EFFECT OF TEMPERATURE ON RATE OF ABSORPTION OF AMMONIA BY WATER IN PACKED TOWER

BY

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ABSTRACT

Measurements of the rate of absorption of ammonia in water have been made using a 4-inch diameter lucite column with ¼-inch porcelain Raschig rings packed to a height of 3 feet. Tests were made with water rates of 462 and 695 lbs./hr-ft^2 and a constant gas rate of 130 lbs./hr-ft^2 with liquid temperature varying from 72° F. to 110° F.

At constant liquid and gas rate, the mass transfer coefficient, K_Ga, decreases with increasing liquid temperature and is represented by straight lines on plot of K_Ga versus temperature. The variation of K_Ga with liquid temperature ranged from 6.05 at 72° F. to 2.5 at 104° F. with a constant liquid rate of 462 lbs. /hr-ft^2 and a constant gas rate of 130 lbs./hr-ft^2. At the same gas rate of 130 lbs./hr-ft^2, K_Ga varied from 6.55 at 78° F. to 5.28 at 100° F.

It was also found that K_Ga increases with an increase in water rate, and may also be represented by straight lines on a log-log plot.

APPROVAL OF THESIS

For

Department of Chemical Engineering

Newark College of Engineering

BY

FACULTY COMMITTEE

Approved: ______________________________

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INTRODUCTION

One of the most widely used industrial methods to bring vapor and liquid phases into intimate contact for the purpose of transferring mass or heat is by means of a packed tower. The device consists of a cylindrical column, equipped with a gas inlet and distributing space at the bottom, a liquid inlet and distributor at the top, and a supported mass of packing consisting of inert solid shapes. The packing provides a large area of contact between the liquid and gas and encourages intimate contact between the phases. The solute in the rich gas is absorbed by the fresh liquid entering the column, and dilute, or lean gas leaves the top.

Absorption of the solute by the liquid is accompanied by the evolution of the heat of condensation and of solution of the solute that is absorbed. The absorption rate is usually a maximum at the bottom of the column, and if the inlet gas is rich, the heat released in that section of the column causes the temperature to rise appreciably above that in most of the apparatus.

The design of packed towers for gas absorption should involve the determination of the most economical combination of the various factors affecting this operation. The variables would be the type of packing, tower diameter, tower height, quantity of liquid and concentration in the exit gas. The individual film coefficients of mass transfer in packed column are affected by the following:

1. Liquid Rate
2. Physical Properties of Liquid
3. Gas Rate
4. Physical Properties of Gas
5. Operating Temperatures
6. Operating Pressure
7. Nature of Packing
8. Diffusion Coefficient for Solute in the InertGas
9. Diffusion Coefficient for Solute in the Liquid

However, the situation is complicated by the facts that the resistances are not entirely independent, since the liquid and gas are not separated physically, and also that chemical reactions may occur.

To describe the absorption process quantitatively, the following must be determined:

1. Material Balance: The law of conservation of matter applies to the overall system and to each material around the entire absorber or any portion of it.

2. Energy Balance: Likewide, the energy balance can be applied to the absorber in its entirety or to any part.

3. Equilibrium Relationships: These establish the maximum transfer that can be effected in a specific situation.

4. Transfer Rate: As in other transfer processes, the rate at which the solute moves from one phase to the other is determined as the quotient of potential and resistance.

The additivity of the mass transfer resistances is shown by the relation;[1]

$$\frac{1}{K_G a} = \frac{1}{k_G a} + \frac{1}{Hk_L a} = \frac{1}{Hk_L a}$$

where the symbols have the meaning shown in the Table of Nomenclature.

The equation used in the evaluation of equilibrium par-pressure of ammonia for inlet and exit gas is;[8]

$$\log \frac{p^*}{C} = 4.699 - \frac{3460}{T(^\circ R)}$$

where the symbols have the meaning shown in the Table of Nomenclature.

This equation was used by various workers (2,12) who studied mass-transfer coefficients with varying temperatures of liquid and with packing of varying nature.

This work is an extension of their investigation with the temperature of the liquid varying from 60° F. to 110° F. in a 4-inch diameter column with ½-inch unglazed porcelain Raschig rings in a bed 3 feet high. Runs were made at a constant gas rate with two different liquid rates.

LITERATURE SURVEY

In the early days of chemical engineering, information on the operation of gas absorption equipment was quite inadequate to permit proper estimates and design for new operations. Lewis and Whiteman[10] concluded that the rate of absorption is controlled by the rate of diffusion of solute through the surface films of gas and liquid at the gas liquid boundary. They stated that the ratio of viscosity to density of the film fluid is probably the controlling factor in determining film thickness.

The effect of temperature on the overall coefficient K_Ga is composed of three individual effects on k_G, on k_L, and on solubility (measured by H). Sherwood[14] concludes that k_G is proportional to the square root of the absolute temperature at a given Reynolds-Number. From the Gilliland-Sherwood[5] equation for film thickness, the definition of gas film coefficient based upon the Maxwell diffusion concept, and the fact that density is inversely proportional to absolute temperature, it is found that diffusivity is proportional to absolute temperature for a given mass velocity, pressure and size of packing, and assuming ideal gases and low concentration of solute gas.

$$\frac{(T)^{0.23}}{(\mu)^{0.39}}$$

Since viscosity of air is approximately proportional to

$T^{0.75}$, k_G should be nearly independent of temperature.[3] However, experimental determinations have shown that this is not true.

Haslam, Hershey and Keen[6] found that K_G for absorption of ammonia in water decreased as temperature increased and from their results deduced the fact that k_G varied inversely as T. Kowalke, Hougen and Watson[8] concifmed the fact that K_G decreases as temperature increases.

The effect of different packings is also important to consider at this point. Sherwood compared eleven different packings, and the overall coefficients K_G at G = L = 500 varied from 21.3 to 8.2 with an area ratio of 5.6. For similar shapes Chilton, Duffey and Vernon[1] found that K_Ga increased as the 0.5 - 0.6 power of the superficial packing area per unit volume. At G = L = 500 they obtained K_Ga values of 10-12 for packing (clay spheres and crushed stone) with an area of 60 square feet per cubic foot. Sherwood and Holloway[15] reported K_Ga of about 12 for 1 inch carbon Raschig rings, which also have an area of about 60 square feet per cubic foot.

The most reliable and complete set of experimental data are those of Fillinger[4], whose data cover ceramic Raschig rings ranging in size from 3/8 to 2 inches; Berl saddles from 1/2 to 1-1/2 inch; and triple spiral tile. Gas rates range from 200 lb/(hr) (sq ft) to the flooding point, or to 1000 lb/(hr) (sq ft) and liquid rates range from 500 to 4500 lb/(hr) (sq ft). The effect of packing size was found to be small.

Table 1 summarizes some of the work done with packed columns of different sizes, with various packings and for a number of systems.

TABLE 1

ABSORPTION IN PACKED TOWER

Investigators	Ref.	Col. Dia.	Packed Height	Packing Material (Inches)	Liquid Rate lbs/hr-ft^2	Gas Rate lbs/hr-ft^2	Solvent	Temp. °F.
Sherwood & Kilgore (Ind. & Eng. Chem., 13 744-6 (1926)	-	4	42	Coke-0.35-0.63	323	149-507	Water	70-90
Kowalke, Hougen & Watson	8	16	41	Quartz-1.25-1.75	16-570	6-240	Water	68-110
Kowalke, Hougen & Watson	-	16	41	Spiral Tile-3	25-800	6-240	Water	68-110
Kowalke, Hougen & Watson	-	16	41	Partition Rings-4	25-800	6-240	Water	68-110
Johnstone and Singh	-	16	41	Wood Grids	21-670	19-240	0.3N	-
Johnstone and Singh	-	16	41	Wood Grids	1100	1180-2780	HAC.	-
Chilton, Duffey, and Vernon	1	3	100	Spheres, 1/2-3/4	500	400-550	Water	72-81
Chilton, Duffey, and Vernon	1	6	48-54	Spheres, 1/2-3/4	495	400-500	Water	72-81

TABLE 1 (CONTINUED)

Investigators	Ref.	Col. Dia.	Packed Height	Packing Material (Inches)	Liquid Rate lbs/hr-ft^2	Gas Rate lbs/hr-ft^2	Solvent	Temp. °F.
Chilton, Duffey, and Vernon	-	11.3	45	Spheres, 1/2-3/4	500	400-500	Water	72-81
Sherwood - Holloway	15	10.0	19-31	Rings - 1	570-830	55-530	Water	77
Sherwood - Holloway	15	10.0	19.31	Rings - 1	660-710	65-700	Water	54
Sherwood - Holloway	15	10.0	19.31	Rings - 1	1520-1850	211	0.5-4.5N	77
Sherwood - Holloway	15	10.0	19.31	Berl Saddles	75-480	3330	H_2SO_4	-
Broden and Squires		FIRST WORK ON RASCHIG RINGS						
Dwyers and Dodge	8	12	5	1" Carbon Raschig Rings	100-1000	100-1000	Water	70-95

EQUIPMENT

The equipment used in this work was designed by the author and was constructed in the machine shop of the Chemical Engineering Department of Newark College of Engineering. A schematic diagram of the apparatus is shown in Figure 1. The apparatus is summarized in three main sections: (1) Gas Inlet System; (2) Column; and (3) Liquid Inlet System.

