GAS ABSORPTION
IN CO-CURRENT FLOW

by

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B. S., National Taiwan University, China, 1954

A THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering

KANSAS STATE UNIVERSITY
OF AGRICULTURE AND APPLIED SCIENCE

1960

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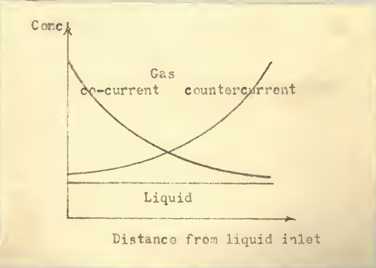
INTRODUCTION

Gas absorption is one of the numerous chemical engineering operations which involve transfer of material from one phase to another. Up to the present time nearly all industrial absorption equipment is operated under the countercurrent flow condition. However, evidence indicates that in certain cases this type of flow is not necessarily the best (17).

The main disadvantage of co-current flow is that generally a smaller driving force is established in the absorption equipment in comparison with the countercurrent flow. Such disadvantage will disappear when there is no appreciable vapor pressure of the transferring component in the liquid phase. For instance, in the absorption of CO_2 into caustic solutions, it has been assumed by various investigators (17), that there is no CO_2 pressure over the solution. Thus, the driving forces in both countercurrent and co-current flows will be the same, as shown by the following graph.



On the other hand, operation under co-current flow has some advantages over that under countercurrent flow. The pressure drop is smaller in the former case, and correspondingly the power requirement will be lower. Besides, there is no limitation of high rates of flow due to flooding or loading.

Various apparatus have been proposed for laboratory scale absorption studies. Two of the frequently used apparatus are the disc column, which was introduced by Stephens and Morris (19), and the short wetted-wall column, which has been widely used during the last few years (4) (22). In both columns the surface areas are measurable, but the disc column provides a condition more like that in the packed absorber.

This investigation was to study the co-current flow absorption. The experiments were performed in both a disc and a packed column under co-current and counter-current flows for the sake of comparison. The CO_2-H_2O system was chosen for this study, not only for the well-known fact (16) that the liquid-film is the only controlling factor, but also for the extensive results of other investigators available for comparison (6).

THEORY

In developing absorption theories, several models have been proposed to describe the absorption mechanism.

Hatta's Film Theory (15)

The film concept pictures a stagnant fluid film at the interface, through which film the substance to be absorbed is transferred by stationary diffusion. The rest of the liquid is considered to be completely homogenized.

Surface Renewal Theory (3)

This is the modified form of the Higbie Penetration Theory due to Danckwerts. In this theory an element of the liquid present at the interface is changed by a transient diffusion process. After some time the element is replaced by another. The chance of the element being replaced within a given time is assumed to be a statistical distribution and independent of its age.

In both concepts use is made of a quantity which can not be directly measured. In the film theory this is the effective film thickness x_f, while in Danckwerts' theory it is the mean rate of production of fresh surface per unit surface F. According to these theories, the liquid film coefficient can be expressed as:

$k_L = D/x_f$ by Hatta's film theory, and

$k_L = \sqrt{DF}$ by surface renewal theory,

where k_L is the liquid film coefficient of physical mass transfer, and D is the diffusivity.

Boundary Layer Theory (14)

In this theory the diffusion boundary layer is considered. The thickness of the layer is the distance measured normally from the interface in which the concentration changes from the interfacial value to the stream value. This theory differs from the film theory on the point that the boundary layer is moving while the film is assumed stagnant. This theory was developed only recently. Owing to mathematical difficulties, only some simple cases have been treated. However, the theory provided a more realistic physical picture than any other theory.

The applicability of the boundary layer theory will likely be reduced considerably by the instability of a fluid-fluid interface, but the same is true of the stagnant film and Surface Renewal theories. Some important papers on this field are listed in the references (12) (14).

EXPERIMENTAL

Scope

Two types of columns, disc column and packed column, were used in the present investigation. In the disc column, the range of liquid flow was determined by the rates at which the column became unstable; that is, from the lowest rate which maintained nearly perfect wetting (cf. section under the heading 'De-wetting' on p.14) of the disc surface, 10.0 lb./hr., to the highest rate which kept the water from spraying-out, 33.0 lb./hr. In the packed column, the liquid rate covered a range of 13.0-52.6 lb./hr. The gas rate varied from 1.55-10.6 cu.ft./hr. (the corresponding Reynolds numbers based on effective column diameter were 606 and 4150 respectively). The highest liquid temperature was 31.6°C, and the lowest was 21.0°C. The column pressures fluctuated between 722 - 755 mm. Hg. The experimental quantity determined was the liquid film coefficient at 25°C.

Equipment

Columns. The disc column consisted of 35 ceramic discs, enclosed in a pyrex glass tube of 1-1/8 inch inside diameter. The discs were threaded edgewise on a vertical fiberglas cord in such a way that the successive ones were maintained at right angles by means of Duco cement.

The general arrangement is shown on Plate I. The water was introduced at the top through a jet, and removed by a central tube and small funnel under the lowest disc. The liquid feed jet was placed 5 cm. above the uppermost disc, as recommended by Stephens and Morris (19).

The packed column was constructed with a 2 inch inside diameter pyrex glass pipe, packed with 8 mm. glass rasching rings. The bed was 5-1/4" in height and supported by a perforated plate. Water was distributed over the packings by a Tygon sprayer. Both ends of column were connected to glass tees, which formed the gas calming sections. Other constants for both columns are listed in Appendix I.

Accessories. A 1/8 hp. centrifugal pump was used to feed water (distilled water) from a 5 gal. carboy to the absorption columns. In the case of the disc column, a constant head tank was used.

A 1/4" needle valve was placed before a flowrator to regulate the liquid flow.

Another 1/4" needle valve was placed before a rotameter to regulate the gas flow from a CO_2 cylinder.

Gas leaving the rotameter passed through three saturation bottles. The difference between the inlet and outlet gas temperature was kept within 1°F to eliminate any effect due to vaporization of water. The guage pressure of the gas flow was measured by a manometer.

A sampling reservoir was used to stabilize the outlet liquid flow during sampling.

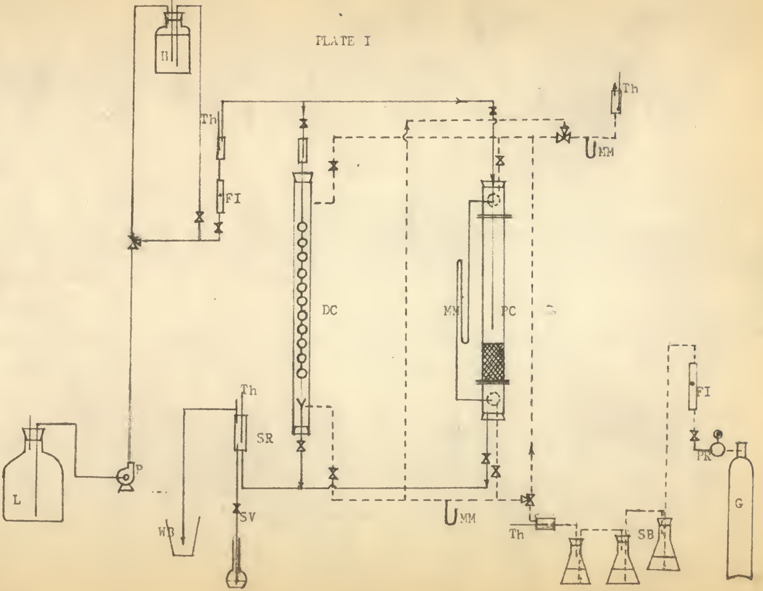
Themometers were provided at the inlets and outlets of both gas and liquid lines.

EXPLANATION OF PLATE I

Schematic~~s~~ Diagram of Experimental Layout

L:	Liquid feed tank	SV:	Sampling valve
P:	Feed pump	SF:	Sampling flask
H:	Constant head tank	DC:	Disc column
WB:	Waste bucket	MM:	Manometer
Th:	Thermometer	PC:	Packed column
FI:	Flow meter	SB:	Saturation bottles
SR:	Sampling reservoir	PR:	Pressure regulator
G:	CO_2 cylinder		

PLATE I



Procedure

1. Discharge remaining liquid from the column and sampling reservoir.
2. Set gas rate G and liquid rate L.
3. Adjust the height of the sampling reservoir to ensure liquid seal with minimum liquid level in the liquid collecting tube.
4. Take the first sample at 10 min. for the disc column, or at 5 min. for the packed column after the start of the experiments.
5. Sampling tube was dipped into the trapping solution (20 ml. of 0.1N $BaCl_2$ and 40 ml. of 0.05N NaOH) in a 100 ml. measuring flask. The flask was plugged with rubber stopper before filtration.
6. Drain off the liquid remaining in the sampling tube.
7. Take the second sample at 16 min. for the disc column, or at 8-10 min. for the packed column.
8. Time of sampling was about 45".

