ring-Packed Tower" which we are submitting in partial fulfillment of the requirements for the degree of Master of Science in Chemical Engineering Practice.

Very truly yours,

ACKNOWLEDGEMENT

The authors are indebted to Professor Thomas K. Sherwood who has suggested and directed this research.

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I. SUMMARY

Data on the transfer coefficients for gases in which the gas film controls the rate of absorption seem to be lacking at the present time, especially for absorption towers packed with Raschig rings. This present investigation has been carried out, therefore, to obtain such data by absorbing ammonia from an ammonia-air mixture with water, using a tower packed with 1" carbon Raschig rings.

Gas rates were varied from 55 - 530 lbs./hr-ft.^{2} and the liquor rates ranged from 440 - 2050 lbs./hr-ft.^{2}. In this range of gas and liquor rates, it has been concluded that $K_G a$ varies with the 0.5 power of the gas rate and with the 0.4 power of the liquor rate. In accordance with this, it was found that $K_G a$'s may be estimated within 10% by the equation:

$$K_G a = 0.0465\, G^{0.5}\, L^{0.4}$$

where $K_G a$ = overall transfer coefficient - #mols/hr.- ft^2 - atm.

G = gas rate - #/hr-ft.^{2}

L = liquor rate - #/hr.-ft.^{2}

in the range of gas and liquor rates investigated. The fact that $K_G a$ varies with $G^{0.5}$ does not agree with the generally accepted conclusion that $K_G a$ is proportional to $G^{0.8}$ for tower packings. No explanation is given for the difference

A secondary study was made of the pressure drop through Raschig ring packing. It was found that the pressure drop as measured through the packings used in these experiments checked very well those calculated by the use of a modified Chilton-Colburn equation.

II INTRODUCTION

To design successfully gas absorption equipment, data on the performance characteristics of such equipment are essential. These data, or more specifically, the data on the performance of absorption tower packing are quite scare at the present time, and hence the designer of absorption equipment is handicapped.

Generally speaking, performance data may be obtained from two sources: 1. from commercial towers already built and operating, and 2. from towers built in the laboratories to similate actual commercial operating conditions. While the former means of collecting data might have some advantages over the latter, the commercial towers are seldom used because of their inaccessibility, their inflexibility, and because of detailed cooperation necessary from the plant. Therefore, data on absorption equipment usually are collected on small scale operating models to more favorably suit the laboratory. These units prove more flexible and more favorable for collecting the necessary data. In them, commercial operation is duplicated as nearly as possible, and it is generally planned to use commercial-sized tower packing. The results of such tests may then be considered applicable to larger-sized equipment.

The performance of a given type of tower packing may be specified by the "overall transfer coefficient" (See Appendix B, Page 25). However, since the active absorbing surface of the packing, "a" is always difficult to measure or to estimate accurately, the overall coefficient is usually grouped with the term "a" and expressed as "$K_g a$" or "$K_L a$". For systems where the gas film controls the rate of absorption and the resistance of the liquid film is negligible, the overall transfer coefficient "$K_g a$" is used to express tower capacity. The absorption of a soluble gas such as ammonia would exemplify such a system. Where the resistance of the gas film is negligible compared to the liquid film, the coefficient is expressed in terms of "$K_L a$". In systems where neither gas nor liquid film controls, both coefficients may be given.

From a theoretical treatment, it is considered possible to correlate and predict overall transfer coefficient data of gases if their individual film coefficients, solubility data, and diffusion coefficients are known. Since the absorption of ammonia is a typical case of absorption in which the gas film resistance controls, data on this system are quite desirable. Considerable data have been obtained on the overall transfer coefficients for ammonia absorption in spray chambers, and towers packed with wood-grids, quartz, stoneware, broken stone, and clay spheres. (See Appendix A, pp. 21). There seems, however, to be little data available on commercial Raschig ring tower packing.

In an endeavor to add to the few data already available, this present investigation has studied the absorption of ammonia by water in an absorption column five feet high using 1" commercial carbon Raschig ring packing. The effects of gas rate and liquor rate on absorption coefficients have been determined. As a secondary study, pressure drops through the packing used have been compared with those obtained from theoretical calculations.

III. PROCEDURE

The tower used in these experiments was 5 feet in overall height, 10 inches in diameter, and was packed with 1 inch commercial Raschig rings. In runs 3 to 10, nineteen and one quarter (19 1/4") inches of packing was used, while for the other runs, the packing height was increased to 31" thereby increasing the absorption. Gas absorption varied from 67% to 97%. The pressure drop through the packing was measured by an Ellison draft gauge.

Gas and water were supplied to the tower countercurrently. The water was led directly from the city water line to the distributor in the top of the tower. Water rates were controlled by an orifice in the inlet line and were measured by catching the actual amount used during a run in a weighing can at the bottom of the tower. Liquor rates varied from 440-2050 lb./hr-ft.^{2} but the majority of the runs were made at rates varying from 500-1000 lb.hr-ft.^{2} The temperature of the exit liquor was measured by a mercury thermometer.

The inlet gas - a mixture of air and ammonia varying from 0.3 to 6.5 mol% NH_3 - was admitted at the bottom of the tower through a 4" pipe. A centrifugal fan was used to drive the gas through the tower and gas rates from 55 - 530 lb./hr-ft.^{2} were used. The air was measured by a sharp-edged orifice

EXPERIMENTAL SETUP

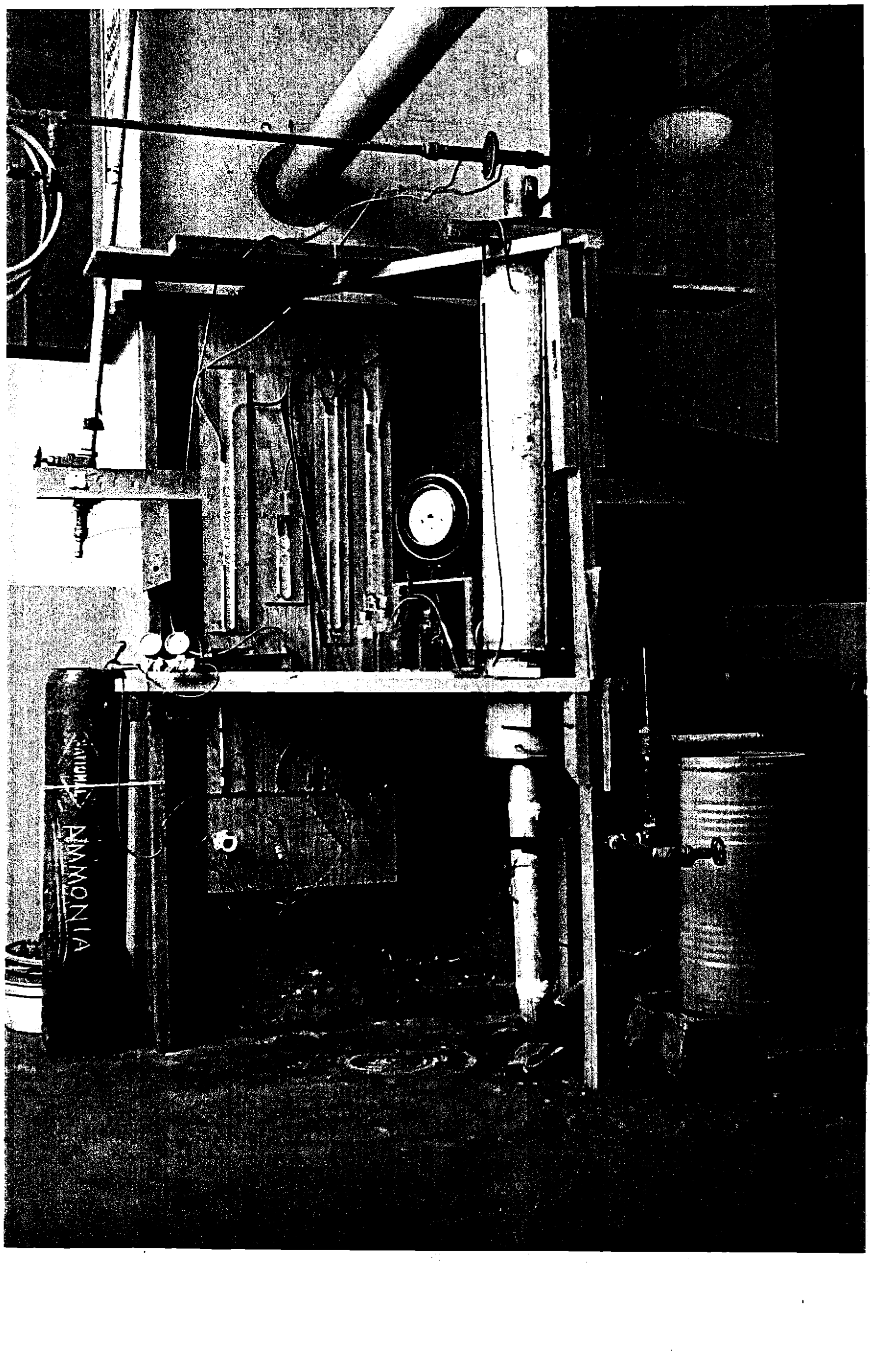
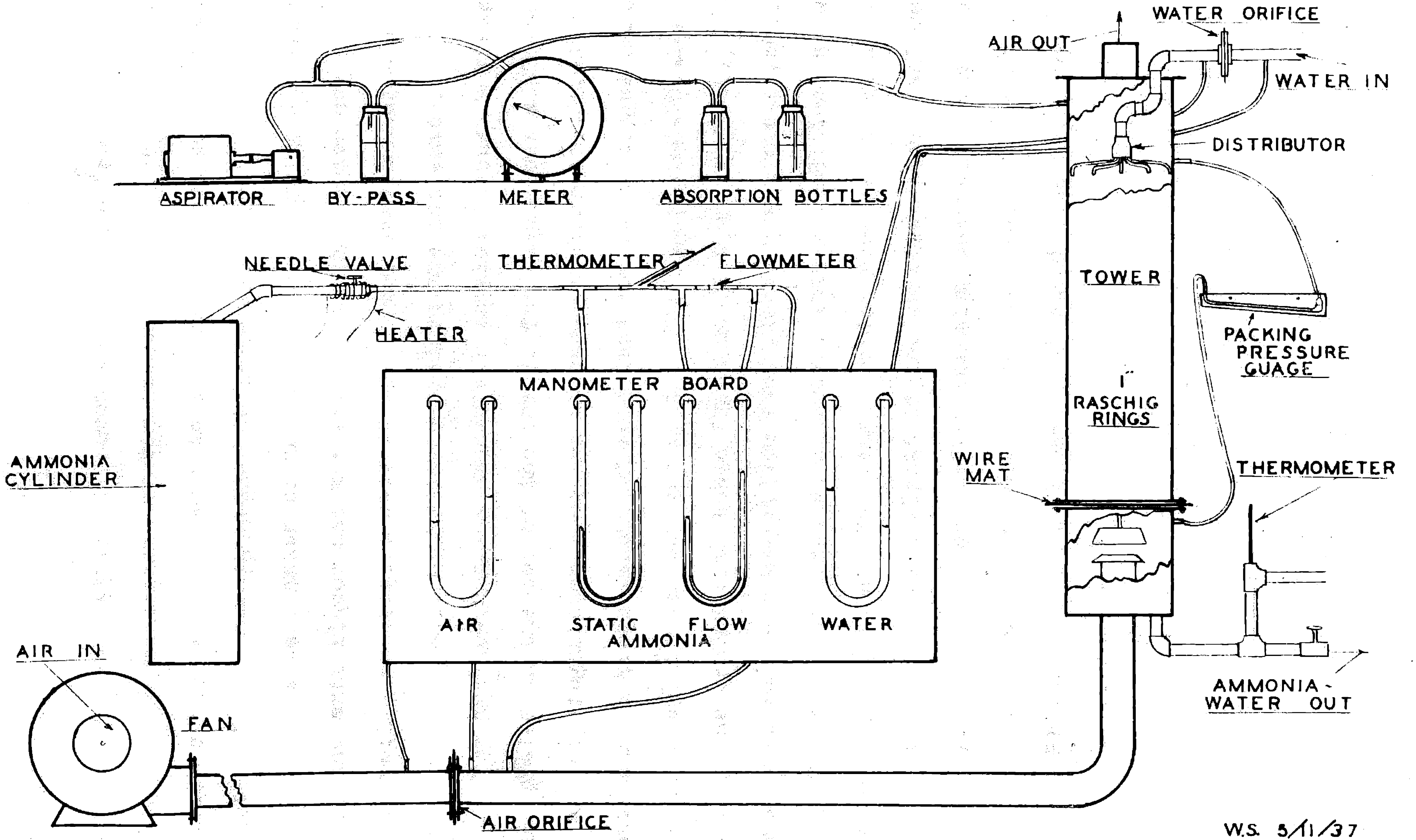


FIGURE 1
AMMONIA ABSORPTION APPARATUS



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in the gas line. Anhydrous ammonia was tapped from a storage cylinder into this line and was measured by a capillary flowmeter. A baffle arrangement in the tower prevented the downflowing liquor from entering the inlet gas line.