Gas Inlet System

Air, the gas phase used, was obtained after humidification from the inlet gas line of a wetted wall column apparatus and was passed through an air flow control valve before entering the air rotometer. The ammonia gas was introduced into the 1/4-inch air flow line after the rotometer with a 1/4-inch glass tee as shown in Figure 1. The ammonia flow rate was metered by a gas rotometer. A mercury manometer was connected into the air-ammonia line to measure the static pressure at the bottom of the column. Inlet gas passed through a 1/4-inch Y with the sampling tap connected to the Y. The thermometer for measuring the inlet gas temperature was located between the Y and the connection to the column.

Column

The column was made with two sections of 3-3/4- inch I.D. lucite pipe joined with split flanges. The packing support plate was a stainless steel grid with 9/16-inch diameter openings and 3/32-inch webs, and had about 70% free area. It was held between the flanges. The top of the column was sealed with a flange plate through which the 1/2-inch water inlet line and the 1/4-inch exit gas line with control valve were connected. The exit gas sampling line was connected to the exit gas line with a 1/4-inch tee. The bottom section of the column was sealed with a flange plate with a water outlet connection. The 1/4-inch gas inlet line entered near the top of this section. Pressure taps above the packing and below the support plate were connected to a U type manometer filled with water. The column was packed with 1/4-inch unglazed porcelain Raschig rings with a packed bed height of 3.073 feet.

Liquid Inlet System

Water from a 1/2-inch line passed through a flowrator with the rate controlled by manual adjustment of a control valve. After the flowrator, the water passed through a Power's hot and cold fluid mixture valve where it was heated by continuous low pressure steam injection. The water temperature was manually controlled by adjustment of the steam injection pressure with a pressure reducing valve. The water distributor within the column consisted of a 3-inch O.D. shower head. 1/8-inch holes were made near the outer periphery for better distribution.

The gas inlet and outlet sampling lines were connected by rubber tubing. The packing tested was 1/4 x 1/4 x 1/16-inch unglazed porcelain Raschig rings (1).

(1) A product of U.S. Stoneware Corp.