Chemical Analysis

<u>Standard solutions.</u> HCl was standardized against Na_2CO_3. The effective concentration of NaOH (OH^- ion only, CO_3^{--} not considered) was standardized against the standard HCl solution, after excess $BaCl_2$ was added.

<u>Inlet H_2O.</u> The concentration of CO_2 in the inlet distilled water was analyzed every six runs. No appreciable content of CO_2 in H_2O was found.

<u>Purity of CO_2.</u> The purity of cylinder CO_2 was analyzed by volumetric method. The result showed that it contained CO_2 more than 99.2 percent. In calculation, 100 percent was assumed.

<u>Analysis of samples.</u> The absorbed CO_2 was precipitated as $BaCO_3$ in the trapping solution. After filtration the excess NaOH was determined by

back titration against HCl solution with phenolphthalein as indicator.

A Magnetic stirrer was used in titration.

Filtration had no appreciable effect on the analytical results, as shown in Appendix II.

Preliminary Experiments

A suspicion of errors introduced by the filtration of the sampling solution in the course of analysis led to the conduction of an auxiliary experiment. Its results are summarized in Appendix II. It was shown in this auxiliary experiment, that the results of analysis were practically unaffected by filtration, the variation of the height of funnel nozzle above filtrate surface, or the exposure time when it was less than 30 minutes.

The same experiment showed that the variation of sample obtained in the disc column was within experimental error for samples taken at longer than 8 minutes after start of the experiment, and another experiment showed that in the packed column it was 4 minutes after start (Appendix II).

Design of Experiment

In the design of experiment letters P,Q, and R denote the co-current flow, and C,D, and E the counter-current flow operation.

A 2x3x3 factorial experiment, PC (2 types of flow, 3 levels of gas rate and 3 levels of liquid rate) was conducted for the disc column study. This experiment contained 2 replicates with total 36 runs and 72 observations.

Another 2x5 factorial experiment, QD (2 types of flow and 5 levels of liquid rate) with various repititions was conducted for the disc column at a fixed gas rate.

A 2x3x4 factorial experiment, RE (2 types of flow, 3 levels of gas rate and 4 levels of liquid rate) with 2 replicates was conducted for the packed column study.

Randomized complete block designs were used for the experiments PC and RE, and completely randomized design was used for the experiment QD.

RESULT AND DISCUSSION OF EXPERIMENT

Calculation of Liquid-Film Coefficients

For calculating liquid-film coefficients from the experimental data, the following equations were used;

for the disc column
$$k_L = \frac{N/A}{(\Delta C)_{l.m.}} \tag{1}$$

for the packed column
$$k_L a = \frac{N/V}{(\Delta C)_{l.m.}} \tag{2}$$

where

k_L = liquid-film coefficient, lb./(hr.-sq.ft.)(lb./cu.ft.)

$k_L a$ = liquid-film coefficient on a volume basis, lb./(hr.-cu.ft.)(lb./cu.ft.)

N = rate of absorption, lb./hr.

V = volume of the packed bed, cu.ft.

A = dry surface area of the discs, sq.ft.

$(\Delta C)_{l.m.}$ = logarithmic mean of (C_e-C) at inlet and outlet, lb./cu.ft.

C_e = liquid concentration in equilibrium with the gas phase, lb./cu.ft.

C = liquid concentration, lb./cu.ft.

The values of C_e were calculated from the Henry's law, $C_e = p/H$, where p is the partial pressure of CO_2, and H the Henry constant (13). The reason for replacing the interfacial concentration with the equilibrium concentration

C_e is based on the fact that the CO_2-H_2O absorption is controlled by the liquid film, as verified by Sherwood and Holloway(16).

All mass transfer coefficients so obtained were corrected to 25°C according to the following equation, (16):

$$k_L^{25} = k_L \cdot e^{0.023(25-t)} \qquad (3)$$

Summary of Data

Data are summarized on Table 3 to 7 in Appendix III. Table 3 lists observed data for PC series experiments. Table 4 gives values of liquid-film coefficients calculated from the data in Table 3. Table 5 contains both observed data and calculated liquid-film coefficients for QD series experiments. Table 6 contains observed data for RE series experiments and Table 7 lists the values of liquid-film coefficients calculated from the data in Table 6.

Analysis of Data

Data obtained from experiments PC and RE were analyzed statistically. The results are given in Table 1 and 2 below. The detail can be found in Appendix IV (p. 62). It is important to notice that the ordinarily assumed additive model in statistical analysis is not applicable to the k_L value, since multiplication is involved in the evaluation of k_L. Such operation will lead to serious error in standard deviation, and thus transformation is necessary before analysis. The logarithmic transformation was carried out for this purpose.

Table 1. Analysis of variance; PC series.

Source of Variation	d.f.	s.s.	m.s.
Replicate (R)	1	0.19995	0.19995
Treatment (T)	17	2.04449	0.12030
Flow type (F)	1	0.02467	0.02467
Liquid rate (L)	2	1.89697	0.94850
Gas rate (G)	2	0.02553	0.01276
FxL	2	0.00241	0.00121
FxG	2	0.01207	0.00604
LxG	4	0.00962	0.00240
FxLxG	4	0.07322	0.01830
Error	53	0.24888	0.00470
RxT	17	0.13487	0.00793
Obs'n : run	36	0.11401	0.00316
Total	71	2.49332	

Table 2. Analysis of variance; RE series.

Source of Variation	d.f.	s.s.	m.s.
Replicate (R)	1	0.00206	0.00206
Treatment (T)	23	3.65824	0.15905
Flow type (F)	1	0.00270	0.00270
Liquid rate (L)	3	3.62859	1.20963
Gas rate (G)	2	0.00079	0.00040
FxL	3	0.00403	0.00134
FxG	2	0.00552	0.00276
LxG	6	0.00472	0.00079
FxLxG	6	0.01189	0.00198
Error	69	0.06956	0.00101
RxT	23	0.04227	0.00183
Obs'n : run	46	0.02729	0.000593
Total	93	3.72986	

Since the m.s. of the main effects (F,L, and G) estimate error terms of very complicated forms (5), it is not suitable to use Snedecor's F to test the significance of those effects. However, comparing the main effects with interaction terms (FxL etc.), it is reasonable to believe that there is no difference between flow types, and only liquid rate has any effect on the liquid-film coefficient within the range of study.

The significance of variation due to replicate in PC series (Table 1) indicates that some unnoticed error might be introduced in either of the two replicates. A discussion on this case is given in Appendix V under the heading, Selection of Data (p. 69).

The standard deviation is 13.8 percent for PC series, 4 percent for QD series, and 5.8 percent for RE series. The high deviation in PC series must result from a few scattered data.

Experimental Error

Error Due to Liquid Sampling. In order to get better reading of sample volume, the sampling nozzle was immersed less than 1-1/2 inches below the surface of liquid in the measuring flask. But this could not ensure no loss of gas from samples. The magnitude of such error is not easy to estimate.

Error Due to Method of Analysis. The method of Emmert and Pigford (4) was used. An average error of 2 percent was supposed to be involved. As mentioned by Taylor and Roberts (20), this method was better than the barium hydroxide method, which generally results 3 percent in error, and the method of Hammerton and Garner, which gives results systematically high by about 10 percent.

Error Due to Liquid Temperature. Thermometers with scale graded to 0.1°C were used on liquid lines for QD and RE series, and with scale graded to 0.5°C were used for series PC. A misreading in 0.1°C would lead to an error in equilibrium constant of about 0.3 percent, and this would further be enlarged by the k_L computation formula to about 0.9 percent, as will be shown in a later section. In RE series experiments, the pump caused the inlet water temperature to continuously increase at a low flow rate. This complicated the absorption process by sensible heat transfer. This unsteadiness of the absorption condition would give rise to some deviation, and this was counted as experimental error. The total error contributed by liquid temperature deviation to the value of k_L is thus considered as 1.5 percent.

De-wetting of the Liquid on the Disc. The de-wetting phenomenon has been reported by a number of investigators, and in some cases the de-wetted areas have been quite extensive, even at liquid flow rates up to 200 lb./hr.-ft. (20). In this experiment, de-wetting was found at a liquid rate as high as 173 lb./hr.ft., e.g. run Q-9-4, and complete wetting was found at the liquid rate as low as 103 lb./hr.ft., e.g. run D-5-1. Generally, de-wetting rarely occurred at the rate higher than 120 lb./hr.ft., and complete wetting was hard to find at the rate below 129 lb./hr.ft. The largest de-wetted area observed visually was about 14 percent of the total area. Loss of absorption surface will cause low absorption coefficients, while the increased flow rate in the wetted areas will tend to offset this. It is possible that partial de-wetting might give rise to either high or low results.