Samples were taken of the two streams leaving the tower - i.e., the exit liquor and the exit gas. The liquor was analyzed by titrating an aliquot part of the liquor leaving the tower with 0.05 N. H_2SO_4, using methyl red as the indicator.

The gas leaving the system was sampled through a glass tube placed in the top of the tower. The sample was aspirated by a centrifugal pump, bubbled through an absorption train containing a known amount of acid, and the residual gas passed through a calibrated wet gas meter. Two absorption bottles in series, the second with but a fraction of a drop of acid, insured that complete absorption took place in the first bottle.

The system was run at as nearly steady conditions as was possible to maintain. The length of the runs was taken as the time required for the analysis of the exit gas sample and varied from 3 1/2 to 40 minutes. After changing operating conditions at least five minutes was allowed for the system to reach equilibrium. Preliminary tests showed that steady state was reached in this time.

IV. RESULTS

The results of this investigation are presented in Tables I to IV and graphically in Figures 1 to 5 and 7.

IV. RESULTS

TABLE I

Run	G #/hr.	L #/hr.	NH_3 entering #/hr.	NH_3 absorbed #/hr.	NH_3 gas leaving #/hr.	NH_3 absorbed + NH_3 gas leaving	% Error in Material Balance	%NH_3 absorbed based on NH_3 entering
3	286	588	.679	0.510	0.129	0.639	-5.9%	75.1%
4	281	498	.627	0.426	0.131	0.557	-11.1	67.9
5	280	795	.666	0.539	0.140	0.679	+ 2.0	81.0
6	287	644	.633	0.476	0.151	0.627	- 0.9	75.2
7	216	664	.656	0.523	0.126	0.649	- 1.1	79.8
8	212	637	.682	0.536	0.132	0.668	- 2.0	78.5
9	288	1113	.670	0.566	0.126	0.692	+ 3.3	84.5
10	288	925	.672	0.538	0.127	0.665	- 1.0	80.0
1A	282	731	1.223	1.050	0.079	1.129	- 7.7	85.9
2	282	821	1.219	1.082	0.062	1.144	- 6.2	89.0
3	209	405	1.070	0.884	0.092	0.976	- 8.8	82.5
4	209	319	1.070	0.852	0.121	0.973	- 9.1	79.5
5	193	495	0.873	0.755	0.0685	0.824	- 5.6	86.5
6	116	407	0.877	0.813	0.0397	0.853	- 2.7	92.7
7	113	333	1.058	0.922	0.052	0.974	- 7.9	87.2
8	113	257	1.058	0.885	0.067	0.952	-10.0	83.7
9A	191	551	1.060	0.935	0.071	1.006	- 5.1	88.2
1B	187	244	1.060	0.757	0.165	0.922	-13.3	71.5
2	187	247	1.060	0.820	0.148	0.968	- 8.7	77.3
3B	113	240	1.360	1.110	0.113	1.223	-10.0	81.7
1C	33.8	453	0.672	0.652	0.0016	0.654	- 2.7	91.0
2	29.7	428	1.208	1.120	0.00179	1.122	- 7.1	92.8
3	29.4	426	1.201	1.140	0.00218	1.142	- 4.9	95.0
4	29.5	326	1.038	0.970	0.00212	0.972	- 6.4	93.5
5	33.0	322	1.038	0.964	0.00364	0.968	- 6.8	92.9
6C	33.0	329	1.038	0.995	0.00400	0.999	- 3.8	96.0
1D	69.5	315	1.042	0.895	0.0228	0.913	-12.4	85.7
2	69.5	314	1.032	0.930	0.0209	0.951	- 7.8	90.0
3	74.8	331	1.032	0.948	0.0217	0.970	- 6.0	91.7
4D	62.0	346.	1.032	0.965	0.0144	0.979	- 5.1	93.3

RESULTS - TABLE II

Runs 3-10 Packing Height = 19 1/4"
Runs 1A-4D " " = 31"

Run	G #/hr-ft^2	L #/hr-ft^2	NH_3 Absorbed #/hr.	NH_3 entering as measured		NH_3 entering as sum leaving		Average K_Ga
				P_m	K_Ga	P_m	K_Ga	
3	525	1079	0.510	1.36	19.15	1.31	19.88	19.52
4	515	915	0.426	1.33	16.38	1.23	17.70	17.04
5	514	1459	0.539	1.47	18.78	1.49	18.51	18.65
6	527	1180	0.476	1.40	17.38	1.39	17.50	17.44
7	396	1219	0.523	1.81	14.78	1.80	14.87	14.82
8	389	1288	0.536	1.91	14.36	1.88	14.58	14.47
9	528	2045	0.566	1.40	20.70	1.43	20.20	20.45
10	528	1700	0.538	1.40	19.70	1.39	19.80	19.75
1A	518	1340	1.050	1.77	18.82	1.66	20.05	19.44
2	518	1508	1.082	1.66	20.70	1.58	21.75	21.16
3	384	744	0.884	2.20	12.75	2.04	13.73	13.24
4	384	585	0.852	2.34	11.54	2.15	12.55	12.00
5	354	909	0.755	1.94	12.33	1.86	12.89	12.60
6	213	746	0.813	2.81	9.18	2.75	9.38	9.28
7	207	612	0.922	3.52	8.30	3.29	8.88	8.59
8	207	472	0.885	3.70	7.60	3.41	8.24	7.92
9	351	1010	0.935	2.29	12.94	2.20	13.48	13.21
1B	343	448	0.757	2.78	8.64	2.47	9.72	9.18
2	343	454	0.820	2.64	9.85	2.45	10.60	10.22
3	207	440	1.110	5.05	6.98	4.62	7.63	6.30
1C	62.0	833	0.652	4.05	5.10	3.94	5.25	5.17
2	54.5	786	1.120	7.46	4.76	7.06	5.04	4.90
3	54.0	782	1.140	7.75	4.66	7.48	4.85	4.76
4	54.2	598	0.970	6.80	4.52	6.43	4.79	4.65
5	60.5	591	0.964	6.68	4.57	6.30	4.85	4.71
6	60.5	604	0.995	6.79	4.65	6.55	4.82	4.73
1D	127.5	578	0.895	4.59	6.18	4.13	6.88	6.53
2	127.5	577	0.930	4.46	6.60	4.15	7.11	6.85
3	127	608	0.948	4.17	7.20	3.95	7.62	7.41
4	113.5	635	0.965	4.60	6.65	4.41	6.95	6.80

RESULTS - TABLE III

Comparison of Calculated K_Ga's and Measured K_Ga's based on K_Ga calculated $= 0.0465\ G^{0.5}\ L^{0.4}$

Run	G #/hr-ft.^{2}	L #/hr.ft.^{2}	$G^{0.5}$	$L^{0.4}$	K_Ga Calculated	K_Ga Measured	% error based on measured K_Ga's
3	525	1079	22.9	16.3	17.4	19.52	-10.7
4	515	915	22.7	15.3	16.2	17.04	- 4.7
5	514	1459	22.7	18.45	19.5	18.65	+ 4.3
6	527	1180	22.9	16.9	18.0	17.44	+3.4
7	396	1219	19.9	17.2	15.9	14.82	+ 7.6
8	389	1288	19.7	17.5	16.0	14.47	+10.3
9	528	2045	22.9	21.4	22.8	20.45	+11.2
10	528	1700	22.9	19.6	20.9	19.75	+ 5.6
1A	518	1340	22.7	17.85	18.8	19.44	- 3.1
2	518	1508	22.7	18.7	19.7	21.16	- 7.1
3	384	744	19.6	14.1	12.9	13.24	- 2.3
4	384	585	19.6	12.8	11.7	12.00	- 2.5
5	354	909	18.8	15.3	13.4	12.60	+ 6.7
6	213	746	14.6	14.1	9.6	9.28	+ 3.2
7	207	612	14.4	13.0	8.7	8.59	+ 1.2
8	207	472	14.4	11.75	7.9	7.92	0
9	351	1010	18.7	15.9	13.8	13.21	+ 4.5
1B	343	448	18.5	11.5	9.9	9.18	+ 7.6
2	343	454	18.5	11.55	9.9	10.22	- 2.9
3	207	440	14.4	11.4	7.6	6.30	+ 2.1
1C	62.0	833	7.87	14.75	5.4	5.17	+ 3.9
2	54.5	786	7.38	14.40	4.9	4.90	0
3	54.0	782	7.35	14.40	4.9	4.76	2.1
4	54.2	598	7.37	12.9	4.4	4.65	-6.5
5	60.5	591	7.77	12.9	4.7	4.71	0
6	60.5	604	7.77	12.95	4.7	4.73	0
1D	127.5	578	11.3	12.75	6.7	6.53	+ 3.1
2	127.5	577	11.3	12.75	6.7	6.85	- 2.9
3	137.0	608	11.7	13.00	7.1	7.41	- 4.0
4	113.5	635	10.66	13.2	6.5	6.80	- 4.4

TABLE IV

Run	G #/hr-ft².	L #/hr.ft².	ΔP measured "H_2O	f'	A_L	μ_0^2	ΔP calculated* "H_2O
3	525	1079	0.30	14.5	1.45	3.77	0.38
4	515	915	0.30	14.5	1.45	3.65	0.37
5	514	1459	0.30	14.5	1.50	3.61	0.38
6	527	1180	0.30	14.5	1.50	3.81	0.40
7	396	1219	0.20	15.5	1.50	2.16	0.24
8	386	1288	0.20	16.0	1.50	2.05	0.24
9	528	2045	0.36	14.5	1.55	3.85	0.42
10	528	1700	0.35	14.5	1.55	3.85	0.42
1A	518	1340	0.575	14.5	1.50	3.70	0.63
2	518	1508	0.60	14.5	1.50	3.70	0.63
3	384	744	0.30	16.0	1.50	2.02	0.38
4	384	585	0.30	16.0	1.50	2.02	0.38
5	354	909	0.27	16.0	1.50	1.72	0.32
6	213	746	0.10	16.5	1.50	0.626	0.12
7	207	612	0.10	16.5	1.45	0.589	0.11
8	207	472	0.10	16.5	1.40	0.589	0.10
9	351	1010	0.27	16.0	1.50	1.69	0.32
1B	343	448	0.26	16.0	1.40	1.62	0.28
2	343	454	0.245	16.0	1.40	1.62	0.28
3	207	440	0.09	16.5	1.40	0.589	0.11
4	207	440	0.09	16.5	1.40	0.589	0.11
1C-6C	Pressure drop too small to measure accurately with the manometer used.						
1D	127.5	578	0.04	17	1.45	0.223	0.043
2	127.5	577	0.04	17	1.45	0.223	0.043
3	137.0	608	0.05	17	1.45	0.259	0.050
4	113.5	635	0.035	17	1.45	0.176	0.034

*-Reference: Sherwood, Absorption and Extraction, pg. 138 ff.