EQUIPMENT DIAGRAM

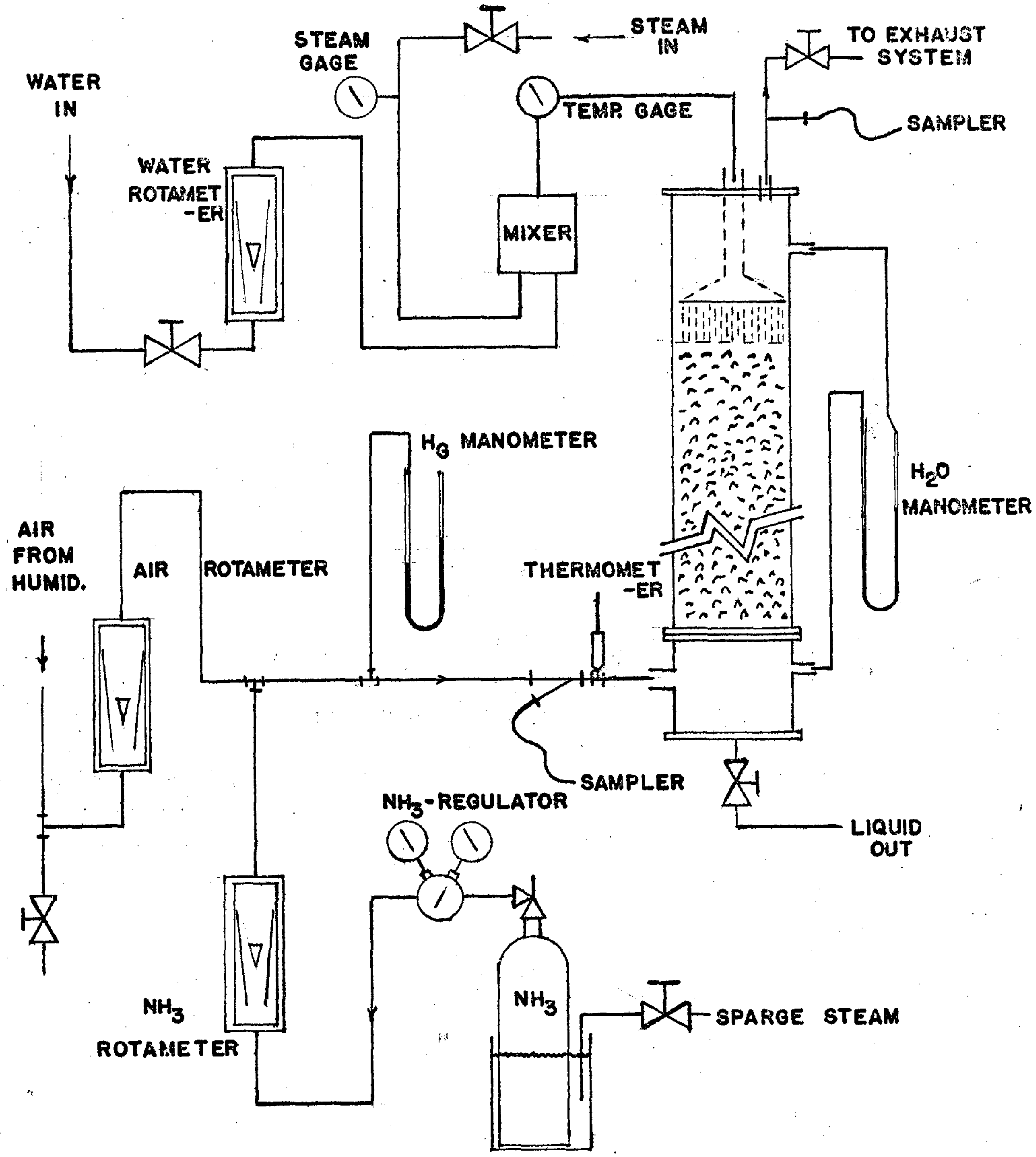


FIGURE - NO.1

COLUMN DETAILS

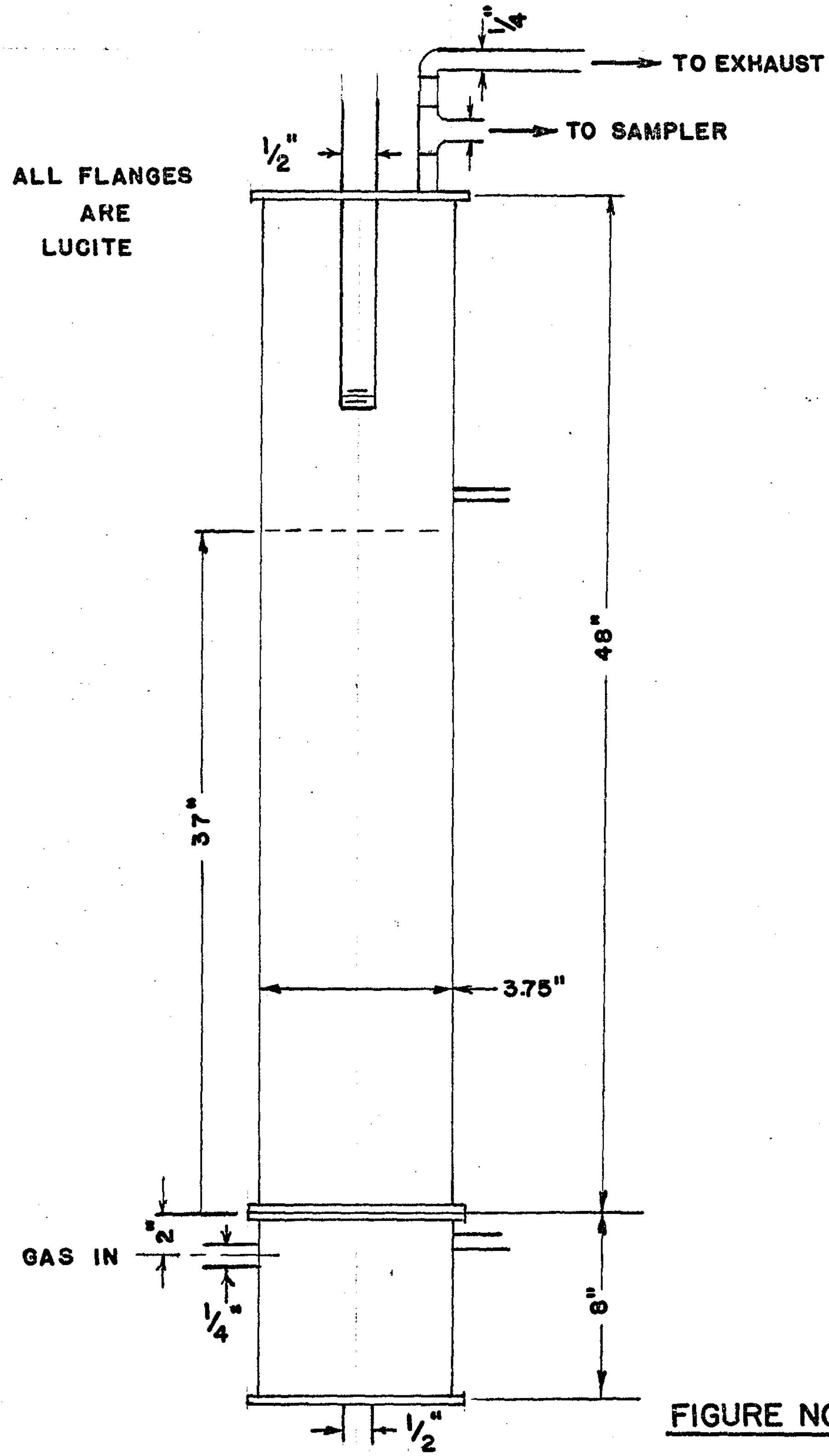


FIGURE NO. 2A

SUPPORT PLATE

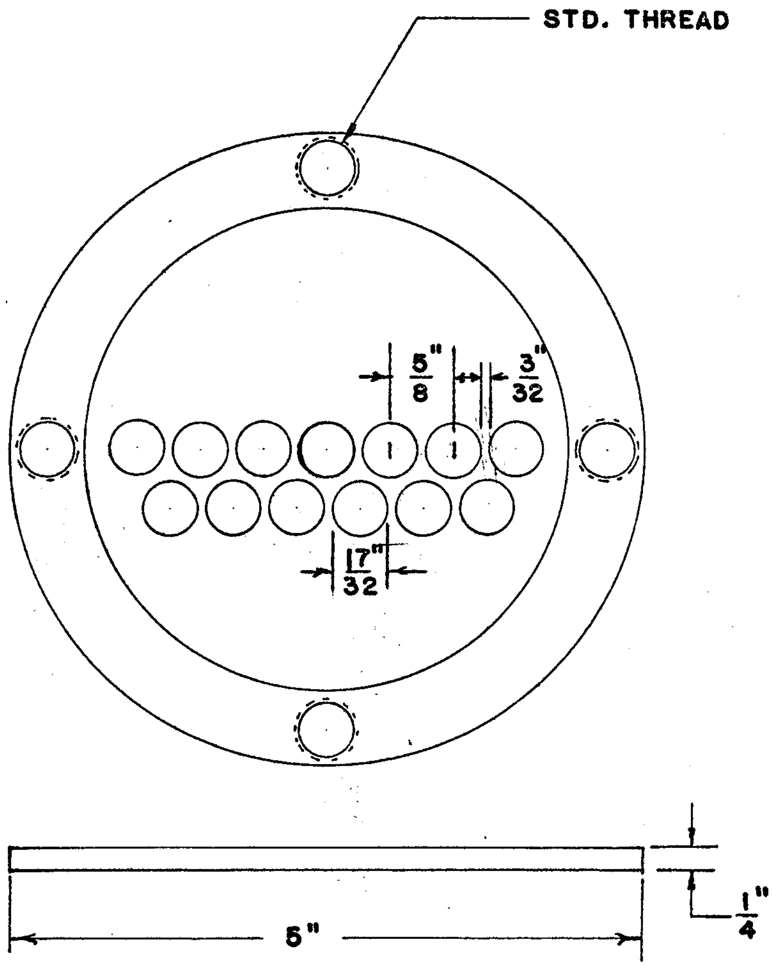
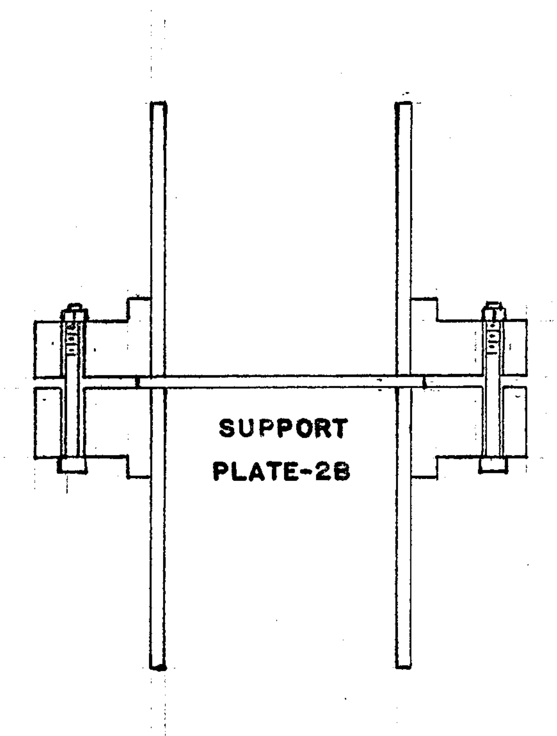


FIGURE NO. 2B

SCREWED JOINT

PLAIN FACE



4" DIA. PIPE

9" OUTSIDE FLANGE DIA.

$\frac{15}{16}$" FLANGE THICKNESS

7 $\frac{1}{2}$" BOLT CIRCLE DIA.

8 BOLTS $\frac{5}{8}$" DIA.

FIGURE NO. 2C

PROCEDURE

The packing was placed in the column by first filling the column with water and then dropping the clean Raschig rings into the top of the column by hand. The weight of packing charged was measured and the density of the Raschig ring was determined. The volume of the bed was determined and the void space was calculated. The ratio of packing surface area to bed volume was determined by measurements on the packing and found to be $A_p/e^3 = 713\ ft^2/ft^3$. The value from Treybal[16] for 1/4-inch Stoneware Raschig rings is 719 ft^2/ft^3. After placing the desired height of rings in the column, the water was drained and the top plate was sealed.

To start up the column, the air and water flow rates were set to the desired value and a liquid level was maintained at the bottom of the inlet gas section of the column to prevent inlet gas from escaping through the liquid outlet. The pressure reducing valve in the steam line was adjusted for each run to give the desired inlet water temperature. Once the desired gas and water rates were obtained along with the selected water temperature, the ammonia supply was turned on and adjusted to give the chosen concentration.

Steady state conditions were obtained more quickly by opening the bottom liquid drain valve in the beginning of each run. Readings of water rate and temperature gas rate and temperature, pressure drop and ammonia flow rate were taken about every five to ten minutes until all readings were constant.

During each run, the following readings were taken before and after each sampling and recorded:

1. Water Rotometer Reading
2. Air Rotometer Reading
3. Ammonia Rotometer Reading
4. Inlet Gas Temperature
5. Outlet Gas Temperature
6. Inlet Water Temperature
7. Outlet Water Temperature
8. Outlet Liquid rate
9. Gas Line Manometer Reading
10. Column Pressure Drop
11. Barometer Reading*

* Barometer reading was taken only before sampling.

SAMPLING AND ANALYTICAL PROCEDURE

The ammonia contents of the gas mixture entering and leaving the tower were found by drawing a one to two liter sample through an absorption bottle containing a measured amount of standardized sulphuric acid and collecting and measuring the volume of the residual air. The excess acid was then titrated with dilute sodium hydroxide solution using phenolphthalein as the indicator.

For liquid analysis, a sample was taken at the tower outlet and titrated with sulphuric acid with a methyl orange indicator.

ILLUSTRATIVE CALCULATION

$$L\text{-lbs/hr-ft}^2 = R_L \text{ cc/min} \times 62.4 \frac{\text{lb}}{\text{ft}^3} \times \frac{1}{0.0764} \text{ ft}^2$$

$$\times \frac{60 \text{ min}}{\text{hr}} \times \frac{1 \text{ ft}^3}{28316 \text{ cc}}$$

$$= R_L \times 1.732$$

Where R_L = Liquid volume measured at exit of column - cc/min.