It was found that, at high flow rate, liquid would sometimes drop from one disc to the next paralleled to it, without touching the neighboring one, which was at the right angle to it. This phenomenon would also decrease the contact surface area of liquid and gas, and resulted a relatively low coefficient.

Errors Amplified by Transfer Equation. Errors will be amplified 2 or 3 times by the transfer equation. This will be shown by the following illustration:

Illustration: Run P00-1 had the following observed data:

p.p. of CO_2 = column pressure - p.p. of H_2O = 730-24 = 706 mm.

Liquid temperature both at inlet and outlet = 24.5°C.

The Henry's Law constant at 24.5°C is 8.10×10^3 mm.Hg/lb.CO_2/cu.ft. The inlet concentration of CO_2 in H_2O is zero, and that at the outlet is 0.0470 lb./cu.ft. k_L was computed accouding to eq.(1), where $N = CxL/62.4$ (L is the liquid mass velocity in unit of lb./hr. per area of contact surface in sq.ft.). The value of k_L = 0.566 at 24.5°C was obtained. If a deviation of 5 percent less than the present value of C occurs, k_L will be equal to 0.517, i.e. it causes an error of 9.15 percent, and if a deviation of 0.5 percent less than the present value of C_e occurs, k_L will become 0.574, and an error of 1.4 percent results. In the case of different C_e at inlet and outlet the deviation will be even larger.

DISCUSSION OF RESULTS

Effect of Flow Type

It was expected that co-current flow and countercurrent flow would have some different effects on the mass transfer coefficient. According to the stagnant film concept, the liquid film should be thinned and the holding time should be much decreased by the co-current flow. According to the boundary layer theory, the relative velocity should play an important part in establishing the thickness of fluid layer. However, this investigation showed that there is no effect of using co-current flow or countercurrent flow on k_L within the range of investigation. In studying the CO_2-H_2O absorption system in wetted-wall columns, Collins (2) found that the use of co-current flow, at Reynolds number of gas higher than 14,800, increased the transfer coefficient appreciably.

Effect of Gas Rate

In this investigation, the gas rate range was too narrow to detect any influence on the liquid film coefficient. Hikita et al. (7) found that the liquid-film coefficient of CO_2-H_2O system in a wetted-wall column was affected by gas rates at Reynolds number greater than 6000 in counter-current flow, when the liquid rate was such that $Re = 300$ and also $Re = 600$. This seems contradictory to what might be expected by boundary layer theory for the simplest case (2-dimensional, co-current flow with horizontal interface), in which the relative velocity as well as the absolute velocity of gas is the determining factor for rate effect on transfer coefficient. It could be explained as that the effect of gas rate was due to ripple formation rather than the change in film thickness.

Effect of Liquid Rate

Since there was no interaction between flow type and liquid rate, as shown by analysis (Table 1 and 2), a single correlation shall be provided for each column. Logarithmic plots of k_L vs. Γ and k_La vs. L were constructed for the disc column and packed column respectively. Γ is the wetting rate (equal to the liquid flow rate in lb./hr. divided by the mean perimeter for liquid flow in ft.) and L is the liquid flow rate in lb./hr.sq.ft. These lines can be represented in the following form:

$$k_L = b\Gamma^n$$

or

$$k_La = bL^n$$

where b and n are the constants to be determined experimentally.

For the disc column the absorption data can be correlated in the following equation:

$$k_L = 0.0203\,\Gamma^{0.745} \quad \text{at } 20^{\circ}C \qquad (4)$$

The equation was based on 88 observations (Appendix V). The sample standard deviation from the equation is 0.0436 in logarithmic scale, or 10.5 percent of the value of k_L. The sample standard deviation of the slope is 0.0298, or 4.0 percent.

For the packed column the absorption data can be correlated by the equation:

$$k_L a = 0.655\,L^{0.85} \quad \text{at } 20^{\circ}C \qquad (5)$$

The equation was based on 88 observations. The sample standard deviation from regression is 0.0284 in logarithmic scale, or 6.75 percent of the value of $k_L a$. The sample standard deviation of the slope (the regression coefficient) is 0.0127, or 1.5 percent.

Generalized Correlation

Sherwood and Holloway (16), investigated desorption of oxygen from water and they proposed the following generalized correlation for k_L:

$$\frac{k_L}{D} = \alpha\left(\frac{4\Gamma}{\mu}\right)^n \left(\frac{\mu}{\rho D}\right)^{0.5} \qquad (6)$$

or

$$\frac{k_L a}{D} = \alpha\left(\frac{L}{\mu}\right)^n \left(\frac{\mu}{\rho D}\right)^{0.5} \qquad (7)$$

where μ is the viscosity of the liquid, ρ is the density of the liquid, and α and n are constants of a particular column. When the general equation is applied to the results of this experiment, the following equations are obtained:

for the disc column $$\frac{k_L}{D} = 7.44\left(\frac{4\Gamma}{\mu}\right)^{0.745}\left(\frac{\mu}{\rho D}\right)^{0.5} \quad (8)$$

for the packed column $$\frac{k_L a}{D} = 84.0\left(\frac{L}{\mu}\right)^{0.85}\left(\frac{\mu}{\rho D}\right)^{0.5} \quad (9)$$

Comparison with Results of Previous Workers

Disc column equation. The liquid-film coefficients obtained are lower than all the published results. Stephens and Morris (19) have mentioned that the absorption coefficients obtained on different disc columns might vary by ± 10 percent. However, data with deviation about 50 percent lower than that given by Stephens and Morris have been found in the literature (6). The present result, though much lower, gives a line nearly parallel to Stephen and Morris'. Their data was represented by the equation:

$$k_L = 0.048\ \Gamma^{0.7}$$

In plotting their data for CO_2 absorption in Doulton disc and pyrophyllite disc columns, Taylor and Roberts (20) observed the existance of a distinct change of slope in liquid film coefficient versus wetting rate plot. Their results for both columns were correlated into a single set of equations, viz:

For $\Gamma < 155$ lb./hr.ft. $\quad k_L = 0.124\,\Gamma^{0.4}$

For $\Gamma > 155$ lb./hr.ft. $\quad k_L = 0.0056\,\Gamma^{1.0}$

Chu (1), using the same column as that for the present study, also observed the break slopes in his data. He obtained the following set of equations:

For $73 < \Gamma < 200$ lb./hr.ft. $\quad k_L = 0.0386\,\Gamma^{0.644} \quad (10)$

For $16 < \Gamma < 73$ lb./hr.ft. $\quad k_L = 0.123\,\Gamma^{0.37}$

EXPLANATION OF PLATE II

Experimental data of disc column plotted
on k_L vs. Γ coordinates

k_L —— Liquid-film coefficient, lb./(hr.-sq.ft.)(lb./cu.ft.) at 25°C

Γ —— wetting rate (liquid rate per mean wetting perimeter ofdisc), lb./hr.ft.

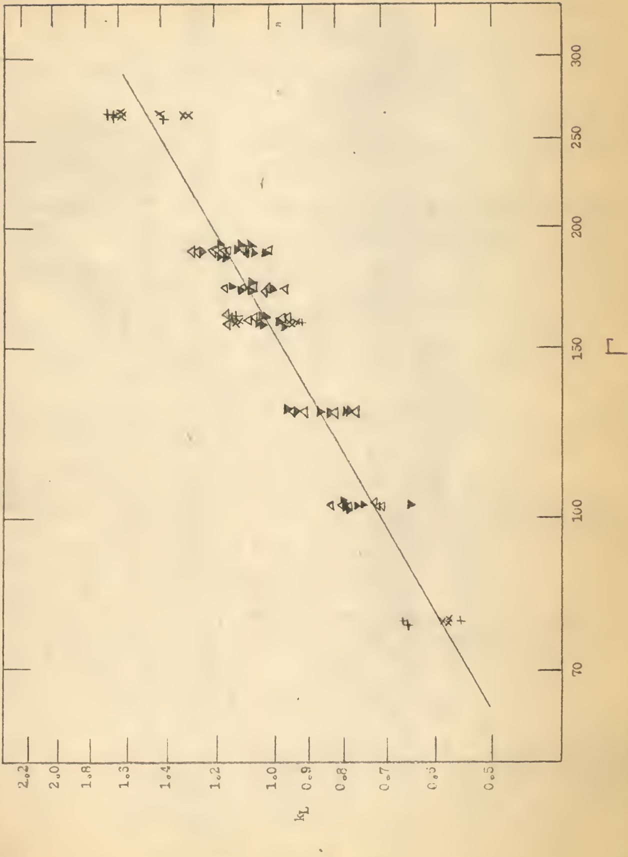
× —— data from PC-1 series for co-current flow

+ —— data from PC-1 series for countercurrent flow

△ —— data form QD series for co-current flow

▼ —— data from QD series for countercurrent flow

PLATE II



The difference in critical flow rates at which the break occurred has been reported by Taylor and Roberts (20) after the study of six different types of disc columns. However no such break was observed in this study, nor in Hwu's work (9). Hwu constructed the present column, and he suggested the equation

$$k_L = 0.0075\,\Gamma^{0.95} \qquad (11)$$

for CO_2 absorption in this column. The liquid-film coefficients found by Hwu were higher than those of Chu (1) and the present investigator. All the results just mentioned and some others are plotted on Plate III for comparison.