A_W taken as 1.0

A_p taken as 0.28 (Fig. 42)

A_L read from curves G (Fig. 43 and 44)

f' read from curve (Fig. 40)

FIGURE 2

PLOT OF K_Ga VS. GAS RATE

LIQUOR RATE = 570 – 830 LBS./HR.-SQ.FT.

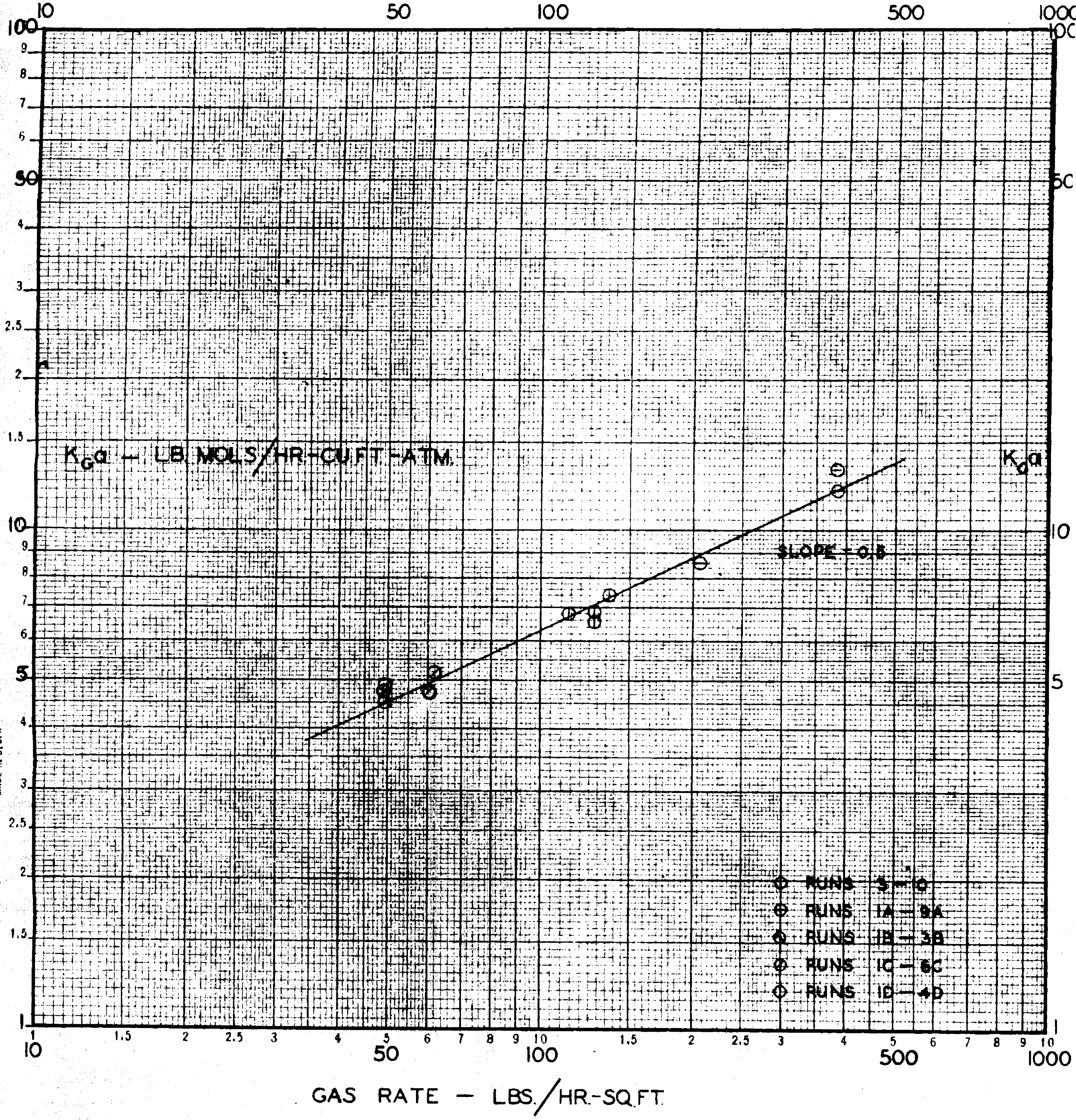

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FIGURE 7

PRESSURE DROP THROUGH PACKING VS. GAS RATE

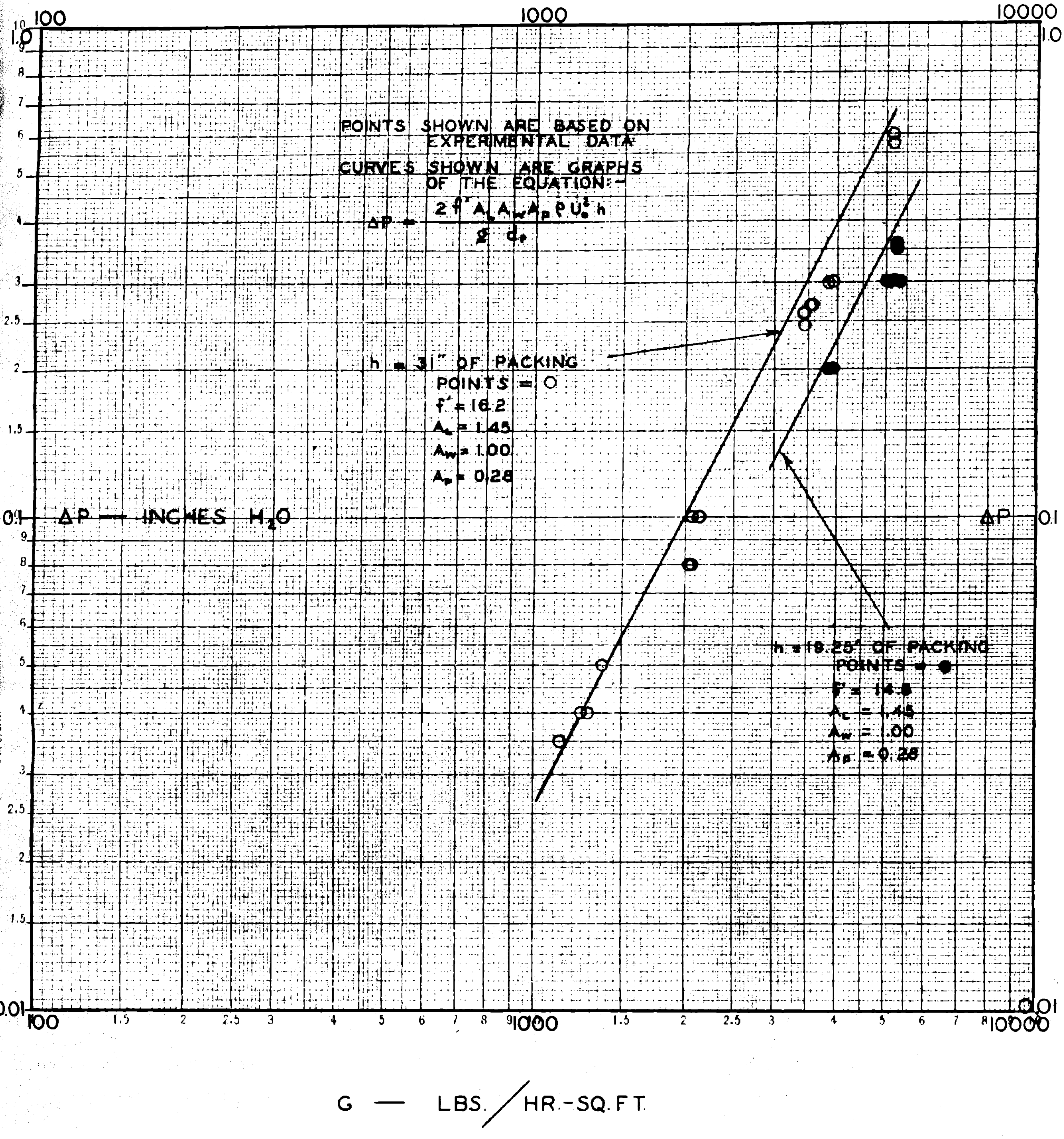

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FIGURE 5

PLOT OF $\frac{K_G a}{G^{0.6}}$ AND $\frac{K_G a}{G^{0.4}}$ VS LIQUOR RATE

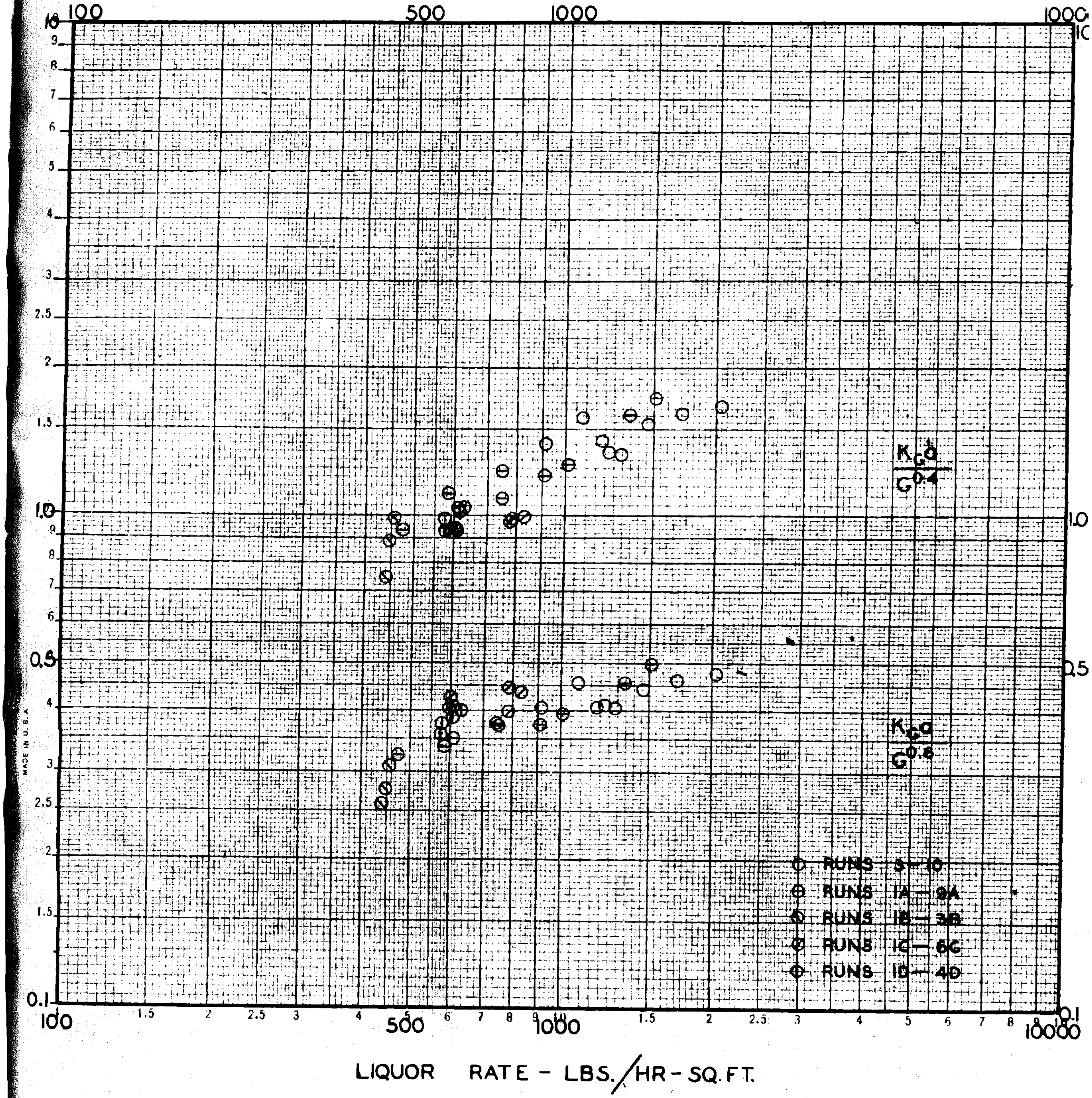

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FIGURE 4

PLOT OF $\frac{K_G a}{L^{0.4}}$ VS. GAS RATE

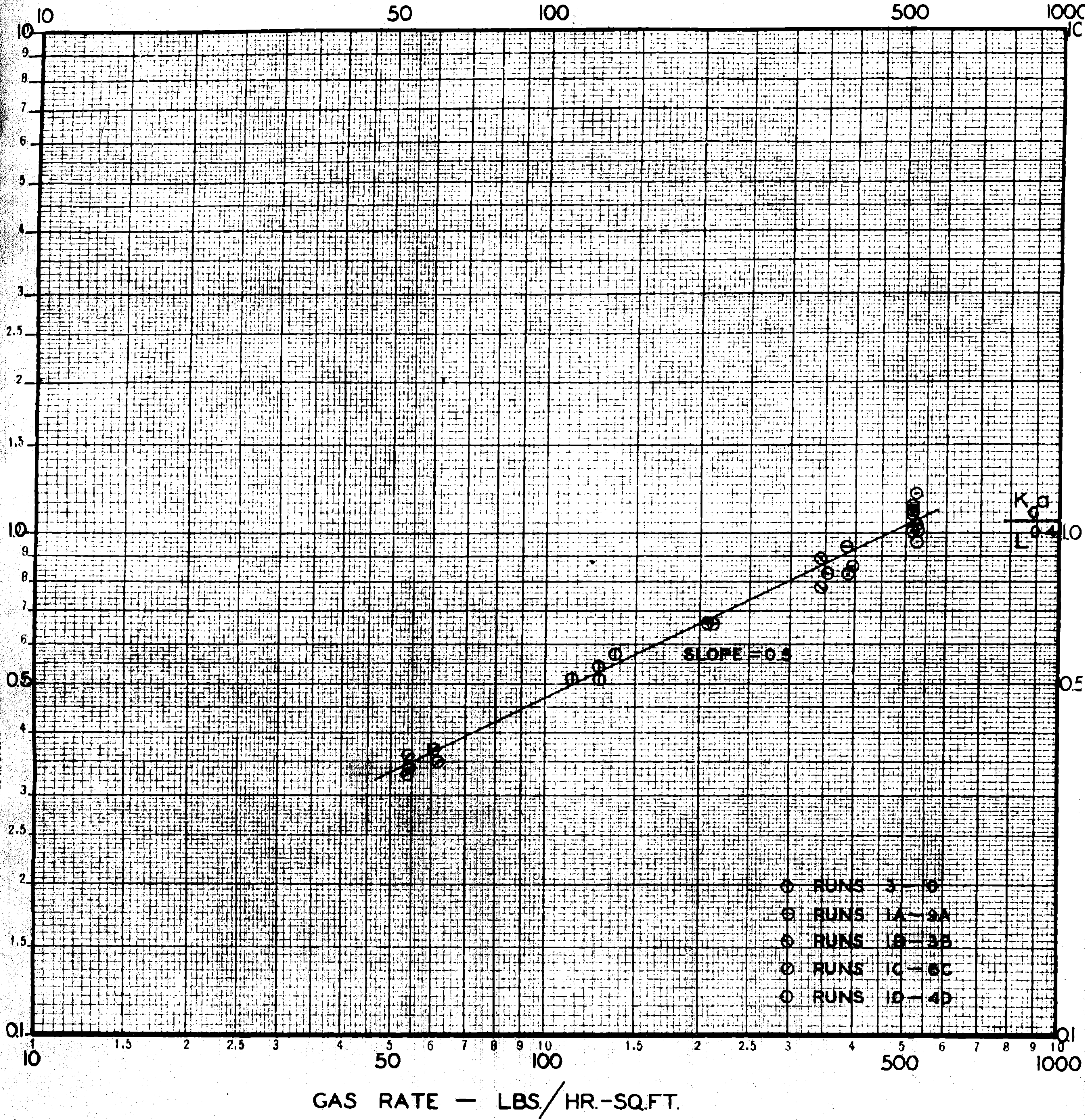

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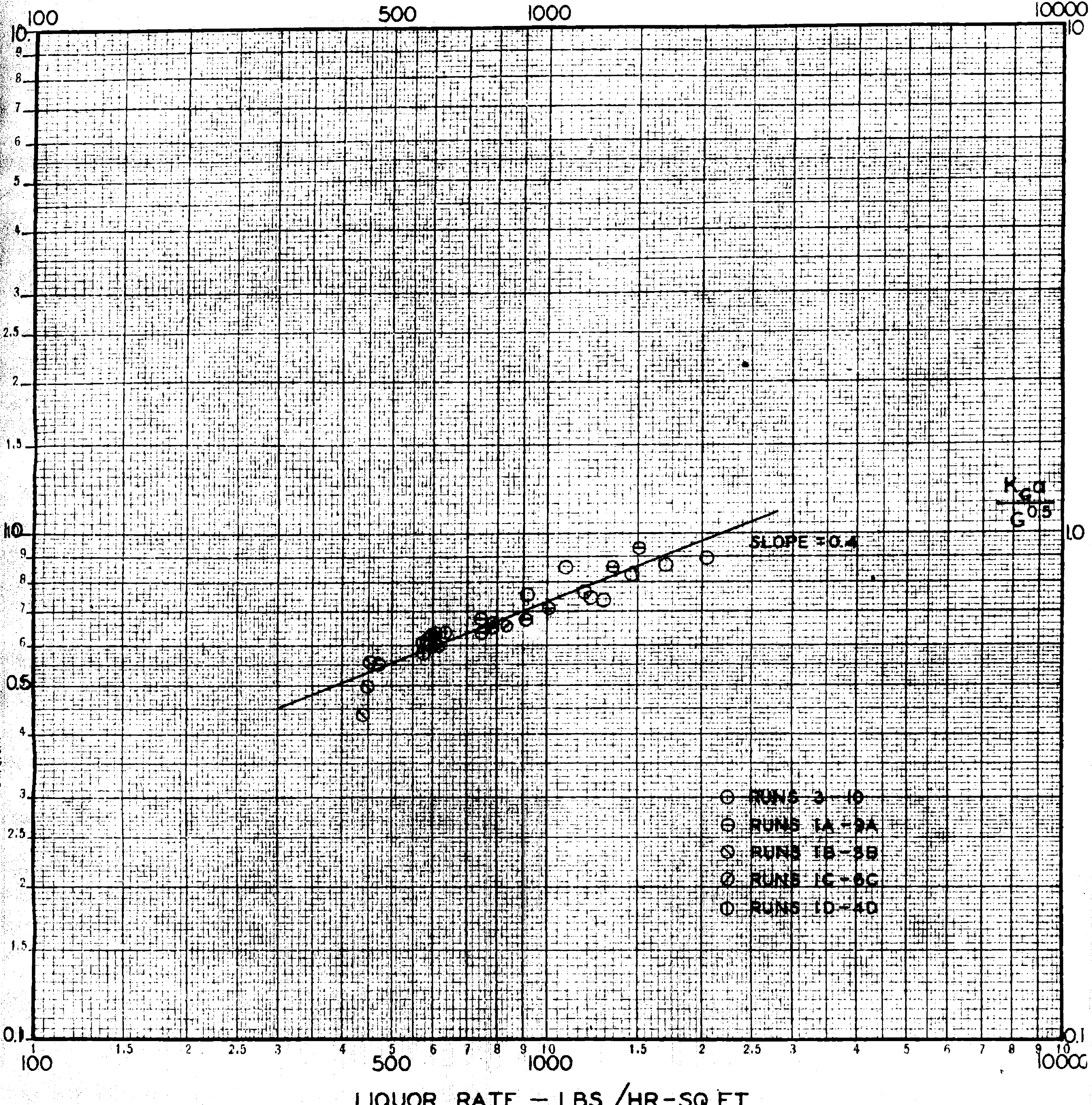
FIGURE 3

PLOT OF $\frac{K_G a}{G^{0.5}}$ VS. LIQUOR RATE



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V. DISCUSSION OF RESULTS

The reliability of the results of the 30 runs may be judged by the checks of the material balances. These material balances check, for the most part, within 10% and the average is between 5 - 6%. It is felt, therefore, that the data are quite satisfactory.

Of the three streams measured and used to calculate material balances, it is believed that the measurement of ammonia entering is most likely to be in error, since the capillary flowmeter used to measure ammonia flow could not conveniently be calibrated with ammonia directly. This might be substantiated by the fact that the material balances are in error in the same direction with but two exceptions. Since K_G a is inversely proportional to the average mean driving force, which itself is proportional in part to the concentration of the ammonia entering, K_Ga's have been calculated based not only on the inlet ammonia concentration as measured, but also using the inlet ammonia concentration calculated from the sum of ammonia absorbed and the ammonia in the gas leaving. An average of these two values has been used as a basis for the plots. The values of K_Ga are considered to be accurate within 10%.

The runs were made at varying gas rates and liquor rates, and the results may be observed from the plots, Figures 2-5. Several runs were made at substantially constant liquor rates but varying gas rates. The results of these runs are presented in Figure 2 and show K_Ga to vary with the 0.5 power of the gas rate. To correlate the entire group of runs and to find the effect of liquor rate, all values of K_Ga have been corrected by dividing by $G^{0.5}$, and