L = Liquid rate - lbs/hr-ft^2

$$G\text{-lbs/hr-ft}^2 = R_G \frac{\text{ft}^3}{\text{hr}} \times 0.0808 \frac{\text{lb}}{\text{ft}^3} \times \frac{1}{0.0764 \text{ ft}^2}$$

$$= (1.06)\ (R_G)$$

Where R_G - Gas rate - ft^3/hr (from Figure 9)

G - Gas rate - lb/hr-ft^2

Now

$$X_E = (N_L)\ (0.017)$$

Where X_E - Content of ammonia at exit of tower - lb/NH_3/ lb water

N_L - Normality of liquid at exit of tower

$$y_1 = V_s\ (N_s - N_1)\ /\ V_{a1} \qquad \text{- C - 3}$$

$$y_2 = (V_s - 50)\ (N_1 - N_2)\ /\ V_{a2} \qquad \text{- C - 4}$$

Where y_1, y_2 - Me NH_3/lit air

V_s - Initial charge of sulphuric acid - ml

N_s - Normality of sulphuric acid before exit gas passed

N_1 - Normality of sulphuric acid after exit gas passed

N_2 - Normality of sulphuric acid after inlet gas passed

V_s-50 - After absorption of exit gas two 25 ml samples were removed for titration and balance of solution (V_s-50) was used to absorb inlet gas

V_{a1}, V_{a2} - Residual air from top and bottom samples respectively ml

$$Y = \left(y \frac{me}{lit}\right)\left(\frac{T^oK}{273^oK}\right)\left(\frac{17 \text{ grams}}{1000 \text{ me}}\right)\left(\frac{22.4 \text{ lit}}{29 \text{ grams}}\right) \qquad - C - 5$$

$$Y' = (y_1) \quad (T_1 \, ^oK) \quad (4.815 \times 10^{-5}) \qquad - C - 6$$

$$Y' = (y_2) \quad (T_2 \, ^oK) \quad (4.815 \times 10^{-5}) \qquad - C - 7$$

Where Y' - lb NH_3/ lb air @ temp. T ^oK

Pressure

mm Hg = mm of water / (13.6)

Run No. B-3

Packing: 1/4-inch unglazed porcelain Raschig rings.

Packed Height: 3.073 feet.

Cross sectional area of column: 0.0764 sq. feet.

Observed Data:

L = 462 lb/(hr) (sq ft)

G' = 130 lb/(hr) (sq ft)

Temperature: 90° F.

Inlet Gas: 81° F.

Exit Gas: 87° F.

Exit Liquid: 90° F.

Pressure drop through packing: 13.6 mm of water

Barometer: 760 mm Hg

Static pressure at bottom of packing = 22.8 mm Hg

Inlet air: $Y_1^* = 0.00630$ lb NH_3/ lb air

Exit air: $Y_2^* = 0.00050$ lb NH_3/ lb air

Liquid at top of packing: $X_2 = 0.000013$ lb NH_3/lb water

Molality: $c_2 = N_1 = 0.00075$ moles/liter

N_1 = Normality of inlet liquid

Liquid leaving tower, $X_E = 0.001589$ lb NH_3/lb water

$c_E = N_L = 0.0935$ moles/liter

Calculation of the partial pressure of ammonia in equilibrium with liquid was made by using the following equation, derived by Molstad, Mc Kenney and Abbey[12]. The equation is based on Henry's Law.

$$\text{Log } \frac{p^*}{c} = 4.699 - \frac{3460}{T(^\circ R)}$$

$$= 4.699 - \frac{3460}{550}$$

$$\frac{p^*}{c} = 0.025$$

$$p_1^* = (0.025)\ (0.0935)\ (760) = 1.780$$

$$p_2^* = (0.025)\ (0.00075)\ (760) = 0.0142$$

Total pressure at bottom of packing =

P_1 = Barometer and static pressure at bottom of packing

$= 760 + 22.8$

$= 782.8$ mm Hg

Total pressure at top of packing =

$$P_2 = P_1 - P$$

$$= 782.8 - 1.0 = 781.8 \text{ mm Hg}$$

Partial pressure of ammonia at bottom of packing =

$$P_1 = \frac{(0.0063/17)}{(0.03485 + 0.0063/17)} \times (782.8)$$

$$= 8.46$$

Partial pressure of ammonia at top of packing =

$$P_2 = \frac{(0.0005/17)}{(0.03485 + 0.0005/17)} \times (781.8)$$

$$= 0.664$$

Calculation of (P) lm

$$(P) \text{ lm, atm} = \frac{(p-p^*)_1-(p-p^*)_2}{760 \ln \frac{(p-p^*)_1}{(p-p^*)_2}}$$

$$= \frac{(8.46-1.780)(0.664-0.0142)}{760 \ln \frac{6.68}{0.65}}$$

$$= 0.0034 \text{ atm.}$$

$$K_Ga = \frac{6(Y_1-Y_2)}{ZM\ (P)} = \frac{(130)(0.005850)}{(3.073)(17)(0.0034)}$$

$$= 4.14 \frac{\text{lb mole}}{\text{hr-ft}^3\text{-atm}}$$

GRAPHICAL RESULTS AND DATA

TABLE - 2

DATA AND CALCULATIONS

Run No.	A-1	A-2	A-3	A-4
Water Rate = cc/min	400	400	400	440
Water Temp. = °F.	78	90	100	110
Gas Rate = ft^3/hr	122.5	123.5	122.5	122.5
Barometer = mm Hg	751.0	751.0	751.0	751.0
Column P = mm water	20.0	19.0	23.0	26.0
Static Pressure = mm Hg	7.62	7.60	7.60	7.60
L = $lb/hr\text{-}ft^2$	695.00	695.00	700.00	765
G' = $lb/hr\text{-}ft^2$	138.00	130.00	130.00	128
X_2 = Lb NH_3/ lb H_2O x 10^{-5}	1.270	1.280	1.27	1.28
X_E = lb NH_3/ lb H_2O x 10^{-3}	1.188	1.045	0.96	0.873
Y_1 = lb NH_3/ lb air, Inlet x 10^{-3}	6.073	6.073	6.073	5.850
Y_2 = lb NH_3/ lb air, Exit x 10^{-4}	1.520	1.630	3.270	6.300
Overall Material Balance = %	106.00	100.00	90.5	98.5
P_1 = mm Hg	758.62	758.60	758.6	758.6
P_2 = mm Hg	757.15	757.14	756.8	756.0

TABLE - 2 (CONTINUED)

	A-1	A-2	A-3	A-4
C_1 = moles NH_3/lit. Inlet	0.00075	0.00075	0.00075	0.00075
C_E = moles NH_3/lit. Exit	0.07	0.0615	0.0565	0.05125
P_1 = mm Hg	7.750	7.75	7.75	7.75
P_2 = mm Hg	0.195	0.344	0.425	0.803
P_1^* = mm Hg	1.0000	1.170	1.435	1.550
P_2^* = mm Hg	0.01012	0.0142	0.019	0.024
ΔP_{LM} = atm multiply x 10^{-3}	2.390	1.750	2.70	3.36
K_Ga at liquid temp. $\frac{\text{lb moles}}{\text{hr ft}^3\text{ atm}}$	6.55	5.80	5.28	3.96

TABLE - 3

DATA AND CALCULATIONS

Run No.	B-1	B-2	B-3	B-4	B-5	B-6	B-7
Water Rate = cc/min	264	264	264	264	264	264	264
Water Temp = °F.	72	84	90	95	100	104	108
Gas Rate = ft^3/hr	122.5	122.5	122.5	122.5	122.5	122.5	122.5
Barometer = mm Hg	760.0	760	760	760	760	760	760
Column P = mm Water	13.6	13.6	13.6	13.6	13.6	13.6	13.6
Static Pressure	22.8	22.8	22.8	22.8	22.8	22.8	22.8
L = $lb/hr\text{-}ft^2$	462	462	462	462	462	462	462
G = $lb/hr\text{-}ft^2$	130	130	130	130	130	130	130
X_2 = lb NH_3/lb H_2O x 10^{-5}	1.27	1.27	1.27	1.27	1.27	1.27	1.27
X_E = lb NH_3/lb H_2O x 10^{-3}	1.775	1.655	1.589	1.476	1.445	1.331	1.315
Y_1 = lb NH_3/lb air, Inlet x 10^{-3}	6.3	6.3	6.3	6.3	6.3	6.3	6.3
Y_2 = lb NH_3/lb air, Exit x 10^{-4}	1.78	3.8[illegible]	5.0	8.0	10.4	13.0	14.8
Overall Material Balance = %	103	100	96.5	95.2	95.5	95.5	95.5
P_1 = mm Hg	782.8	782.8	782.8	782.8	782.8	782.8	782.8
P_2 = mm Hg	781.0	781.0	781.0	781.0	781.0	781.0	781.0
C_E = moles NH_3/lit Exit	0.103	0.0975	0.0935	0.087	0.084	0.0784	0.0774

TABLE - 3 (CONTINUED)