Prediction of Correlation for Cl_2-H_2O System by the Present Result. The absorption of chlorine is a typical liquid-film controlled system, as has been shown by Sherwood on the basis of CO_2 and oxygen absorption and desorption data. It has also been recognized that in the tower with a small diameter the variation of gas rate has no effect on the transfer coefficient, as verified by Vivian and Whitney (23). Therefore, the result obtained from CO_2 absorption study is expected to be applicable to the chlorine-water absorption data.

Using the general equation (6), or remembering that k_L varies with $D^{0.5}$ for the same absorbent at the same liquid rate, we can derive an equation for Cl_2-H_2O system as:

$$k_L = 0.0178\,\Gamma^{0.745} \qquad (12)$$

Similarly we have the corresponding equations derived from Chu's equation and Hwu's equation. These are:

$$k_L = 0.0338\,\Gamma^{0.644} \qquad (13)$$

$$k_L = 0.00657\,\Gamma^{0.95} \qquad (14)$$

respectively. The three predicted equations are represented by lines II,

EXPLANATION OF PLATE III

Comparison of the present result of CO_2-H_2O
Absorption with those of previous workers on a k_L vs. Γ plot

k_L —— liquid-film coefficient, lb./(hr.-sq.ft.)(lb./cu.ft.) at 20°C

Γ —— wetting rate (liquid rate per mean wetting perimeter of disc), lb./hr.ft.

Curve I —— the present result

Curve II —— result of Stephens and Morris (19)

Curve III —— result of Taylor and Roberts (20)

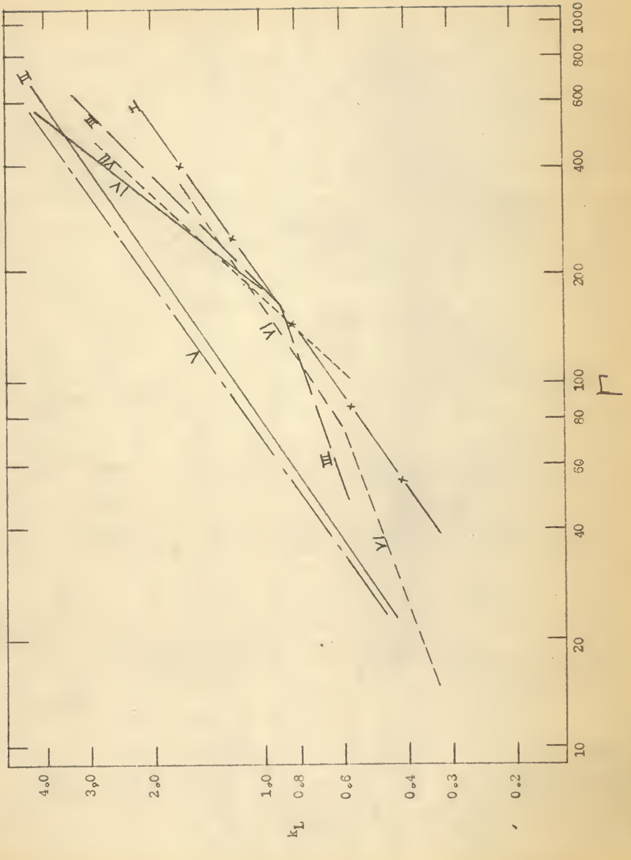
Curve IV —— result of Garner (6)

Curve V —— result of Imperial Chemical Industries Ltd. (6)

Curve VI —— result of Chu (1)

Curve VII —— result of Hwu (9)

PLATE III


k_L
4.0
3.0
2.0
1.0
0.8
0.6
0.4
0.3
0.2
10
20
40
60
80
100
200
400
600
800
1000
Γ
I
II
III
IV
V
VI
VII

III, and IV on Plate IV, and compared with the line directly drawn from the experimental data by Tien (21) in the same column. The corresponding equation for the experimental data is:

$$k_L = 0.0163\,\Gamma^{0.81}$$

The agreement of equation (12) with that obtained by Tien within the range of experiment (100-400 lb./hr.ft.) is clearly shown by Plate IV. The predicted values of liquid film coefficient by use of Chu's equation (13) are little higher than the experimental values, and those predicted by Hwu's equation were even higher. The derivation of the equations, and their representative points are given in Appendix VII.

Prediction of Gas-film Coefficient of NH_3-H_2O system. By the combination of liquid-film coefficient data and overall mass-transfer coefficient, K_G, data, we can calculate the gas-film coefficient from the following relationship:

$$\frac{1}{k_G} = \frac{1}{K_G} - \frac{H}{k_L}$$

where H is Henry constant.

Hwu has determined the overall mass transfer coefficient of NH_3-H_2O system, and calculated the gas-film coefficient by using his own equation for liquid-film coefficient. Since equation (12) predicts liquid film coefficients in the Cl_2-H_2O system better than Hwu's equation, an attempt was thus made to use equation (4) of the present investigation together with Hwu's experimental data of K_G to calculate k_G for NH_3-H_2O system. The detail of calculation are given in Appendix VII. The resulting equation is:

$$k_G = 3.90\,\Gamma^{0.30} \qquad (15)$$

EXPLANATION OF PLATE IV

Chlorine-water absorption correlation (k_L vs. Γ)
in the disc column

k_L —— liquid film coefficient, lb./(hr.-sq.ft.)(lb./cu.ft.) at 20°C

Γ —— wetting rate (liquid rate per mean wetting perimeter of disc), lb./hr.ft.

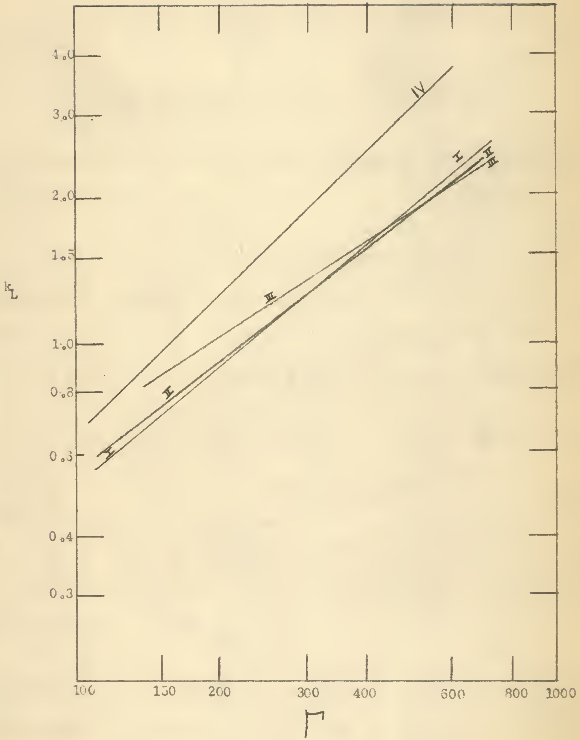
Curve I —— experimental result by Tien (21)

Curve II —— predicted by the present work on the basis of CO_2-H_2O system

Curve III —— predicted by the result of Chu's work on the basis of CO_2-H_2O system

Curve IV —— predicted by the result of Hwu's work on the basis of CO_2-H_2O system

PLATE IV


4.0
3.0
2.0
1.5
1.0
0.8
0.6
0.4
0.3
k_L
IV
I
II
III
100
150
200
300
400
600
800
1000
Γ

EXPLANATION OF PLATE V

Correlation of gas-film coefficient with wetting rate of NH_3-H_2O system in disc column

k_G —— gas-film coefficient, lb./(hr.sq.ft.atm.) at 20°C.

Γ —— wetting rate (liquid rate per mean wetting perimeter of disc), lb./hr.ft.