the result, $\frac{K_Ga}{G^{0.5}}$, plotted against liquor rate in Figure 3. A power curve with a slope of 0.4 has been fitted to this plot indicating that for the range of liquor rates studied, K_Ga varies with $L^{0.4}$. Next, by correcting all runs for liquor rate, the result, $K_Ga/L^{0.4}$, has been plotted against G -- Figure 4. This curve also had a slope of 0.5 showing the results of Figure 2 -- that K_Ga varies with $G^{0.5}$ -- to hold over the entire range of liquor rates investigated. It has been found that this latter curve may be represented by the following empirical equation for liquor rates from 440 - 2000 lb./hr-ft.^{2} and gas rates from 55 - 530 lbs/hr-ft.^{2}:-

$$K_Ga = 0.0465\ G^{0.5}\ L^{0.4}$$

The results of these tests showing K_Ga to vary with $G^{0.5}$ contradicts the generally agreed conclusions that K_Ga is proportional to $G^{0.8}$ for tower packing.[15] Tests indicating this relationship of K_Ga and $G^{0.8}$ have not been specifically made on Raschig rings but on other types of packing. It is not felt, however, that Raschig rings should have such a different effect on the variation of K_Ga with gas rate. The only published data on Raschig ring packing available seems to be that of Johnstone and Singh[11] who have studied the absorption of SO_2 in caustic -- a case of absorption where the gas film controls -- in a tower packed with 1" Raschig rings. Their results indicate K_Ga to be proportional to $G^{0.95}$ for gas rates varying from 625 - 2400 lbs/hr-ft² and a liquor rate of 1080 lbs./hr-ft² which is a much higher range of gas rates than investigated by the present tests. Since Johnstone and Singh have used a packing height of only 0.5 feet in their experiments, the reliability of their results may be questionable. With such a low packing height the effect of spray either above or below the packing would be very pronounced and tend to make the results not wholly representative of the packing itself.

To show that the results of K_Ga obtained in these tests cannot be proportional to any other power of G other than0.5, Figure 5 has been plotted. K_Ga has been corrected for gas rate by using $G^{0.4}$ and $G^{0.6}$ instead of $G^{0.5}$. The scattered points obtained by plotting $K_Ga/G^{0.4}$ and $K_Ga/G^{0.6}$ against the liquor rate show that K_Ga proportional to $G^{0.5}$, as shown in Figure 4, is the best correlation of the data available. It is evident that correcting K_Ga for gas rate to a higher or lower power than 0.6 or 0.4, respectively, will only cause a more diverse scattering of the points.