Run No.	B-1	B-2	B-3	B-4	B-5	B-6	B-7
C_1 = moles NH_3/lit Inlet	0.00075	0.00075	0.00075	0.00075	0.00075	0.00075	0.00075
P_1 = mm Hg	8.46	8.46	8.46	8.46	8.46	8.46	8.46
P_2 = mm Hg	0.136	0.502	0.644	1.056	1.372	1.72	1.95
P_1^* = mm Hg	1.239	1.618	1.780	1.90	2.125	2.15	2.33
P_2^* = mm Hg	0.00901	0.0124	0.0142	0.0164	0.01902	0.0206	0.0224
$(\Delta P)_{LM}$ = atm multiply x 10^{-3}	2.62	3.41	3.4	3.93	4.2	4.66	4.77
$K_G a$ - at liquid temp. $\frac{\text{lb moles}}{\text{hr-ft}^3\text{-atm}}$	6.05	4.32	4.14	3.28	2.82	2.53	2.44

TABLE - 4

DATA AND CALCULATIONS

Run No.	A-1	A-2	A-3	A-4	A-5	A-6
L = lb/hr-ft^2	1500	1500	1500	1500	1500	1500
G' = lb/hr-ft^2	85	85	85	85	85	85
X_E = lb NH_3/lb water x 10^{-4}	3.80	3.80	3.04	2.76	2.56	2.42
X_2 = lb NH_3/lb water x 10^{-5}	1.27	1.27	1.27	1.27	1.27	1.27
C_2 = moles NH_3/cc	0.0224	0.0189	0.0178	0.0163	0.0150	0.0144
Temp - Exit Gas	61	67	71	77	80	98
Temp - Exit Liquid	64	78	89	94	100	117
Y_1' = lb NH_3/lb air x 10^{-2}	1.07	1.07	1.07	1.07	1.07	1.07
Y_2' = lb NH_3/lb air x 10^{-3}	3.62	5.1	5.4	6.1	6.3	6.5
Overall Material Balance = %	95	105	101	106	103	102
p_1 = mm Hg	14.6	14.6	14.6	14.6	14.6	14.6
p_2 = mm Hg	4.680	6.590	7.050	7.790	8.420	8.502
p_1^* = mm Hg	0.200	0.273	0.339	0.372	0.382	0.546
p_2^* = mm Hg	0.00672	0.0114	0.0140	0.0159	0.0191	0.0285
P_1 = mm Hg	792.5	792.5	792.5	792.5	792.5	792.5

TABLE - 4 (CONTINUED)

Run No.	A-1	A-2	A-3	A-4	A-5	A-6
p_2 = mm Hg	764.5	764.5	764.5	764.5	764.5	764.5
ΔP_{Lm} - atm: multiply x 10^{-3}	0.01250	0.01315	0.01350	0.01392	0.01455	0.0147
$K_G a$ at Liquid temp $\frac{\text{lb moles}}{\text{hr-ft}^3\text{-atm}}$	0.870	0.725	0.643	0.568	0.505	0.466

FIGURE 3

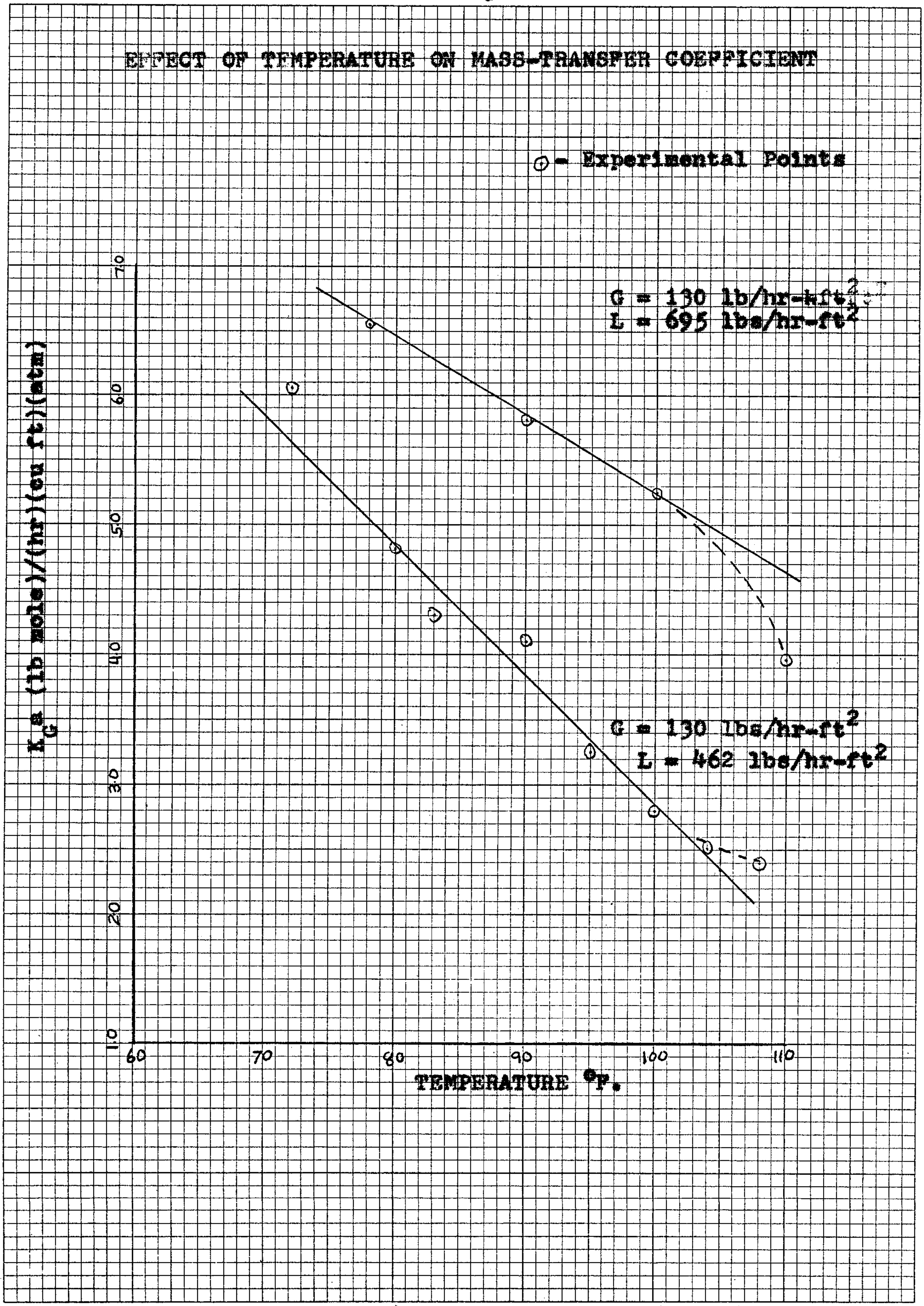

EFFECT OF TEMPERATURE ON MASS-TRANSFER COEFFICIENT
⊙ - Experimental Points
G = 130 lb/hr-ft²
L = 695 lbs/hr-ft²
G = 130 lbs/hr-ft²
L = 462 lbs/hr-ft²
K_Ga (lb mole)/(hr)(cu ft)(atm)
1.0
2.0
3.0
4.0
5.0
6.0
7.0
60
70
80
90
100
110
TEMPERATURE °F.

FIGURE - 4

CORRELATION OF GAS RATE VERSUS
MASS - TRANSFER COEFFICIENT

From: Dwyer and Dodge
Ind. and Eng. Chem., 33 p. 485-491 (1941)