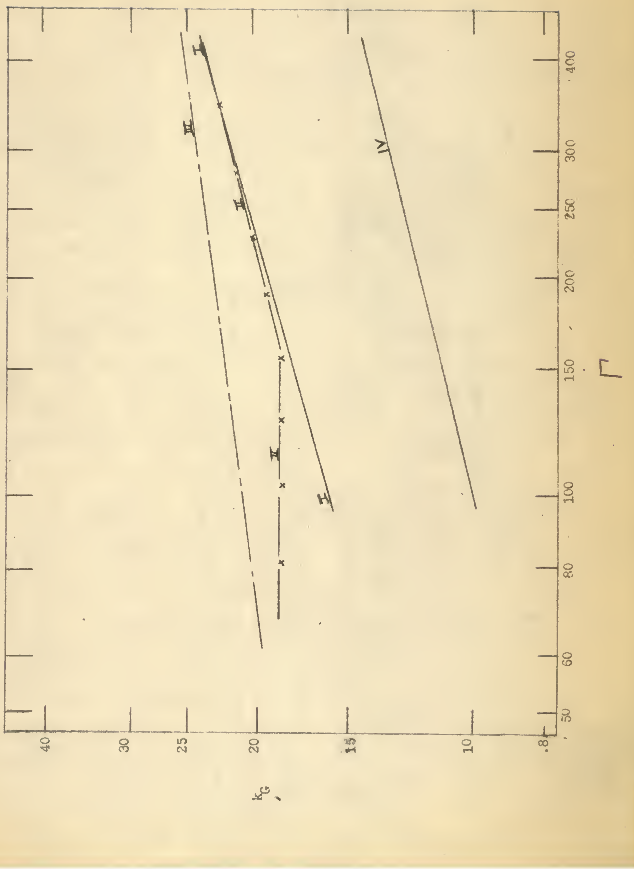
Curve I —— predicted by the experimental data of overall gas phase coefficient as obtained by Hwu (9), and the liquid film coefficient versus wetting rate given by this investigation.

Curve II —— result obtained by Taylor and Roberts (20)

Curve III —— result obtained by Stephens and Morris (19)

Curve IV —— result obtained by Hwu (9)

PLATE V



or in the general form

$$\frac{k_G P}{V \rho d} = 0.0326 \Gamma^{0.30} \left(\frac{Vd\rho}{\mu}\right)^{-0.33} \left(\frac{\mu}{\rho D}\right)^{-.56} \frac{P}{P_{BM}} \quad (16)$$

The equation (15) was corrected to a relative velocity of 8.4 ft./sec. for the convenience of comparison with published data (Hwu corrected his data to the relative velocity 5.84 ft./sec.). Plate V shows the comparison of the results from various sources. It may be noted that, over the range of studied by Hwu (Γ = 155-395 lb./hr.ft.), equation (15) is quite consistent with the experiment data of Taylor and Roberts. Hwu's equation corrected to 8.4 ft./sec. gives relatively low gas-film coefficients. The equations of the curves are:

S. and M. (19) $\quad k_G = 11.1 \Gamma^{0.23}$

T. and R. (20) $\quad k_G = 5.3 \Gamma^{0.25}$

Hwu (9) $\quad k_G = 2.99 \Gamma^{0.26}$

<u>Packed Column Equation</u>. Koch et al. (10) studied CO_2 absorption in 6- and 10-inch towers with a considerable variety of packing rings. He correlated all his data by the equation:

$$K_L a = 0.015 \, L^{0.96} \text{ , or}$$

$$H_{oL} = 1.05 \, L^{0.04}$$

where the result of the present investigation, equation (5) and the corresponding equation:

$$H_{oL} = 0.103 \, L^{0.15} \qquad (17)$$

($H_{oL} = L/K_L a$) is the height of transfer unit give much higher liquid-film coefficients at the low liquid rate range than Koch's.

Since the diffusivity of CO_2 and O_2 are 6.8-7.0 $\times 10^{-5}$ sq.ft./hr. at 20°C (11) (17), equation (5) should directly be applicable to O_2-H_2O

EXPLANATION OF PLATE VI

Experimental data of CO_2-H_2O system in the packed column plotted on k_La vs. L coordinates

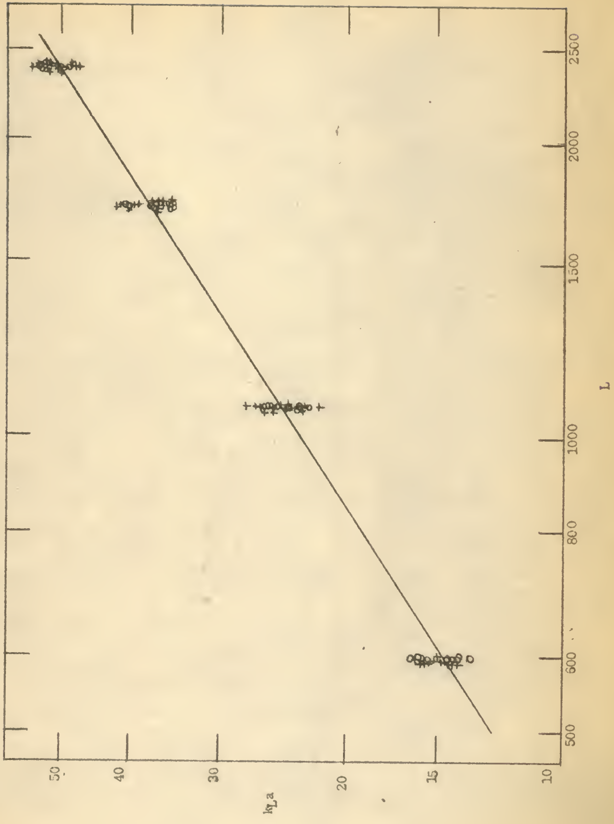
k_La —— liquid-film coefficient, lb./(hr.-cu.ft.)(lb./cu.ft.) at 25°C

L —— liquid mass velocity, lb./hr.-sq.ft.

o —— data for co-current flow

+ —— data for countercurrent flow

PLATE VI



system. A comparison with O_2-H_2O absorption data by Sherwood and Holloway (16) is shown on Plate VIII. The present results give higher H_{oL} values.

Chu (1) worked with the same CO_2-H_2O system in the same packed column. The values of k_La obtained by Chu are 18 percent higher than those obtained in this investigation. A comparison plot is given on Plate VII.

CONCLUSION

The results of the present investigation lead to the following conclusions:

(1) This investigation fails to show any different effect of flow types, countercurrent and co-current, on the value of liquid-film coefficient within the range of study. The significantly higher liquid-film coefficient found by Collins (2) in wetted-wall column for the co-current flow did not appear in the present investigation.

(2) Discrepancies between the present results in disc column and those quoted in the literature have been found. This inconsistency also exixts among other investigator's work.

(3) Though the performance is quite different from one disc column to another, the data from the same column are likely self-consistant, as justified by the agreement of the predicted correlation for Cl_2-H_2O system with the experimental results.

(4) The empirical correlation for liquid film coefficient in the disc column was found to be:

$$k_L = 0.0203\,\Gamma^{0.745}$$

This correlation is better than both Hwu's and Chu's correlations in view of the successfulness in predicting Cl_2-H_2O system data.

EXPLANATION OF PLATE VII

Comparison of k_La vs. L plot with results obtained by previous workers on CO_2-H_2O system in packed column

k_La —— liquid-film coefficient, lb./(hr.-cu.ft.)(lb./cu.ft.) at 20°C

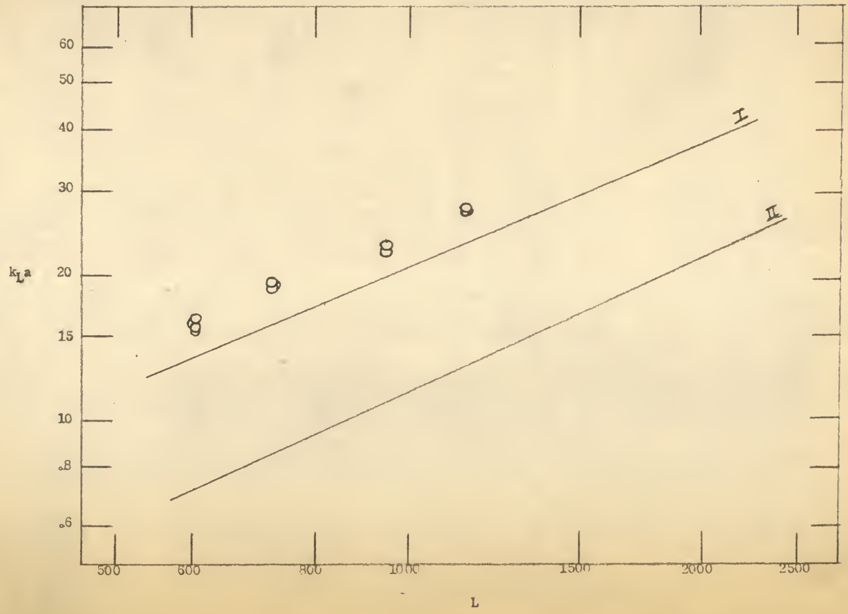
L —— liquid mass velocity, lb./ hr.-sq.ft.