It is already known that K_Ga is increased within a certain range by increased water rate[15]. It is thought probable that this increase is caused by the fact that the packing is only partially wetted at low liquor rates and increased water rate results in an increase of the wetted surface. Further, it is felt that after the packing is completely wetted, increased water rate will only tend to increase the thickness of the water layer over the surface of the packing and thus has little effect on K_Ga for the case in which the gas film is controlling. In view of this fact, it is felt that the packing of the tower used in these experiments was not completely wetted at liquor rates of 2000 lbs./hr-ft.^{2}. While a power equation has been fitted to the curve of Figure 3, it must be borne in mind that the slope of 0.4 holds only in the range investigated and is likely to break down for liquor rates above 2000 lbs./hr-ft.^{2} or below 440 lbs/hr-ft^2. The equation derived from these tests:

$$K_Ga = 0.0465\ G^{0.5}\ L^{0.4}$$

where K_Ga = overall transfer coefficient - # mols/hr-ft^3-atm.

G = gas rate - #/hr-ft.^{2}

L = liquor rate - #/hr-ft.^{2}

may be taken to be accurate to within 10% for the estimation of K_Ga's (See Table III).

The pressure drop through the tower packing is shown in Table IV and compared with values calculated from the following modified equation of Chilton and Colburn[16]:-

$$\Delta P = \frac{2 f' A_W A_p A_L u_0^2 h}{g \, d_p}$$

where A_W taken as unity

A_p = 0.28

A_L = taken from Fig. 44, Sherwood, Absorption and Extraction, pg. 143

f' taken from Fig. 40, Sherwood, Absorption and Extraction, pg. 139.

The pressure drop in runs 1C - 6C was too small to measure with the set-up used. To correlate this data, the measured pressure drops have been plotted in Figure 7, where two curves are drawn representing the above equation for the two tower packing heights used. For these curves, average values of 14.8 and 16.2 have been used for f', an average value of 1.45 has been used for A_L, while A_p and A_W have been taken as 0.28 and 1, respectively. The correlation is quite good, and the errors are partly due to errors in the measurement of pressure drops which is not considered to be more accurate than 10% with the instrument used.

VI. CONCLUSIONS

The absorption data reported were obtained in the range of gas rates from 55 - 530 lbs/hr-ft.^{2}, and liquor rates of 440 - 2000 lbs/hr-ft^2. Over this range of gas and liquor rates, it is concluded that:-

1. The experimental apparatus is quite satisfactory for obtaining data on transfer coefficients of ammonia.

2. K_Ga's for 1" carbon Raschig ring packing are directly proportional to $G^{0.5}$.

3. K_Ga's for 1" carbon Raschig ring packing are directly proportional to $L^{0.4}$.

4. K_Ga's may be estimated within 10% by using the following empirical equation:

$$K_G a = 0.0465\, G^{0.5} L^{0.4}$$

5. Pressure drops as measured through the heights of 1" Raschig rings employed in these tests compare favorably with those calculated by the modified Chilton and Colburn equation.

VII. RECOMMENDATIONS

Since the range covered by these experiments is rather limited, it would seem desirable to collect further data on 1" carbon Raschig rings over an extended range using the same experimental set-up with minor modifications, or a similar apparatus. The ammonia-water system seems to be a very desirable one for collecting data on absorption for the case in which the gas film controls the rate of absorption.

It would be very desirable to obtain performance data on both large and smaller sized Raschig rings, The tower used in these tests would be satisfactory for smaller ring sizes but it is felt that a tower of larger diameter would be required for ring sizes of 1 1/2" or greater. Lastly, it would be interesting to compare the performance of the carbon rings with that of stoneware packing. These results would tend to aid the designer in specifying the exact packing to use for a given absorption system.

VIII. APPENDIX

A. Abstract of Literature

B. Theory of Gas Absorption Calculations

C. Detailed Procedure

D. Summarized Data

E. Sample Calculations

F. Calibration Calculations

G. Nomenclature

H. Bibliography

APPENDIX A

ABSTRACT OF LITERATURE

A survey of the literature was made in preparation for this thesis. Data on absorption of NH_3 by water in packed tower seems to be scarce. However, brief abstracts of pertinent articles and theses pertaining to the absorption of ammonia by water or absorption equipment and packing are presented below:

1. Smith[8] studied the absorption of ammonia in water and found that the basic absorption equation

$$\frac{dW}{d\Theta} = kaV\Delta P$$

held over a range of pressures from 4 to 80 mm. with an average deviation of 2%. It was also found that the gas film offered the main resistance to the absorption of ammonia.

2. Whitman and Davis[5] reported values of K_G and K_L for the absorption of ammonia in water in a beaker-type absorption apparatus. Both the gas and liquid were stirred with propellors and the effect of the stirring on absorption coefficient noted.

3. Haslam, Hershey, and Kean[2] obtained absorption coefficients for ammonia in water on a small wetted wall tower 3" in diameter and reduced their results to the form

$$k_g = A\ G^{0.8}\ T^{-1.4}$$

4. Kowalke, Hougen and Watson[1] conducted a very intensive study including hundreds of runs on the absorption of ammonia in water. Their investigation was carried out in a simple spray chamber as well as in towers packed with wood-grid, quartz, and two sizes of stoneware. The towers used were 16" in diameter and 4' in height. From their results, K_ga has been expressed by empirical equations.

5. Sherwood and Kilgore[3] obtained overall transfer coefficients for the absorption and desorption of NH_3 in a small tower 10.2 cm. in diameter packed with 9-16 mm. coke packing. Liquid velocities were held constant and gas velocity varied. The coefficients for absorption and desorption reported were found to be the same within the limit of experimental error.

6. Butcher[7] reviewed the several different types of tower packings used for gas absorption correlating such data as surface of packing, free gas space, etc.

7. Hanks and McAdams[4] obtained values of K_g for the absorption of NH_3 and water in a small wetted wall tower 2" in diameter.

8. O'Connor and Walsh[9] compared multi-tube packing with spiral ring packing by absorbing air in water using a semi-commercial sized tower (18" in diameter, 10' in height).

9. Edmonds[10] correlated previous data obtained on transfer coefficients in an attempt to replace the many empirical equations covering special cases with a more general one. He reported that in the case of gas film resistance controlling

$$K_G a = \lambda G^A L^\alpha$$

10. Hixson and Scott[6] reported overall transfer coefficients for the absorption of NH_3 in water in a small spray tower 2 7/8" in diameter. The effect of variable fluid flow at three tower heights was investigated and empirical equations correlating these variables developed.

11. Johnstone and Singh[11] studied the absorption of SO_2 in NaOH as an example of gas film controlling absorption using several kinds of tower packings. For 0.5 feet of 1" x 1" Raschig ring packing and a liquor rate of 1080 lbs./hr.-ft.^{2}, they report $k_G a = 0.107\ G_0^{0.95}$ for gas rates varying from 625 - 2410 lbs./hr.-ft.^{2}.

12. Chilton, Duffey, and Vernon[12] reported values of K_G from 0.11 to 0.29 lbs.mols/hr.-ft.^{2}atm. for the absorption of NH_3 by water using crushed stone and clay sphere packing in three different tower sizes. $K_g a$'s were found to increase with the 0.5 to 0.6 power of the surface per unit volume. Tower diameter is without effect on the absorption efficiency provided the initial distribution is satisfactory,

and the ratio of tower diameter to packing diameter is 8 to 1 or greater. A previous test is referred to where a four-point distributor was found to be adequate for a 12" tower.

APPENDIX B

THEORY OF GAS ABSORPTION CALCULATIONS

To specify the capacity of an absorption tower, the overall transfer coefficient is generally used. This unit is derived from equations based on simple material balances and on rates of absorption and will be derived below.

Based on the two-film theory of gas absorption, the rate of absorption may be considered to be

$$\frac{dW}{d\theta} = k_L aA(x_e - x)dH = k_G aA(y - y_e)dH$$

where $\frac{dW}{d\theta}$ = rate of solute gas transferred per unit time

k_L = film coefficient of the liquid film

k_G = " " " " gas "

A = cross sectional area of apparatus

H = height of apparatus

$a = \frac{\text{area of liquid-gas interface}}{A\ H} =$ active absorbing surface of packing

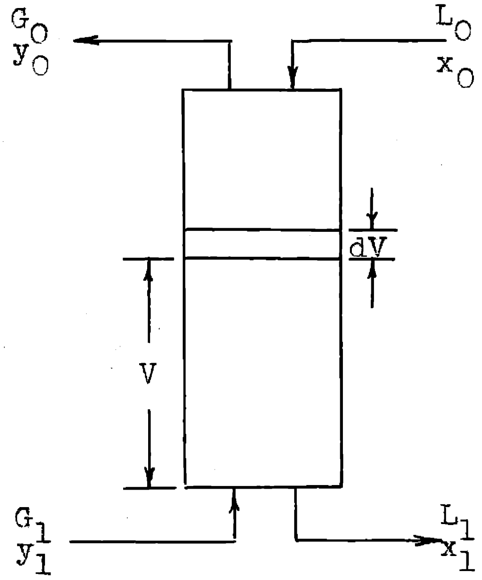
x = concentration of liquid phase

x_e = concentration of liquid phase at equilibrium

y = concentration of gas phase

y_e = concentration of gas phase at equilibrium

Referring now to the material balance. Absorption towers are usually operated on the counter-flow principle, the gas entering at the bottom of the tower and the liquid at the top.



G = lbs. of inert gas passing through the tower/unit time.

L = lbs. of absorbing liquid/ unit time.

y = gas phase composition - lbs. solute/lb. inert gas.

x = liquid phase composition - lbs. solute/lb. absorbing liquid.

1 = subscript referring to base of tower.

O = subscript referring to top of tower.

V = volume of packed surface in tower.

By an overall material balance,

$$G_1y_1 + L_Ox_O = G_Oy_O + L_1x_1$$

However, assuming no change in weight of inert gas or absorbing liquid,

$$G_1 = G_O = \text{constant} = G$$

$$L_1 = L_1 = \text{constant} = L$$

$$(y_1 - y) = \frac{L}{G} (x_1 - x)$$

This last equation relating gas composition and liquid composition is one of a straight line with slope $\frac{L}{G}$ and represents the actual relations between gas and liquid at any point in the tower.

Over an infinitesimally small volume, dV,

$$\frac{dW}{d\theta} = G\ dy = L\ dx$$

However,

$$\frac{dW}{d\theta} = k_G aA(y - y_e)dH = k_L aA\ (x_e - x)dH$$

$$L\ dx = k_G aA\ (y - y_e)dH$$

Or, $$L\int_{x_0}^{x_1}\frac{dx}{y - y_e} = \int_0^H k_G aA\ dH = \int_0^V k_G a\ \ dV$$

Upon integrating, assuming $k_G a$ remains constant throughout the tower,

$$L\int_{x_0}^{x_1}\frac{dx}{y - y_e} = k_G aV$$

If the solute content of the gas is sufficiently low so that the partial pressure, p, may be taken as proportional to the concentration, y, in stoichiometric units, and if the individual film coefficient is replaced by the overall transfer coefficient, the equation becomes

$$K_G a = \frac{L}{V}\int_{x_0}^{x_1}\frac{dx}{p - p_e}$$

where K_G = overall transfer coefficient

p = partial pressure of solute in the main gas phase corresponding to y.

p_e = equilibrium partial pressure corresponding to y_e.