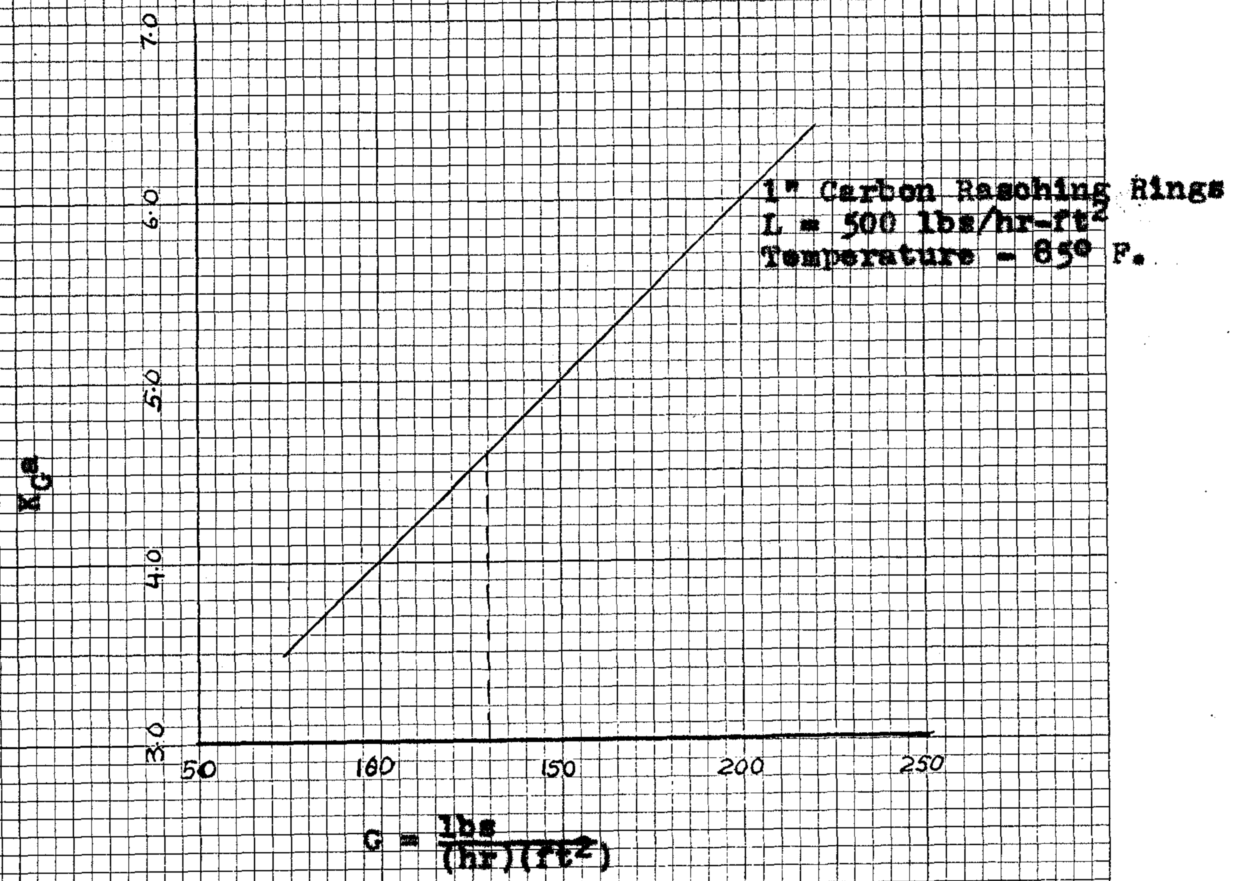


FIGURE - 5

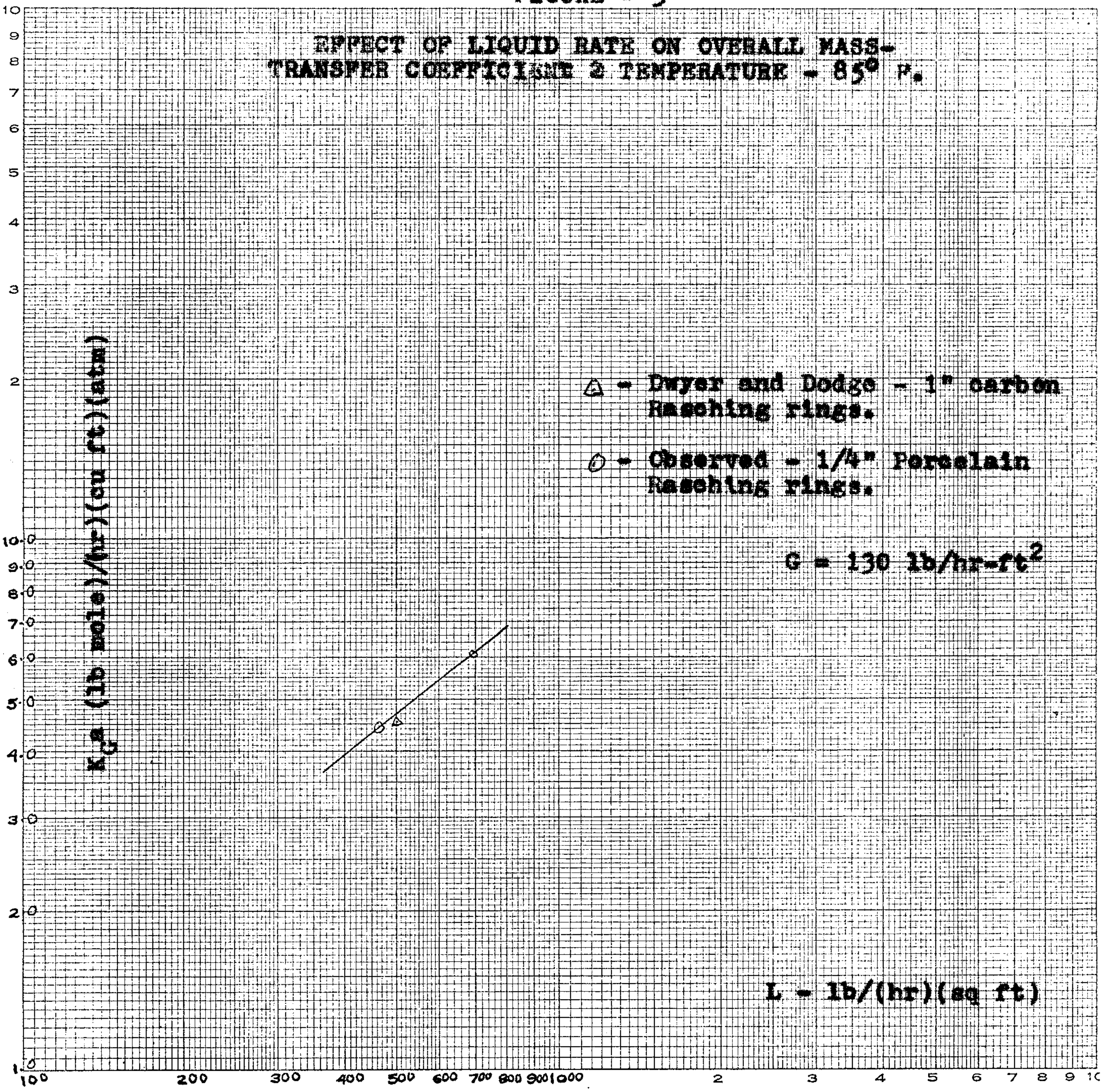

EFFECT OF LIQUID RATE ON OVERALL MASS-
TRANSFER COEFFICIENT @ TEMPERATURE - 85° F.
△ - Dwyer and Dodge - 1" carbon Rasching rings.
○ - Observed - 1/4" Porcelain Rasching rings.
G = 130 lb/hr-ft²
K_Ga (lb mole)/(hr)(cu ft)(atm)
L - lb/(hr)(sq ft)
LOGARITHMIC
2 CYCLES X 2 CYCLES
10
9
8
7
6
5
4
3
2
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
100
200
300
400
500
600
700
800
900
1000
2
3
4
5
6
7
8
9
10

FIGURE - 6

EFFECT OF TEMPERATURE ON MASS-TRANSFER COEFFICIENT

From: Dwyer and Dodge
Ind. and Eng. Chem., 33 p. 487 (1941)