Curve I —— result of the present work

Curve II —— result of Koch et al. (10)

O —— experimental data of Chu's work (1)

PLATE VII



EXPLANATION OF PLATE VIII

H_{oL} vs. L plot for oxygen-water system in packed column

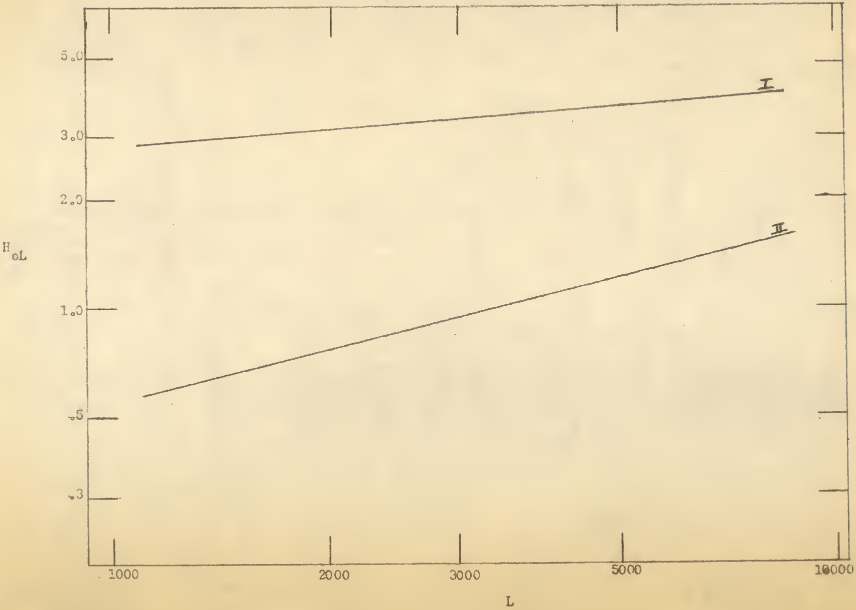
H_{oL} —— transfer unit ($= L/K_La$)

L —— liquid mas velocity, lb./hr.-sq.ft.

Curve I —— predicted by the present work on the basis of CO_2-H_2O absorption data

Curve II —— result obtained by Sherwood and Holloway (16)

PLATE VIII



(5) A correlation of liquid film coefficient with liquid rate for Cl_2-H_2O system in the disc column is suggested as:

$$k_L = 0.0178\ \Gamma^{0.745}$$

or the generalized equation can be represented by:

$$\frac{k_L}{D} = 7.44\ \left(\frac{4\Gamma}{\mu}\right)^{0.745}\left(\frac{\mu}{\rho D}\right)^{0.5}$$

(6) The gas-film coefficient for NH_3-H_2O system in the disc column can be represented by:

$$\frac{k_G P}{V \rho d} = 0.0326\,\Gamma^{0.30}\left(\frac{V d \rho}{\mu}\right)^{-0.33}\left(\frac{\mu}{\rho D}\right)^{-0.56}\frac{P}{p_{BM}}$$

(7) The liquid film coefficient for the packed column is given by:

$$k_L a = 0.0655\ L^{0.85}$$

or by the general form:

$$\frac{k_L a}{D} = 84.0\ \left(\frac{L}{\mu}\right)^{0.85}\left(\frac{\mu}{\rho D}\right)^{0.5}$$

or expressed in transfer unit as:

$$H_{oL} = 0.103\ L^{0.15}$$

(8) The satisfactory interpretation of Cl_2-H_2O system data justifies the relation given by the Penetration Theory, that k_L is proportional to $D^{0.5}$ rather than D. The latter is predicted by Hatta's film theory.

ACKNOWLEDGMENT

The author wishes to express his gratitude to Dr. Liang-tseng Fan and Dr. Henry T. Ward for their guidance and advice during the course of this work, and to the Kansas State University Engineering Experiment Station for financial support.

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APPENDIX

I. Principal Constants of Columns

(a) Disc column

Number of discs	35
Disc diameter	1.5 cm. (0.0492 ft.)
Disc thickness	0.48 cm. (0.0304 ft.)
Dry surface area of discs	0.218 sq. ft.
Mean perimeter for liquid flow	0.127 ft.
Tube internal diameter	0.0938 ft.

(b) Packed column

Size of packing	8 mm.
Height of bed	5-1/2 inches
Tube internal diameter	2 inches
Cross section area	0.0218 sq. ft.
Volume of bed	0.00954 cu. ft.

II. Preliminary Experiments

Test for filtration effect.

A test run was performed in the disc column under countercurrent flow condition. The recorded data are given as follows:

Barometric pressure	731 mm. Hg		
Gas rate	5.42 cu.ft./hr.		
Gas temperature, inlet	85°F	outlet	85°F
Column gauge pressure	90 mm. water		
Liquid rate	14.6 lb./hr.		
Liquid temperature, inlet	30.5°C	outlet	20.5°C

Sample No.	1	2	3	4	5	6
Sampling time, min. after run started	8	10	12	14	16	18
Filtration	+	-	+	-	+	-
Approx. height, cm., nozzle to filtrate	5		11		9	
Time of filtration, minute	6		12		10	
Titration time, min. after filtration started	6		17		10	
CO_2 absorbed lb./cu.ft.	0.0431	0.0438	0.0445	0.0408	0.0434	0.0431

Sampling flasks were rubber-stopped before filtration. The various factors indicated above were so combined that all the effects in a single sample were additive and easy to detect. The result favors the statement that there is no effect of filtration on CO_2 absorbed.

Test for Effect of Exposure Time on the Trapped Sampling Solution.

Three samples were used for this test. Each sample contained 40ml.

0.051 N NaOH and 20 ml. 0.1N $BaCl_2$ solutions, and was put in a 400 ml. beaker. Then the following data were obtained:

Sample No.	1	2	3
Exposure time, min.	0	15	30
CO_2 absorbed mole/initial mole of NaOH, x10^4	0*	0.865	1.37

*The effective concentration of NaOH was determined under this assumption.

No correction for CO_2 so absorbed has been made in evaluating k_L.

Test for Time for Reaching Steady State in The Packed Column.

A test run for this purpose was performed under co-current flow condition. Observed data and results are given below:

Barometric pressure	752.8 mm. Hg.	Room Temp. 93°F
Gas Rate	5.42 cu. ft./hr.	
Gas temperature, inlet	83°F	outlet 83°F
Liquid rate	42.9 lb./hr.	
Liquid temperature, inlet	27.8°C	outlet 27.9°C

Sample No.	1	2	3	4	5
min. after run started	4	6	8	10	12
CO_2 absorbed lb./cu.ft.	0.0218	0.0236	0.0233	0.0221	0.0236

The result of this run, though quite inconsistent with other runs, shows that the data taken from the 4th min. deviate from the mean within 5 percent. It may also be noted that the small standard deviation of the result of HE series (for the packed column) leads to the same conclusion.

III. Experimental Data

Sample Calculation.

(a) Observed data for Run R00-1A, co-current flow, packed column,

Barometric pressure	744.8 mm. Hg at 75°F
Gas rate	1.55 cu.ft./hr.
Gas temperature, inlet	78°F outlet 78°F
Column gauge pressure	2.2 cm. water
Liquid rate	13.0 lb./hr.
Liquid temperature, inlet	30.8°C outlet 28.2°C

CO_2 concentration in water, at inlet 0.0000
at outlet 0.0397 lb./cu.ft.

(b) Published data

Correction factor for 800 mm. brass scale barometer (13) = 0.130 mm./°C

Vapor pressure of H_2O at 78°F, from Keenan's Thermodynamical Properties of Steam p.28, = 0.9666 in. Hg, or 24 mm. Hg

Henry constant (13) at 30.8 = 9.44×10^3 mm. Hg/(lb. CO_2/cu.ft.)

at 28.2°C = 8.88×10^3 mm. Hg/(lb.CO_2/cu.ft.)

(c) Calculation

p.p. of CO_2 in the column = 718 mm.Hg

$C_e = P_{co_2}/H$ = 0.0761 lb./cu.ft. at inlet, and

= 0.0809 lb./cu.ft. at outlet

$\Delta C = (C_e - C)_{in} - (C_e - C)_{out}$ = 0.0397 lb./cu.ft.

$\ln(C_e - C)_{in} - \ln(C_e - C)_{out}$ = 0.615

$(\Delta C)_{l.m.} = \Delta C / \ln(C_e - C)_{in} - \ln(C_e - C)_{out}$ = 0.0568 lb./cu.ft.

$N = (C_{out} - C_{in}) \times$ Liquid rate / 62.4 = 8.41×10^{-3} lb/hr.

A = 0.0218 sq. ft.

Substitute the above values into equation (1), and obtain the value of k_La at average temperature 29.5°C, 15.5. Correct this value to 25°C with equation (3) on page 11, and the resulting k_La will be 14.1 (lb./hr.-cu.ft.)(lb./cu.ft.).

<u>Data</u> Experimental data are listed in the following tables:

Table 3. Absorption data of CO_2-H_2O system in the disc column (PC).