In a like manner, it may be shown that

$$K_La = \frac{L}{V}\int_{x_0}^{x_1}\frac{dx}{x_e - x}$$

The exact evaluation of the above equations necessitates graphical integration of $\frac{1}{p - p_e}$ or $\frac{1}{x_e - x}$ against x. However, if the equilibrium line is straight or relatively straight over the range in question, the calculations may be simplified and accomplished without resort to graphical integration. In this special case, it is possible to use an average mean driving force based on the log mean of the terminal conditions. That is,

$$\frac{W}{\theta} = L\ (x_1 - x_o) = K_Ga\ V\ \Delta p_m$$

$$K_Ga = \frac{L\ (x_1 - x_o)}{V\ \Delta p_m}$$

$$\text{where } \Delta p_m = \frac{(p_1 - p_{e1}) - (p_o - p_{eo})}{\ln \frac{p_1 - p_{e1}}{p_o - p_{eo}}}$$

APPENDIX C

DETAILED PROCEDURE

Tower: The tower used in these experiments was 5 feet in overall height, 10" in diameter and was constructed of 26 gauge galvanized sheet iron (Toncan iron). It was built in two parts - the lower section, being one foot in height, acted as the liquor reservoir and gas inlet section; the upper section was four feet in height and was the packed section. The sheet iron was turned, rolled, and soldered, thus being absolutely tight. The two sections were flanged with a 14" diameter plate and were sealed together with rubber gaskets. A 4" galvanized iron pipe about 18" long was soldered into the lower section. This piece was fitted so as to be concentric with the tower and was extended 8" up from the bottom. A 2" lip beveled about 30° was soldered on to the upper end of this pipe. The packing was supported on a meshed screen (1/2" mesh) placed between the upper and lower tower sections. To this screen an inverted pan 6" in diameter and 3" deep was attached. This pan together with the lip on the inlet line prevented the liquor flowing down the tower from entering the gas line. A 1" iron pipe was soldered to the bottom of the liquor reservoir to serve as a liquid exit line. The top of the tower was left open to the atmosphere. (Arrangement had been made to connect an outlet gas line to an exhaust hood, but the dilute concentration of ammonia in the gas made the use of this unnecessary.) The inside of the tower was lacquered to lessen corrosion.

Packing: The packing used in these experiments was 1" commercial carbon Raschig rings dumped into the tower. These rings were very uniform in size and shape. Since they had been used before and were covered with iron rust, before being used in this test, the rings were scrubbed in dilute acid, washed and thoroughly rinsed in fresh water. The bulk density of the packing used in these runs was about 30 pounds per cu. ft.

Pressure Drop: The pressure drop through the tower packing was measured by an Ellison inclined draft gage. Pressure taps were fitted on the lower section of the tower below the packing support and on the upper section about 4" above the packing.

Water Distributor: City water was used for the absorption and was piped to the tower through 1/2" iron pipe. After passing through an orifice for control purposes, the water passed to the water distributor in the tower. The distributor head consisted of a 1 1/2" iron nipple into which short lengths of 3/16" copper tubing were soldered. The distributor had 13 openings which were adjusted to give uniform streams of water by pinching the ends of the tubes. This arrangement served to distribute the water very effectively over the top of the packing without giving spray. The head was placed about 3-4" above the packing. Liquor rates of 440-2050 pounds per hr. per square foot were used in these experiments. The temperature of the exit liquor was measured by a mercury thermometer and was found to remain fairly constant throughout all runs (13-20°C.). Since it was necessary to only crack the valve in the water line to obtain the liquor rates desired, the liquor rate remained constant during any run. This was proven by successive runs at the same valve setting which gave indentical rates of flow each time.

Gas Inlet: Air, the inert gas, was blown into the tower by a centrifugal blower through a 4" galvanzied inlet line. With this fan, gas velocities of from 55-530 pounds per hour per square foot were obtained and used; these represented linear velocities of from 0.2-2.00 ft. per sec. through the tower. The air was measured by means of a sharp-edged orifice in the line 12 feet from the fan and 4 feet from the tower. Three sizes of orifices were used -- 1/2", 3/4", and 1 7/16" depending on the air rates desired. The manometer taps were connected 4" upstream and 1 1/2" downstream, thus satisfying the requirements for throat tap connections.[13, 14] An orifice coefficient varying with the ratio of orifice and pipe diameter was used for each orifice.[13] The ammonia flowed in the line at a point about 6" downstream from the downstream orifice connection.

Ammonia Inlet: Anhydrous ammonia was used in these experiments. The gas was bled from a storage cylinder standing on end and controlled by a needle valve. A wire heating element was required around the valve to prevent the gas from freezing upon expansion from the cylinder. The gas was measured by passing it through a 1.5 mm. capillary flowmeter about 2" long. The flowmeter was calibrated with air against a calibrated wet gas meter three times during the experimental work and check results were obtained. After passing the flowmeter, the gas was led directly into the air inlet line. Temperature and static pressure measurements were made of the ammonia on the upstream side of the flowmeter.

Liquor Flow and Liquor Sample: The exit liquor line was designed so that a constant head of 1 - 2" of liquor was maintained in the reservoir at all times during a run. The rate of flow was taken by catching and weighing the amount of liquor flowing from the tower during a given run, the time being measured by a stop-watch. The exit liquor sample was taken from the amount of liquor collected during the entire run. Partial pressures of NH_3 were calculated by assuming Henry's law for the solubility of a gas in a liquid.

Exit Gas Sample: A sample of the exit gas was withdrawn continuously from the tower at a point directly above the water distributor by means of a small Cenco aspirating pump. No entrainment was found to collect in this line, and therefore an entrainment separator was found unnecessary. This sample was then passed through an absorption train of two bottles in series, one of which contained a known amount of sulfuric acid (5 or 10 cc. of 0.05 N H_2SO_4, and methyl red indicator. The second bottle contained a fraction of a drop of acid and indicator and served to insure that complete absorption took place in the first bottle. The sample denuded of its ammonia content was then passed through a calibrated wet gas meter to measure the inert gas and then through the Cenco aspirator. (It was necessary to withdraw from 4 to 70 liters of sample to neutralize the acid used in a run. The runs for the most part required between 8 - 12 liters.) A by-pass around the absorption train and meter was used to flush the sample line at the start of a run. The wet gas meter was calibrated under operating conditions both against a meter calibrated to within 0.5% and against calibrated bottles by the displacement method. In each case, the meter factor was found to be 1.00.

Chemical Analysis:[18]

1. Exit Liquor: The sample of exit liquor obtained as described above was analyzed by titrating an aliquot part directly against 0.05 N. H_2SO_4, methyl red being used as

the indicator.

2. Standardization of H_2SO_4. The acid used for the analysis of the exit liquor and exit gas was titrated against 0.5 N. NaOH, methyl red as an indicator. The NaOH in turn, was standardized directly against 2.000 g. of $KHC_8H_4O_4$ -- potassium acid phthalate -- phenolphthalein being used as the indicator. The standardizations were made before the runs in this experiment were begun, and were checked to less than 0.5% during the latter part of the experimentation.

APPENDIX D

SUMMARIZED DATA

TABLE V

Summarized Data for Figure 2

Plot of G vs $K_G a$ at Constant Liquor Rate

Run	G	L	$K_G a_{Av.}$
3A	384	744	13.24
4A	384	584	12.00
7A	207	612	8.59
1C	62	833	5.17
2C	54.5	786	4.90
3C	54.0	782	4.76
4C	54.2	598	4.65
5C	60.5	591	4.71
6C	60.5	604	4.73
1D	127.5	578	6.53
2D	127.5	577	6.85
3D	137.0	608	7.41
4D	113.5	635	6.80

TABLE VI

Summarized Data for Figure 3

Run	K_Ga	G	$G^{.5}$	$\frac{K_Ga}{G^{.5}}$	L
3	19.52	525	22.9	.853	1079
4	17.04	515	22.7	.751	915
5	18.65	514	22.7	.821	1459
6	17.44	527	22.9	.762	1180
7	14.82	396	19.9	.745	1219
8	14.47	389	19.7	.735	1288
9	20.45	528	22.9	.892	2045
10	19.75	528	22.9	.863	1700
1A	19.44	518	22.7	.857	1340
2A	21.16	518	22.7	.934	1508
3A	13.24	384	19.6	.675	744
4A	12.00	384	19.6	.612	585
5A	12.60	354	18.8	.669	909
6A	9.28	213	14.6	.635	746
7A	8.59	207	14.4	.596	612
8A	7.92	207	14.4	.550	472
9A	13.21	351	18.7	.707	1010
1B	9.18	343	18.5	.496	448
2B	10.22	343	18.5	.555	454
3B	6.30	207	14.4	.437	440
1C	5.17	62	7.87	.657	833
2C	4.90	54.5	7.38	.664	786
3C	4.76	54	7.35	.648	782
4C	4.65	54.2	7.37	.630	598
5C	4.71	60.5	7.77	.606	591
6C	4.73	60.5	7.77	.609	604
1D	6.53	127.5	11.3	.578	578
2D	6.85	127.5	11.3	.606	577
3D	7.41	137	11.7	.633	608
4D	6.80	113.5	10.66	.638	635

TABLE VII

Summarized Data for Figure 4

Run	L	$L^{0.4}$	K_Ga	$\frac{K_Ga}{L^{0.4}}$	G
3	1079	16.3	19.52	1.20	525
4	915	15.3	17.04	1.11	515
5	1459	18.45	18.65	1.01	514
6	1180	16.9	17.44	1.03	527
7	1219	17.2	14.82	.86	396
8	1288	17.5	14.47	.83	389
9	2045	21.4	20.45	.96	528
10	1700	19.6	19.75	1.01	528
1A	1340	17.85	19.44	1.09	518
2	1508	18.7	21.16	1.13	518
3	744	14.1	13.24	.94	384
4	585	12.8	12.00	.94	384
5	909	15.3	12.60	.83	354
6	746	14.1	9.28	.66	213
7	612	13.0	8.59	.66	207
8	472	11.75	7.92	.67	207
9	1010	15.90	13.21	.83	351
1B	448	11.5	9.18	.78	343
2	454	11.55	10.22	.89	343
3	440	11.40	6.30	.55	207
1C	833	14.75	5.17	.35	62
2	786	14.40	4.90	.34	54.5
3	782	14.4	4.76	.33	54.0
4	598	12.90	4.65	.36	54.2
5	591	12.90	4.71	.37	60.5
6	604	12.95	4.73	.37	60.5
1D	578	12.75	6.53	.51	127.5
2	577	12.75	6.85	.54	127.5
3	608	13.00	7.41	.57	137.0
4	635	13.20	6.80	.51	113.5

TABLE VIII

Summarized Data for Figure 5.

Run No.	G	Log G	.6 Log G	$G^{.6}$	.4 Log G	$G^{.4}$	K_Ga	$\frac{K_Ga}{G^{.6}}$	$\frac{K_Ga}{G^{.4}}$	L
3	525	2.72	1.632	42.85	1.088	12.25	19.52	.456	1.595	1079
4	515	2.712	1.6272	42.4	1.0848	12.17	17.04	.402	1.40	915
5	514	2.7105	1.6263	42.3	1.0842	12.15	18.65	.441	1.535	1459
6	527	2.722	1.6332	43.0	1.0888	12.27	17.44	.406	1.42	1180
7	396	2.598	1.5588	36.2	1.0392	10.95	14.82	.409	1.35	1219
8	389	2.590	1.5540	35.8	1.0360	10.86	14.47	.404	1.33	1288
9	528	2.7225	1.6335	43.0	1.0890	12.28	20.45	.476	1.67	2045
10	528	2.7225	1.6335	43.0	1.0890	12.28	19.75	.460	1.61	1700
1A	518	2.714	1.6284	42.5	1.0856	12.18	19.44	.458	1.60	1340
2A	518	2.714	1.6284	42.5	1.0856	12.18	21.16	.498	1.74	1508
3A	384	2.584	1.5504	35.5	1.0336	10.8	13.24	.373	1.23	744
4A	384	2.584	1.5504	35.5	1.0336	10.8	12.00	.338	1.11	585
5A	354	2.549	1.5294	33.8	1.0196	10.46	12.60	.373	1.205	909
6A	213	2.328	1.3968	24.95	.9312	8.53	9.28	.372	1.087	746
7A	207	2.316	1.3896	24.55	.9264	8.45	8.59	.35	1.015	612
8A	207	2.316	1.3896	24.55	.9264	8.45	7.92	.322	.937	472
9A	351	2.5455	1.5273	33.65	1.0182	10.42	13.21	.393	1.27	1010
1B	343	2.5355	1.5213	33.2	1.0142	10.35	9.18	.276	.886	448
2B	343	2.5355	1.5213	33.2	1.0142	10.35	10.22	.308	.988	454
3B	207	2.316	1.3896	24.5	.9264	8.45	6.30	.257	.746	440
1C	62	1.7925	1.0755	11.9	.7170	5.21	5.17	.435	.992	833
2C	54.5	1.736	1.0416	11.0	.6944	4.95	4.90	.445	.99	786
3C	54	1.732	1.0392	10.95	.6928	4.93	4.76	.398	.966	782
4C	54.2	1.734	1.0404	10.97	.6936	4.94	4.65	.425	.941	598
5C	60.5	1.782	1.0692	11.72	.7128	5.05	4.71	.402	.933	591
6C	60.5	1.782	1.0692	11.72	.7128	5.05	4.73	.403	.935	604
1D	127.5	2.1055	1.2633	18.3	.8422	6.96	6.53	.357	.938	578
2D	127.5	2.1055	1.2633	18.3	.8422	6.96	6.85	.374	.983	577
3D	137	2.1365	1.2819	19.4	.8546	7.15	7.41	.387	1.037	608
4D	113.5	2.055	1.2330	17.1	.8220	6.64	6.80	.398	1.04	635