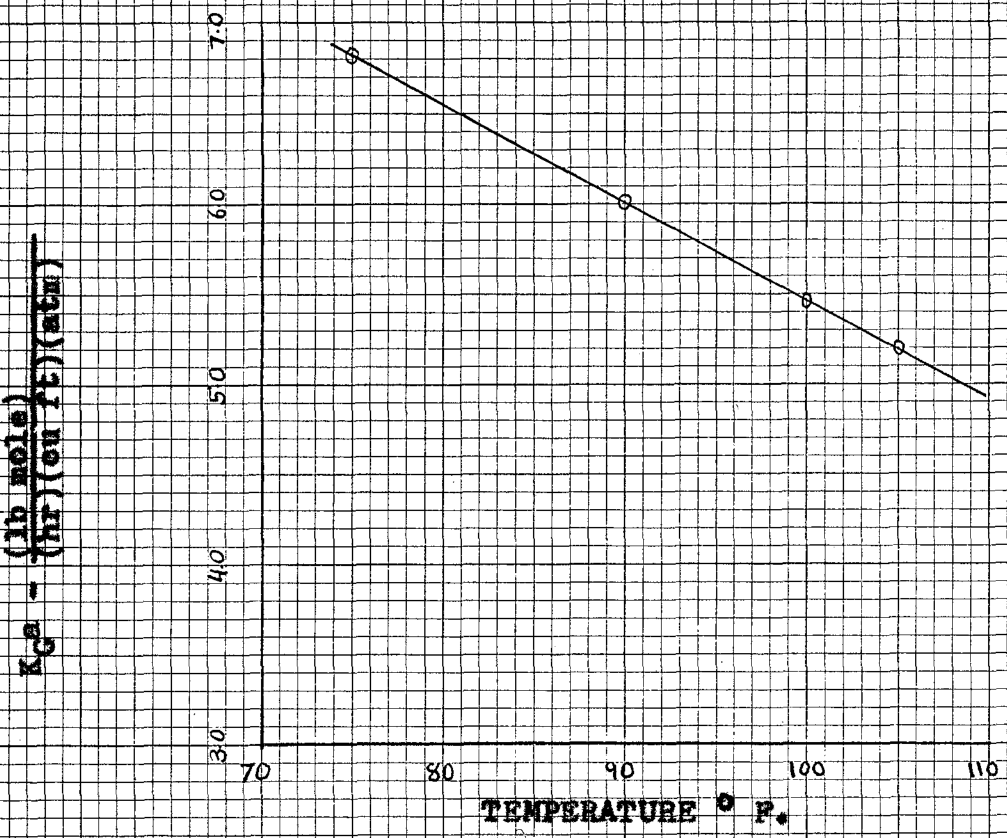


FIGURE - 7

EFFECT OF LIQUID RATE ON MASS-TRANSFER COEFFICIENT AT VARIOUS TEMPERATURE

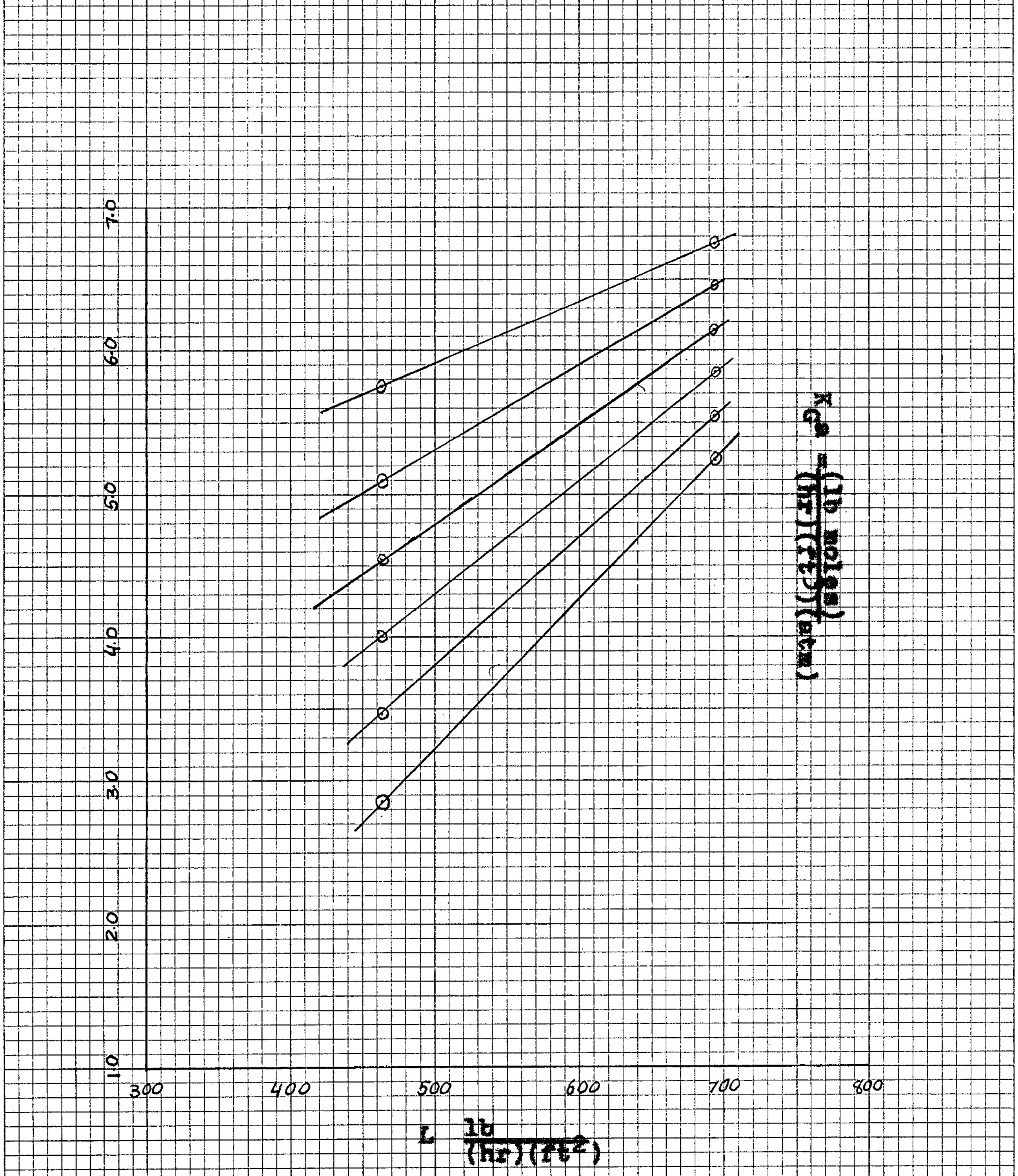
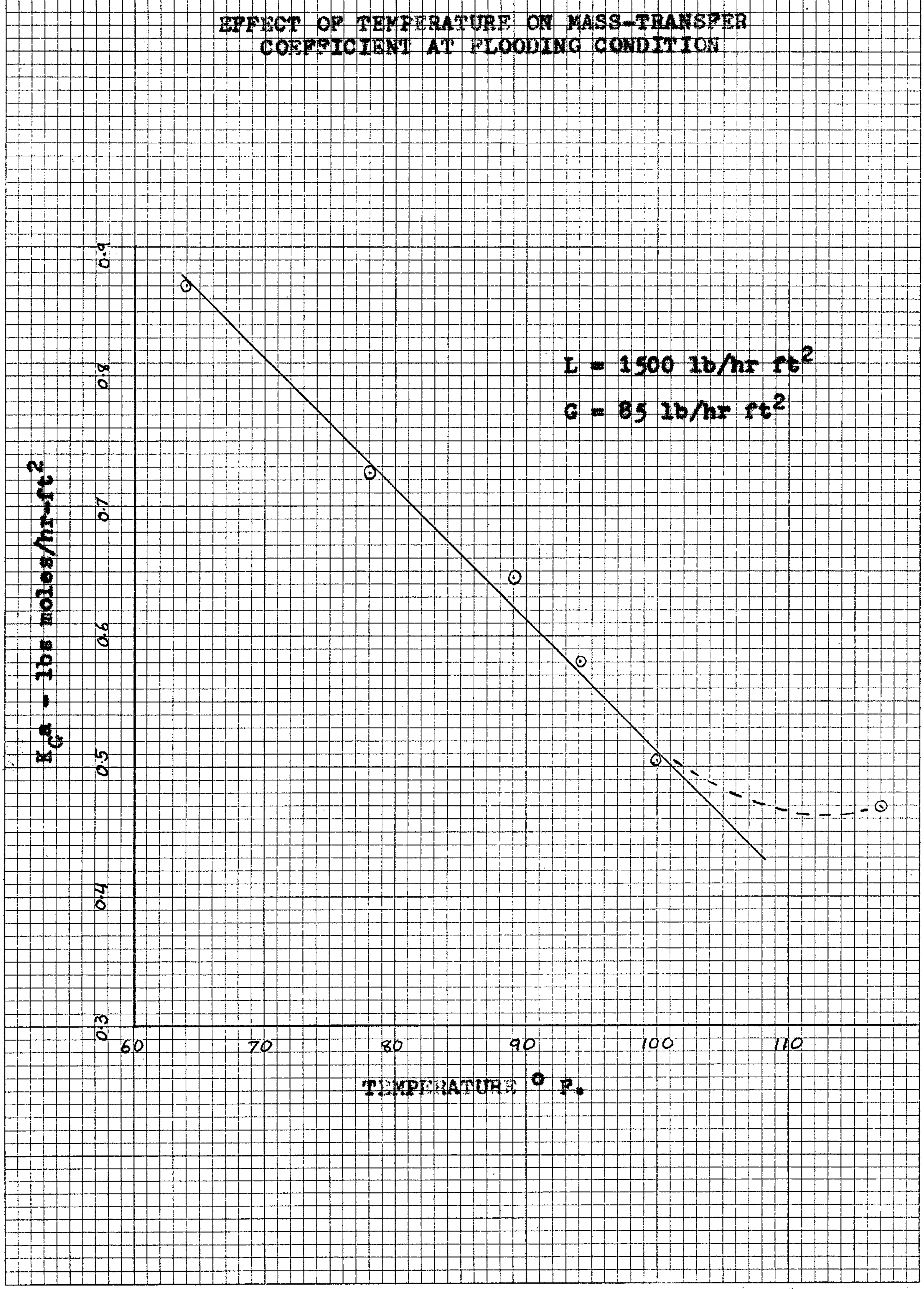


FIGURE - 8


EFFECT OF TEMPERATURE ON MASS-TRANSFER
COEFFICIENT AT FLOODING CONDITION
L = 1500 lb/hr ft²
G = 85 lb/hr ft²
$K_G a$ - lbs moles/hr-ft²
0.9
0.8
0.7
0.6
0.5
0.4
0.3
60
70
80
90
100
110
TEMPERATURE ° F.

RESULTS

Two sets of runs were made in which the temperature varied from 72° to 110° F. The first set consisted of four separate runs and the second covered seven individual experiments. The data and results obtained in this investigation are summarized in Tables 2 and 3, and Figure 3.