Table 4. Liquid film coefficient for CO_2-H_2O absorption in the disc column (PC).

Table 5. Absorption data of CO_2-H_2O system in the disc column at gas rate of 5.42 cu.ft./hr. (QD).

Table 6. Absorption data of CO_2-H_2O system in the packed column (RE).

Table 7. Liquid film coefficeint for CO_2-H_2O absorption in the packed column (RE).

In recording gas rate the effect of variation of temperature and pressure was ignored. This would introduce a maximum error of less than 3 percent (cf. Catalog 98-A, Fisher & Porter Company).

The differences between gas inlet and outlet temperatures were kept within 1°F, and therefore only the inlet temperature was listed in the tables.

Since the operating liquid temperatures fluctuated around 25°C, all observed data of liquid film coefficient were corrected to 25°C rather than 20°C, in order to reduce effect of any error associated with the correction equation (3). However, for comparison with published data, equations drawn from data at 25°C were corrected to 20°C with equation (3).

Table 3. Absorption data of CO_2 - H_2O system in the disc column.

Run No.	Gas Rate cu. ft./hr.	Gas Temp. °F.	Column Pressure mm. Hg.	Liquid Rate lb./hr.	Wetting Rate lb./hr.ft.	Liquid Temp. Inlet °C	Liquid Temp. Outlet °C	CO_2 absorbed lb./cu.ft. $x10^2$
P00-1A	0.64	77	730	10.0	78.7	24.5	24.5	4.70
B	0.64	77	730	10.0	78.7	24.5	24.5	4.70
-2A	0.64	84	722	10.0	78.7	29.0	29.0	4.77
B	0.64	84	722	10.0	78.7	29.0	29.0	4.88
P01-1A	5.42	78	739	10.0	78.7	25.5	25.4	4.11
B	5.42	78	739	10.0	78.7	25.5	25.4	4.43
-2A	5.42	85	727	10.0	78.7	29.0	29.0	5.63
B	5.42	85	727	10.0	78.7	29.0	29.0	5.35
P02-1A	10.60	76	739	10.0	78.7	24.5	24.5	4.83
B	10.60	76	739	10.0	78.7	24.5	24.5	4.44
-2A	10.60	77	737	10.0	78.7	24.5	24.5	5.94
B	10.60	77	737	10.0	78.7	24.5	24.5	5.68
P10-1A	0.64	75	737	20.0	159.0	24.0	24.0	4.36
B	0.64	75	737	21.0	159.0	24.0	24.0	4.44
-2A	0.64	84	725	21.0	159.0	29.0	29.0	5.02
B	0.64	84	725	21.0	159.0	29.0	29.0	4.04
P11-1A	5.42	79	730	21.0	159.0	24.5	25.0	4.83
B	5.42	79	730	21.0	159.0	24.5	25.0	4.66
-2A	5.42	84	728	21.0	159.0	29.0	29.0	5.15
B	5.42	84	728	21.0	159.0	29.0	29.0	4.40
P12-1A	10.60	78	738	21.0	159.0	24.0	24.0	4.97
B	10.60	78	738	21.0	159.0	24.0	24.0	4.80
-2A	10.60	80	738	21.0	159.0	24.5	25.0	5.45
B	10.60	80	738	20.2	159.0	24.5	25.0	4.74

Table 3. (Cont'd)

Run No.	Gas Rate cu. ft./hr.	Gas Temp. °F.	Column Pressure mm. Hg.	Liquid Rate lb./hr.	Wetting Rate lb./hr.ft.	Liquid Temp. Inlet °C	Liquid Temp. Outlet °C	CO_2 absorbed lb./cu.ft. x10^2
P20-1A	0.64	79	728	33.0	260	25.0	25.0	4.15
B	0.64	79	728	33.0	260	25.0	25.0	4.96
-2A	0.64	84	725	33.0	260	29.0	29.0	3.82
B	0.64	84	725	33.0	260	29.0	29.0	3.48
P21-1A	5.42	78	732	33.0	260	23.5	23.5	3.56
B	5.42	78	732	33.0	260	23.5	23.5	3.62
-2A	5.42	85	728	33.0	260	30.0	30.0	4.38
B	5.42	85	728	33.0	260	30.0	30.0	4.41
P22-1A	10.60	78	742	33.0	260	25.0	25.0	3.59
B	10.60	78	742	33.0	260	25.0	25.0	3.67
-2A	10.60	84	734	33.0	260	29.5	29.5	5.60
B	10.60	84	734	33.0	260	29.5	29.5	6.24
C00-1A	0.64	79	729	10.0	78.7	26.0	26.0	5.27
B	0.64	79	729	10.0	78.7	26.0	26.0	4.44
-2A	0.64	85	725	10.0	78.7	30.0	30.0	5.14
B	0.64	85	725	10.0	78.7	30.0	30.0	5.04
C01-1A	5.42	77	735	10.0	78.7	25.0	25.0	5.15
B	5.42	77	735	10.0	78.7	25.0	25.0	5.18
-2A	5.42	85	726	10.0	78.7	29.0	29.0	6.82
B	5.42	85	726	10.0	78.7	29.0	29.0	5.50
C02-1A	10.60	78	746	10.0	78.7	25.0	25.0	4.67
B	10.60	78	746	10.0	78.7	25.0	25.0	4.30
-2A	10.60	80	738	10.0	78.7	25.5	25.5	5.65
B	10.60	80	738	10.0	78.7	25.5	25.5	5.61

Table 3. (Cont'd)

Run No.	Gas Rate cu. ft./hr.	Gas Temp. °F.	Column Pressure mm. Hg.	Liquid Rate lb./hr.	Wetting Rate lb./hr.ft.	Liquid Temp. Inlet °C	Liquid Temp. Outlet °C	CO_2 absorbed lb./cu.ft. x10^2
C10-1A	0.64	78	728	20.2	159	24.5	24.5	4.78
B	0.64	78	729	20.2	159	24.5	24.5	4.65
-2A	0.64	80	729	20.2	159	25.5	25.5	5.55
B	0.64	80	729	20.2	159	25.5	25.5	4.95
C11-1A	5.42	75	739	20.2	159	25	25	3.62
B	5.42	75	739	20.2	159	25	25	3.71
-2A	5.42	85	726	20.2	159	29	29	4.26
B	5.42	85	726	20.2	159	29	29	4.17
C12-1A	10,60	76	746	20.2	159	24.5	24.5	3.71
B	10.60	76	746	20.2	159	24.5	24.5	3.88
-2A	10.60	80	737	20.2	159	25	25.5	5.27
B	10.60	80	737	20.2	159	25	25.5	5.19
C20-1A	0.64	79	729	33.0	260	24.5	24.5	3.76
B	0.64	79	729	33.0	260	24.5	24.5	3.39
-2A	0.64	84	722	33.0	260	28	28	4.14
B	0.64	84	722	33.0	260	28	28	4.41
C21-1A	5.42	77	735	33.0	260	25	25	4.95
B	5.42	77	735	33.0	260	25	25	4.40
-2A	5.42	80	731	33.0	260	25	25	5.45
B	5.42	80	731	33.0	260	25	25	4.62
C22-1A	10.60	76	742	33.0	260	25	25	4.46
B	10.60	76	742	33.0	260	25	25	4.37
-2A	10.60	85	732	33.0	260	28	28	4.46
B	10.60	85	732	33.0	260	28	28	4.75

Table 4. Liquid film coefficient for $CO_2 - H_2O$ absorption in the disc column.

Run No.	Wetting Rate lb./hr.ft.	Absorption Rate per area lb./hr.-sq.ft. $\times 10^2$	$(\Delta C)_{l.m.}$ lb./cu.ft. $\times 10^2$	k_L at 25°C $\frac{lb.}{(hr.-sq.ft.)(lb./cu.ft.)}$	log (K_L x 10)
P00-1A	78.7	3.46	6.10	0.573	0.7852
B	78.7	3.46	6.10	0.573	0.7852
-2A	78.7	3.51	4.89	0.650	0.8129
B	78.7	3.59	4.80	0.679	0.8319
P01-1A	78.7	3.02	6.37	0.467	0.6693
B	78.7	3.26	6.65	0.485	0.6857
-2A	78.7	4.15	4.30	0.875	0.9420
B	78.7	3.93	4.53	0.790	0.8976
P02-1A	78.7	3.56	6.15	0.586	0.7679
B	78.7	3.26	6.41	0.517	0.7135
-2A	78.7	4.36	5.35	0.825	0.9165
B	78.7	4.18	5.50	0.770	0.8865
P10-1A	159	6.08	5.03	0.931	0.9689
B	159	6.59	7.12	0.724	0.8597
-2A	159	7.46	4.75	0.948	0.9768
B	159	6.00	5.43	1.010	1.0043
P11-1A	159	7.18	5.91	1.212	1.0835
B	159	6.93	6.05	1.145	1.0588
-2A	159	7.65	4.66	1.490	1.1732
B	159	6.55	5.21	1.145	1.0588
P12-1A	159	7.38	6.13	1.212	1.0835
B	159	7.15	6.24	0.953	0.9786
-2A	159	8.10	5.65	1.470	1.1673
B	159	7.03	6.15	0.887	0.9479