TABLE IX-A

Summarized Data
NH_3 entering as measured

Run	NH_3 entering Mol Frac.	p_1-mm.Hg	p_{i_e} mm. Hg.	NH_3 leaving Mol Frac.	p_o-mm.Hg	Δp_1	$\Delta p_1 - \Delta p_o$	log $\frac{\Delta p_1}{\Delta p_o}$	Δp_m mm. Hg.
3	.00405	3.08	0.43	.000770	.585	2.65	2.06	0.656	1.36
4	.00380	2.88	0.40	.000795	.604	2.48	1.88	0.613	1.33
5	.00405	3.08	0.29	.000854	.648	2.79	2.14	0.634	1.47
6	.00376	2.86	0.36	.000895	.682	2.50	1.82	0.564	1.40
7	.00518	3.94	0.39	.000995	.756	3.55	2.79	0.671	1.81
8	.00549	4.17	0.42	.001053	.801	3.75	2.95	0.670	1.91
9	.00396	3.01	0.22	.000747	.568	2.79	2.22	0.690	1.40
10	.00398	3.03	0.25	.000752	.572	2.78	2.21	0.686	1.40
1A	.00741	5.63	0.63	.000478	.363	5.00	4.64	1.138	1.77
2	.00738	5.61	0.57	.000375	.285	5.04	4.75	1.247	1.66
3	.00874	6.64	1.07	.000750	.570	5.57	5.00	0.990	2.20
4	.00874	6.64	1.34	.000988	.751	5.30	4.55	0.848	2.34
5	.00771	5.86	0.72	.000605	.460	5.14	4.68	1.048	1.94
6	.01290	9.81	0.98	.000584	.444	8.83	8.39	1.299	2.81
7	.01596	12.11	1.36	.000785	.596	10.75	10.15	1.256	3.52
8	.01596	12.11	1.70	.001010	.768	10.41	9.64	1.132	3.70
9	.00947	7.20	0.80	.000635	.482	6.40	5.92	1.122	2.29
1B	.00968	7.35	1.86	.001505	1.142	5.49	4.35	0.680	2.78
2	.00968	7.35	1.93	.00135	1.026	5.42	4.39	0.722	2.64
3	.02050	15.58	2.72	.001706	1.296	12.86	11.56	0.996	5.05
1C	.0328	24.90	0.71	.0000807	0.0614	24.19	24.13	2.595	4.05
2	.0649	49.30	1.34	.0001029	0.0782	47.96	47.88	2.786	7.46
3	.0652	49.50	1.29	.0001265	0.0962	48.21	48.11	2.700	7.75
4	.0566	43.00	1.53	.0001224	0.0931	41.47	41.38	2.648	6.80
5	.0510	38.80	1.54	.000188	0.1428	37.26	37.12	2.416	6.68
6	.0510	38.80	1.63	.000207	0.1571	37.17	37.01	2.373	6.79
1D	.0250	19.00	1.50	.000560	0.425	17.50	17.07	1.614	4.59
2	.0248	18.84	1.56	.000513	0.390	17.28	16.89	1.646	4.46
3	.0230	17.50	1.51	.000495	0.376	15.99	15.61	1.628	4.17
4	.0277	21.00	1.50	.000396	0.301	19.50	19.20	1.811	4.60

TABLE IX-B

Summarized Data

NH_3 entering as sum of NH_3 leaving and NH_3 absorbed.

Run	NH_3 entering		p_{1e}	NH_3 leaving		Δp_1	$\Delta p_1-\Delta p_o$	log $\frac{\Delta p_1}{\Delta p_o}$	Δp_m
	Mol Frac.	p_1-mm.Hg.	mm.Hg.	Mol Frac.	p_o-mm.Hg.				mm.Hg.
3	.00381	2.89	.43	.000769	.585	2.46	1.87	.624	1.306
4	.00338	2.57	.40	.000795	.604	2.17	1.57	.555	1.23
5	.00414	3.14	.29	.000853	.649	2.85	2.20	.642	1.49
6	.00372	2.83	.36	.000898	.683	2.47	1.79	.558	1.392
7	.00513	3.90	.39	.000994	.755	3.51	2.75	.667	1.795
8	.00538	4.08	.42	.001051	.800	3.66	2.86	.660	1.88
9	.00410	3.11	.221	.000745	.566	2.89	2.32	.708	1.430
10	.00394	2.99	.25	.000752	.571	2.74	2.17	.680	1.39
1A	.00682	5.18	.63	.000478	.363	4.55	4.19	1.098	1.660
2	.00692	5.26	.57	.000375	.285	4.69	4.40	1.216	1.580
3	.00795	6.05	1.07	.000750	.570	4.98	4.41	.941	2.04
4	.00793	6.02	1.34	.000987	.750	4.68	3.93	.795	2.15
5	.00729	5.54	.72	.000605	.460	4.82	4.36	1.020	1.86
6	.01255	9.54	.98	.000583	.443	8.56	8.12	1.287	2.745
7	.01470	11.15	1.36	.000785	.596	9.79	9.19	1.215	3.285
8	.01438	10.92	1.70	.001011	.769	9.22	8.45	1.079	3.41
9	.00900	6.84	.80	.000634	.482	6.04	5.56	1.098	2.20
1B	.00841	6.39	1.86	.001503	1.145	4.53	3.38	.597	2.465
2	.00883	6.71	1.93	.00135	1.027	4.78	3.75	.668	2.445
3	.01845	14.01	2.73	.001705	1.297	11.28	9.98	.939	4.62
1C	.0319	24.20	.71	.0000807	.0614	23.49	23.43	2.582	3.94
2	.0608	46.20	1.34	.0001029	.0781	44.86	44.78	2.758	7.06
3	.0624	47.40	1.29	.0001265	.0961	46.11	46.01	2.680	7.48
4	.0532	40.40	1.53	.0001225	.093	38.87	38.78	2.620	6.43
5	.0477	36.20	1.54	.000188	.143	34.66	34.52	2.384	6.30
6	.0491	37.30	1.63	.000207	.1575	35.67	35.51	2.354	6.55
1D	.0219	16.65	1.50	.00056	.426	15.15	14.72	1.550	4.13
2	.0228	17.30	1.56	.000513	.390	15.74	15.35	1.606	4.15
3	.0216	16.40	1.51	.000495	.376	14.89	14.51	1.598	3.95
4	.0262	19.95	1.50	.000396	.301	18.40	18.10	1.786	4.41

APPENDIX E

SAMPLE CALCULATIONS

A. Calculation of K_Ga - Run 1 C

1. Calculation of Air Flow

Orifice diameter = 0.5"

Area of orifice = $\frac{\pi(0.25)^2}{4 \quad 144}$ = 0.001363 sq. ft.

ρ Air, 1 atm., 68°F. = 0.0750 lbs./cu.ft.

ρ Water = 62.4 lbs./cu.ft.

Orifice Manometer Reading = h = 5.15" H_2O

Area of tower = $\frac{\pi \; (10)^2}{4 \quad 144}$ = 0.545 sq. ft.

From page 73, Walker, Lewis, and McAdams notes,

Orifice coefficient = 0.606 = $\frac{c}{\sqrt{1 - (A_0/A_p)^2}}$

$$\text{Lbs. air/hr.} = \rho_{Air} \times 3600 \times \frac{c \, A_0 \sqrt{2gh}}{\sqrt{1 - (A_0/A_p)^2}}$$

$$= 0.0750 \times 3600 \times 0.606 \times 0.001363 \sqrt{2 \times 32.2 \; \frac{62.4 \, h}{0.0750 \times 12}}$$

$$= 14.86 \sqrt{h}$$

where h = manometer reading in inches of water.

= 33.8 lbs./hr.

Lbs. air/hr.-sq.ft. = 33.8/0.545 = 62.0 lbs./hr.-sq.ft.

2. Calculation of Water Flow

Amount of liquor collected = 143.5 lbs.

Time for measurement of water = 19 min-0 sec.

Concentration of ammonia in water = less than 0.002 g/cc of solution. Therefore ammonia in the water is negligible.

Water rate = 143.5 x 60 / 19.0 = 453 lbs./hr.

= 453/0.545 = 833 lbs./hr-sq.ft.

3. Concentration of ammonia in water.

25cc sample of solution titrated with H_2SO_4

Acid required for titration = 40.86 cc

Normality of acid = 0.0517N.

g. NH_3/cc of solution = 40.86 x 0.0517 x 0.017/25

= 0.001438 g./cc.

Since ammonia concentration in water is negligible,

NH_3 concentration = 0.001438 lbs. NH_3/lb.H_2O

NH_3 absorbed = water rate x NH_3 concentration

= 453 x 0.001438

= 0.652 lbs. NH_3/hr.

4. Calculation of ammonia flow

Flowmeter manometer reading = 21.75" H_2O

Static pressure on gas before flowmeter = 1.68"Hg.

Temperature of gas = 34°C.

$$\rho_{NH_3} \text{ before flowmeter} = \frac{17}{359} \times \frac{273}{307} \times \frac{31.60}{29.92} = 0.0445$$

$$\rho_{NH_3} \text{ after flowmeter } 17/359 \times 273/307 = 0.0421$$

$$\rho_{NH_3 \text{ av.}} = 0.0433$$

lbs./hr. of ammonia = $M\sqrt{\rho_{NH_3 \text{ av.}}}$, where M = a value from figure 6, corresponding to the orifice manometer reading (See Calibration Calculations).

$$\text{Lbs. } NH_3/\text{hr.} = 3.23\sqrt{0.0433}$$
$$= 0.672 \text{ lbs./hr.}$$

5. Calculation of ammonia in gas exit

Acid used in absorption train = 5.0 cc.

Normality of acid = 0.0517 N

Inert gas = 78.3 liters

$$\frac{\text{lbs. } NH_3}{\text{lb. air}} = \frac{\text{cc of acid x N.}}{\text{liters of inert gas}} \times 0.017 \times \frac{28.35}{453} \times \frac{1}{0.075}$$

$$= \frac{\text{cc. of acid x N}}{\text{liters of inert gas}} \times 0.0143$$

$$= \frac{5 \times 0.0517}{78.3} \times 0.0143 = 0.0000472 \text{ lbs. } NH_3/\text{lb. Air}$$

NH_3 leaving in gas = Gas rate x lbs. NH_3/lb. air

= 33.8 x 0.0000472

= 0.00160 lbs. NH_3/hr.

6. Material Balance

NH_3 entering (as measured) = 0.672 lb./hr.

NH_3 absorbed = 0.652 lb./hr.

NH_3 leaving in gas = 0.002 lbs./hr.

NH_3 entering (by material balance) = 0.654 lbs./hr.

$$\% \text{ error (based on } NH_3 \text{ as measured)} = \frac{-0.018}{0.672} \times 100$$
$$= -2.7\%$$

7. Calculation of $K_G a$

NH_3 entering (as measured)

$$\text{Mol fraction} = \frac{\frac{0.672}{17}}{\frac{33.8}{29} + \frac{0.672}{17}} = 0.0328$$

$p_1 = 760 \times 0.0328 = 24.90$ mm. of Hg.

NH_3 in equilibrium with aqua-NH_3 leaving tower

Temp. = 15°C.