DISCUSSION OF RESULTS

The most pertinent results are shown in Figure 3, which is a plot of $K_G a$ vs. temperature at a constant gas rate of 130 lbs/hr-ft^2 and two liquid rates of 462 and 695 lbs/hr-ft^2. This plot shows that the overall mass transfer coefficient, $K_G a$, decreases with increasing liquid temperature. It is also shown in Figure 3 that the overall mass transfer coefficient, $K_G a$ increases with an increase in water rate. The points above 100° F. have maximum deviation of about 20%. The point at a liquid temperature of 110° F. on the curve for a liquid rate of gas lbs/hr-ft^2 is below the line because of an unexpected change in the liquid rate and the concentration of ammonia in inlet gas.

Correlations of gas rate vs. mass-transfer coefficient for this same system were obtained from the data of Dwyer and Dodge(3) and are represented in Figure 3, which is a plot of $K_H a$ vs. gas rate at a constant liquid rate of 500 lbs/hr-ft^2, and a constant liquid temperature of 85° F. These data were obtained using a 12-inch diameter column with a packed height of 5 feet of 1 inch carbon Raschig rings.

The comparison of the results of this investigation with the date of Dwyer and Dodge(3) is shown in Figure 4, which is a plot of K_Ga vs. liquid rate at a constant gas rate of 130 lbs/hr-ft^2 and constant liquid temperature of 85° F. The point marked as △ is obtained from Figure 3 at a gas rate of 130 lbs/hr-ft^2. This point is very near the line of Figure 4, and shows good correlation for the two investigations.

Figure 6 is a plot of K_Ga vs. temperature from the data of Dwyer and Dodge(3), which shows the same effect of liquid temperature on mass-transfer coefficient as shown in Figure 3. The effects of liquid rate on mass-transfer at various temperatures and a constant gas rate of 130 lbs/hr-ft^2 are summarized in Figure 7. From this figure, the difference of mass-transfer coefficients for each 5° F. change of liquid temperature are shown to be 0.55 lb moles/hr-ft^3 - atm. at liquid rate of 462 lbs/hr-ft^2 and 0.3 at liquid rate of 695 lbs/hr-ft^2. From these results, one may conclude that the change of mass-transfer coefficients with temperature is greater at a lower liquid rate, but the actual values are always less at the same temperature.

FLOODING VELOCITY

Initially the column was operated under flooding conditions. The overall mass-transfer coefficients have been found to range from 0.870 lb. moles/hr-ft^3-atm. at a liquid temperature of 64° F. to 0.466 lb moles/hr-ft^3-atm. at a liquid temperature of 117° F. The plot of mass-transfer coefficient vs. temperature is shown in Figure 8. This plot indicates that with an increase in liquid temperature, the mass-transfer coefficient decreased. Also it shows that at a temperature of liquid above 100° F., the slope of line changes. This effect is also shown in Figure 2. These values are considerably below the values obtained under non-flooding conditions, as would be expected since the surface area of the packing in the flooded section is not available for mass-transfer.

The static pressure was 792 mm Hg at the bottom of the column and the pressure drop in the column was 28 mm Hg. This larger pressure drop would be expected since the gas has to force its way through a bed of liquid.

CONCLUSION

The data obtained for absorption of ammonia in water using a 4-inch diameter lucite column, packed with 1/4-inch porcelain Raschig rings showed that:

1. The mass-transfer coefficient decreases as the temperature of liquid increases.

2. The mass-transfer coefficient decreases as the liquid rate decreases.

3. The change of mass-transfer coefficients with temperature is greater at the lower liquid rate, but the actual values are always less at the same temperature.

RECOMMENDATIONS

It is recommended that additional absorption data be obtained for this system in a temperature range above 100° F.

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APPENDIX

FIGURE 9

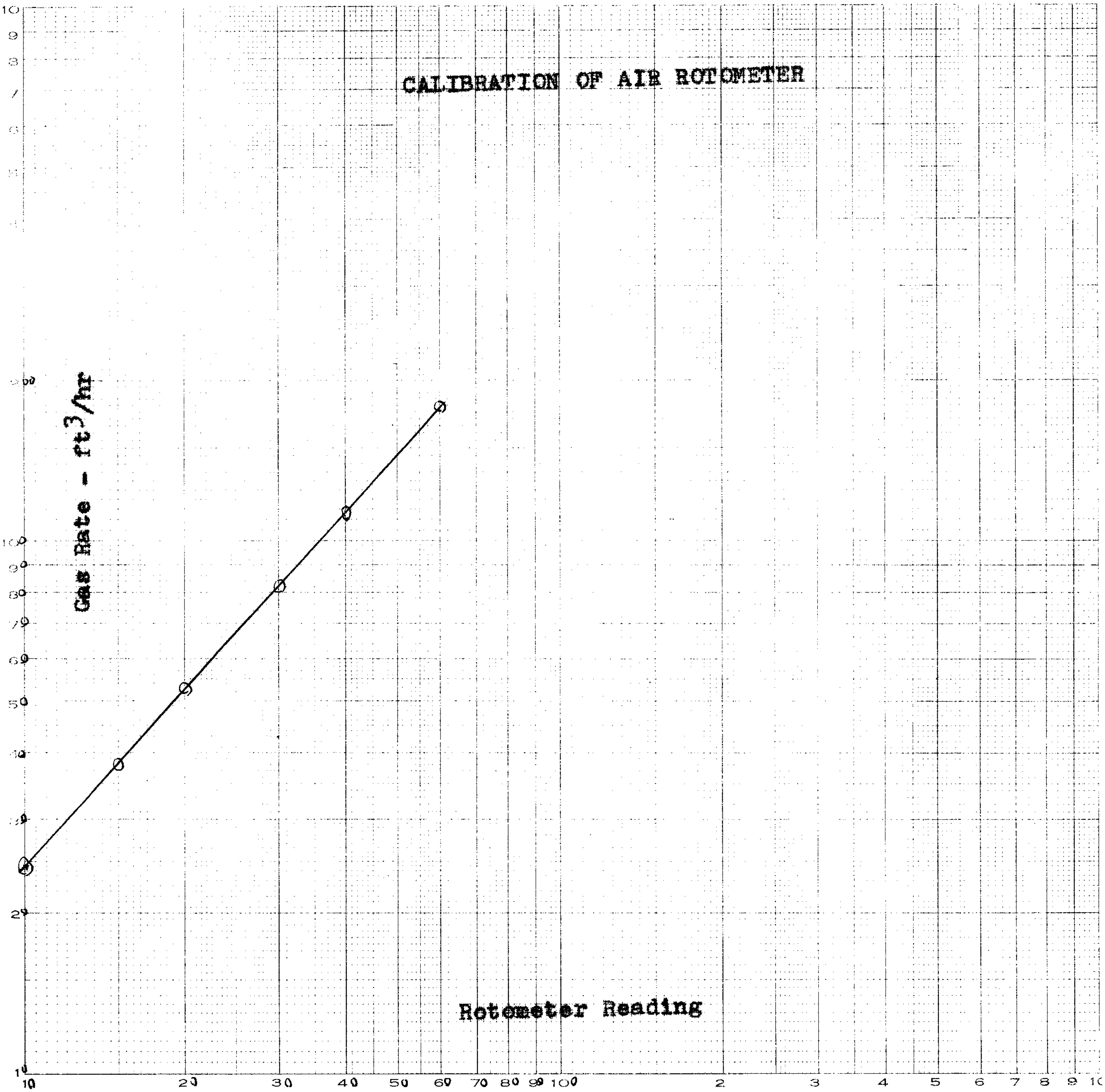
CALIBRATION OF AIR ROTOMETER
Gas Rate - ft³/hr
Rotometer Reading
10
20
30
40
50
60
70
80
90
100
200

TABLE OF NOMENCLATURE

A_c = Cross sectional area of column, - ft^2.

c = Liquid phase ammonia concentration - meNH_3/ml.

G = Gas flow rate, lb/hr-ft^2.

K_Ga = Overall volumetric gas film mass-transfer, coefficient, lb moles/hr-ft^3-atm.

K_La = Overall volumetric liquid film mass-transfer coefficient, lb moles/hr-ft^3-atm.

k_Ga = Volumetric gas film mass transfer coefficient, lb moles/hr-ft^3-atm.

k_La = Volumetric liquid film mass-transfer coefficient, lb moles/hr-ft^3-atm.

L = Liquid flow rate lb/hr-ft^2.

M = Molecular weight.

P = Total pressure.

p = Partial pressure.

p^* = Partial pressure at equilibrium.

X = Liquid phase ammonia concentration lb NH_3/ lb water.

Y = Gas phase ammonia concentration, lb NH_3/ lb air.

Z = Height of packing.

ρ = Density of fluid - lb mass/ft^3.

$(\Delta p)_{lm}$ = Log mean pressure drop.