(Reference: Perry's Chem. Eng. Handbook, page 996)

$p_e\ 15°C = 492$ mm. Hg/lb. NH_3/lb.H_2O

$p_e\ 15°C = 492 \times 0.001438 = 0.71$ mm Hg.

NH_3 leaving top of tower:-

$$\text{Mol fraction} = \frac{\frac{0.0016}{17}}{\frac{33.8}{29} + \frac{0.0016}{17}} = 0.0000807$$

$p_o = 760 \times 0.0000807 = 0.0614$ mm. Hg.

NH_3 in equilibrium with water entering the tower analyzed but found to be negligible

$\Delta p_1 = 24.90 - 0.71 = 24.19$

$\Delta p_o = 0.0614 = 0 = 0.0614$

$\Delta p = \Delta p_1 - \Delta p_o = 24.19 - 0.06 = 24.13$

$$\Delta p_m = \frac{\Delta p_1 - \Delta p_o}{\ln \frac{\Delta p_1}{\Delta p_o}}$$

$$= \frac{24.13}{\ln \frac{24.19}{0.0614}} = 4.05 \text{ mm Hg.}$$

Tower packed with 31" of packing.

$$K_G a = \overset{\text{lb.mol/hr.-ft.}^2}{\frac{\text{lb.NH}_3\text{ absorbed/hr.}}{17 \times 0.545}} \Bigg| \overset{\text{lb.mols/hr.ft.}^2\text{atm.}}{\frac{1}{\frac{\Delta p_m}{760}}} \Bigg| \overset{\text{lb.mol/hr-ft}^3\text{-atm.}}{\frac{}{\frac{31}{12}}} \Bigg|$$

$$= \frac{\text{lb.NH}_3\text{ absorbed/hr.}}{\Delta p_m} \times 31.75$$

$$= \frac{0.652}{4.05} \times 31.75 = 5.10 \text{ lb. mols/hr-ft.}^3\text{-atm.}$$

B. Pressure drop through the packing - Run 1 A

(Reference: - Sherwood - Absorption and Extraction, p.138)

$$\Delta P = \frac{2\ f'\ A_W\ A_p\ A_L \rho u_0^2\ h}{g\ \ d_p} \times \frac{12}{62.4}$$

ΔP = pressure drop in "H_2O

u_0 = linear gas velocity based on tower cross section-ft/sec.

ρ = density of gas - lbs./cu.ft.

h = tower height - ft.

g = acceleration of gravity - ft./sec.^{2}

d_p = nominal size of packing - ft.

f' = modified friction factor correlated against $d_p \rho u_0 / \mu$, a modified Reynold's Number.

A_W = "wall effect factor"

A_p = correction factor for hollow packing

A_L = correction for the wetting of the packing by the solvent circulated.

For 1" ring packing, $A_p = 0.28$ and $A_W = 1$

ρ air = 0.075

$$\Delta P = \frac{2\ f' \times 1 \times 0.28 \times A_L \times 0.075\ u_0^2\ h}{32.2 \cdot \frac{1}{12}} \times \frac{12}{62.4}$$

$$= 30.1 \times 10^{-4}\ f'\ A_L\ u_0^2\ h$$

For Run 1 A,

$G = 518$ lb./hr-ft.^{2}

$$u_0 = \frac{518}{\rho \times 3600} = \frac{518}{0.075 \times 3600} = 1.92 \text{ ft./sec.}$$

$f' = 14.5$

A_L (corresponding to $L = 1340$ lb./hr-ft.^{2}) = 1.50

$h = 31''$

Thus, $\Delta P_{calc.} = 30.1 \times 10^{-4} \times 14.5 \times 1.50 \times (1.92)^2 \times 31/12$

$= 0.625'' \, H_2O$

$\Delta P_{measured} = 0.575'' \, H_2O$

APPENDIX F

CALIBRATION CALCULATIONS

Calibration of Ammonia Flowmeter

The capillary flowmeter used to measure the NH_3 was calibrated using air. Hence it was necessary to convert the calibration measurements obtained with air to measurements using ammonia. This has been done in the following manner:-

$$v_{air} = K' \left(\frac{2gh'}{12}\,\frac{62.4}{\rho_{air}}\right)^n$$

$$v_{NH_3} = K'' \left(2g\,\frac{h''\;62.4}{12\,\rho_{NH_3}}\right)^n$$

Assuming $K' = K''$, since the coefficient of the flowmeter presumably does not change for the gas flowing through, and letting $h' = h''$,

$$v_{NH_3} = v_{air} \left(\frac{\rho_{air}}{\rho_{NH_3}}\right)^n$$

Since for most flowmeters or orifices, the velocity is proportional to the 0.5 power of the manometer differential across the orifice, we shall let $n = 1/2$. (In this case, v_{air} was actually proportional to $(1/\rho_{air})^{0.5}$:-

$$v_{NH_3} = v_{air}\sqrt{\frac{\rho_{air}}{\rho_{NH_3}}}$$

$$\text{or,}\quad v_{NH_3}\,\rho_{NH_3} = v_{air}\sqrt{\rho_{air}}\sqrt{\rho_{NH_3}}$$

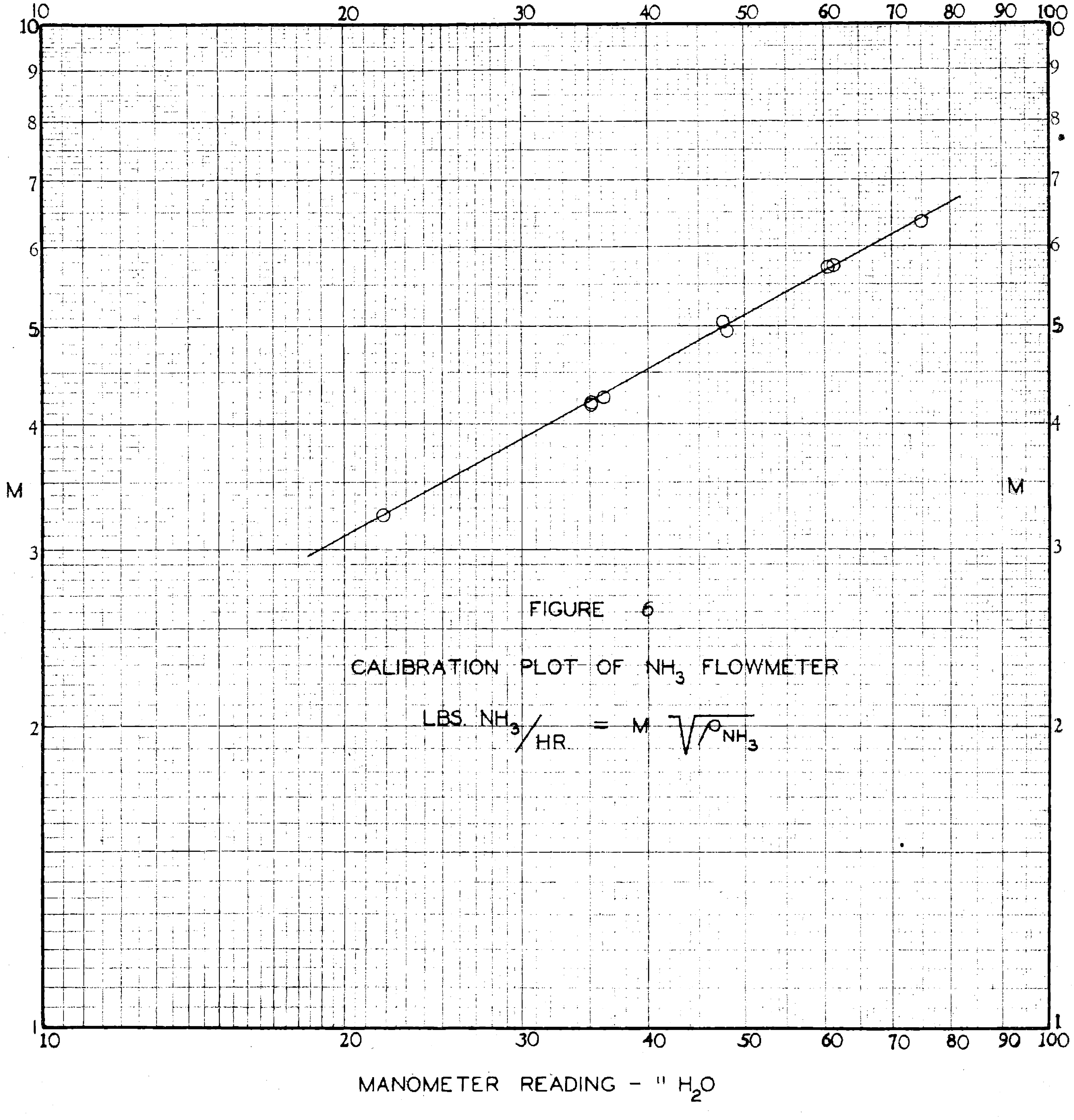


FIGURE 6

CALIBRATION PLOT OF NH_3 FLOWMETER

$$\text{LBS. } NH_3/HR = M\sqrt{\rho_{NH_3}}$$

H.M.B 5-12-37

Tabulated Data for Calibration Plots

h - "H_2O	Metered Flow-v_{air} cu.ft./sec.	$\rho\ air_{av.}$	$\sqrt{\rho Air_{av.}}$	M $v_{air} \times 3600 \times \sqrt{\rho Air_{av.}}$
21.8	.00327	.0763	.276	3.25
35.1	.00418	.0776	.278	4.18
35.1	.00419	.0775	.278	4.20
36.1	.00422	.0781	.279	4.24
47.6	.00494	.0796	.284	5.06
48.0	.00490	.0786	.280	4.94
60.5	.00560	.0808	.283	5.71
61.2	.00562	.0802	.283	5.73
74.9	.00618	.0812	.285	6.34

APPENDIX G

NOMENCLATURE

a = active absorbing surface of packing - sq.ft./cu.ft.

A = cross-sectional area of tower - sq.ft.

A_L= correction for the wetting of the packing by the solvent

A_O= area of orifice opening - sq.ft.

A_p= correction factor for hollow packing

A_P= cross-sectional area of pipe - sq.ft.

A_W= "wall effect factor"

c = orifice coefficient

d_p= nominal size of packing - ft.

e = subscript denoting equilibrium conditions

f'= modified friction factor correlated against a modified Reynold's number, $\frac{d_p \rho u_O}{\mu}$

g = acceleration of gravity - ft./sec.^{2}

G = gas rate - lbs./hr.-sq.ft. unless noted as lbs./hr.

h = manometer reading - "H_2O or "Hg

h, H = height of tower - ft.

k_G = film coefficient of the gas film - lb.mols/hr.-sq.ft.-atm.

k_L = film coefficient of the liquid film - lb.mols/hr.-sq.ft.-unit driving force.

K_G, K_L = overall transfer coefficient - lb.mols/hr.-sq.ft.-unit overall driving force.

$K_G a$ = overall transfer coefficient - lb.mols/hr.-cu.ft.-atm.

K', K'' = flowmeter constants

L = absorbing liquor rate - lbs./hr.-sq.ft. unless noted as lbs./hr.

M = flowmeter calibration constant - $\frac{\text{lbs. } NH_3\text{/hr.}}{\sqrt{\rho_{NH_3}}}$

p_1 = partial pressure of NH_3 in entering gas - mm. Hg.

p_o = " " " NH_3 in exit gas - mm. Hg.

p_{e_1} = equilibrium partial pressure of NH_3 in exit liquor - mm. Hg.

p_{eo} = " " " " NH_3 in entering liquor - mm.Hg.

Δp_m = log mean of partial pressure differences - mm. Hg.

ΔP = pressure drop through the tower packing - "H_2O

v = volume rate of flow - cu.ft./unit time

V = volume of tower packing - cu.ft.

W = amount of solute gas transferred - lbs.

x = liquid phase composition in stoichiometric units - lbs. solute/lb. absorbing liquor.

y = gas phase composition in stoichiometric unit - lbs. solute/lb. inert gas

ρ = density - lbs./cu.ft.

θ = time - hours or seconds

μ = gas viscosity - lbs./sec.-ft.

APPENDIX H

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