Table 4. (Cont'd)

Run No.	Wetting Rate lb./hr.ft.	Absorption Rate per area lb./hr.-sq.ft. x10^2	$(\Delta C)_{l.m.}$ lb./cu.ft. x10^2	k_L at 25°C $\frac{\text{lb.}}{(\text{hr.-sq.ft.})(\text{lb./cu.ft.})}$	log (k_L x 10)
P20-1A	260	10.1	6.35	1.60	1.2041
B	260	12.0	5.80	2.08	1.3181
-2A	260	9.26	5.56	1.51	1.1761
B	260	8.84	5.77	1.34	1.1271
P21-1A	260	8.63	7.14	1.40	1.1461
B	260	8.76	6.47	1.62	1.2095
-2A	260	10.6	5.04	1.88	1.2742
B	260	10.7	5.03	1.89	1.2765
P22-1A	260	8.71	6.85	1.28	1.1072
B	260	8.90	6.77	1.31	1.1173
-2A	260	11.1	5.02	2.21	1.3444
B	260	10.3	5.10	2.02	1.3032
C00-1A	78.7	3.88	5.41	0.702	0.8463
B	78.7	3.27	4.70	0.684	0.8351
-2A	78.7	3.78	4.53	0.743	0.8710
B	78.7	3.70	4.60	0.720	0.8573
C01-1A	78.7	3.88	3.75	0.655	0.8129
B	78.7	3.80	5.76	0.660	0.8195
-2A	78.7	5.00	3.12	1.470	1.1673
B	78.7	4.04	4.40	0.835	0.9217
C02-1A	78.7	3.44	6.23	0.550	0.7404
B	78.7	3.16	6.45	0.491	0.6911
-2A	78.7	4.15	5.28	0.775	0.8893
B	78.7	4.13	5.35	0.762	0.8820

Table 4. (Cont'd)

Run No.	Wetting Rate lb./hr.ft.	Absorption Rate per area lb./hr.-sq.ft. x10^2	$(\Delta C)_{l.m.}$ lb./cu.ft. x10^2	K_L at 25°C $\frac{\text{lb.}}{(\text{hr.-sq.ft.})(\text{lb./cu.ft.})}$	log (K_L x 10)
C10-1A	159	7.12	6.00	1.183	1.0730
B	159	6.91	6.12	1.135	1.0550
-2A	159	8.25	5.24	1.570	1.1959
B	159	7.35	5.66	1.300	1.1139
C11-1A	159	5.38	5.84	0.922	0.9643
B	159	5.51	5.77	0.955	0.9800
-2A	159	6.34	4.73	1.338	1.1265
B	159	5.80	5.10	1.135	1.0550
C12-1A	159	5.04	5.92	0.867	0.9380
B	159	5.76	6.86	0.842	0.9253
-2A	159	7.84	5.19	1.500	1.1761
B	159	7.70	6.19	1.240	1.0934
C20-1A	260	9.13	6.72	1.39	1.1430
B	260	8.22	6.96	1.20	1.0792
-2A	260	10.1	5.49	1.69	1.2279
B	260	10.7	5.30	1.88	1.2742
C21-1A	260	12.0	5.95	2.02	1.3032
B	260	10.7	6.32	1.69	1.2272
-2A	260	13.2	5.47	2.42	1.3820
B	260	11.2	6.13	1.83	1.2625
C22-1A	260	10.8	6.32	1.72	1.2355
B	260	10.6	6.44	1.65	1.2175
-2A	260	10.8	5.45	1.85	1.2672
B	260	11.5	5.25	2.20	1.3424

Table 5. Absorption data of CO_2 - H_2O System in the disc column at gas rate of 5.42 cu.ft./hr.

Run No.	Gas Temp. °F	Column Press. mm.Hg.	Wetting Rate lb./hr.ft.	Liquid Temp. Inlet °C	Liquid Temp. Outlet °C	CO_2 absorbed lb./cu.ft. x10[2]	K_L at 25°C $\frac{lb.}{(hr\text{-}sq.ft)(lb/cu.ft.)}$	$\log(K_L \times 10)$
Q5-1A	80	730	103	27.2	27.3	4.86	0.832	0.9135
B	80	730	103	27.2	27.3	4.67	0.785	0.8949
-2A	70	727	103	21.7	21.7	4.73	0.715	0.8543
B	70	727	103	21.7	21.7	4.75	0.717	0.8555
-3A	78	737	103	24.0	24.3	4.60	0.705	0.8482
B	78	737	103	24.0	24.3	5.04	0.810	0.9085
Q6-1A	80	730	129	26.9	27.9	3.91	0.735	0.8663
B	80	730	129	26.9	27.9	4.15	0.826	0.9170
-2A	70	727	129	21.5	21.6	4.25	0.771	0.8871
-3A	73	739	129	22.3	22.5	2.91	0.495	0.6946
B	73	739	129	22.3	22.5	3.11	0.516	0.7126
-4A	76	739	129	24.8	24.9	4.13	0.945	0.9754
B	76	739	129	24.8	24.9	4.27	0.905	0.9566
Q7-1A	76	742	159	23.8	24.0	4.66	1.163	1.0656
B	76	742	159	23.8	24.0	4.65	1.154	1.0622
-2A	76	722	159	23.0	23.3	4.11	0.953	0.9791
B	76	722	159	23.0	23.3	4.42	1.050	1.0212
-3A	78	737	159	23.9	24.1	4.34	1.010	1.0043
B	78	737	159	23.9	24.1	4.18	0.958	0.9814
-4A	77	741	159	25.0	25.1	3.85	1.098	1.0407
B	77	741	159	25.0	25.1	4.21	1.050	1.0212
Q8-1A	78	737	189	26.0	26.1	4.80	1.332	1.1245
-2B	76	742	189	25.9	25.9	4.65	1.352	1.1309
-3A	77	722	189	23.0	23.3	4.12	1.142	1.0577
B	77	722	189	23.0	23.3	4.17	1.150	1.0607
-4A	77	723	189	22.6	23.0	4.25	1.172	1.0690
B	77	723	189	22.6	23.0	4.20	1.160	1.0645

Table 5. (Cont'd)

Run No.	Gas Temp. °F	Column Press. mm.Hg.	Wetting Rate lb./hr.ft.	Liquid Temp. Inlet °C	Liquid Temp. Outlet °C	CO_2 absorbed lb./cu.ft. x10^2	K_L at 25°C lb./(hr-sq.ft)(lb/cu.ft.)	log(K_L x 10)
Q8-5A	74	739	189	22.1	22.3	4.06	1.066	1.0278
B	74	739	189	22.1	22.3	4.05	1.048	1.0203
-6A	71	739	189	21.0	21.2	3.94	0.998	0.9991
B	71	739	189	21.0	21.2	4.50	1.190	1.0755
-7A	74	739	189	22.6	22.8	4.18	1.142	1.0577
B	74	739	189	22.6	22.8	4.06	1.092	1.0382
-8A	77	741	189	24.3	24.5	3.98	1.270	1.1038
B	77	741	189	24.3	24.5	3.88	1.290	1.1106
Q9-1A	76	737	173	24.7	24.8	4.25	1.016	1.0068
B	76	737	173	24.7	24.8	4.08	1.018	1.0076
-2A	75	723	173	22.7	23.9	4.19	1.056	1.0237
B	75	723	173	22.7	23.9	4.28	1.095	1.0395
-3A	75	737	173	23.3	23.5	4.56	1.161	1.0653
-4A	71	739	173	21.2	21.4	4.20	0.952	0.9786
D5-1A	78	737	103	25.8	25.9	4.90	0.800	0.9031
B	78	737	103	25.8	25.9	4.83	0.780	0.8921
-2A	77	723	103	22.9	23.4	4.95	0.791	0.8982
B	77	723	103	22.9	23.4	4.78	0.750	0.8751
-3A	77	737	103	24.1	24.4	4.58	0.795	0.9004
B	77	737	103	24.1	24.4	4.86	0.766	0.8842
-4A	78	741	103	24.1	24.4	5.05	0.642	0.8075
B	78	741	103	24.1	24.4	4.19	0.636	0.8036
D6-1A	77	737	129	24.9	25.1	4.16	0.785	0.8949
B	77	737	129	24.9	25.1	4.23	0.795	0.9004
-2A	75	723	129	22.5	22.8	4.47	0.865	0.9370
B	75	723	129	22.5	22.8	4.36	0.828	0.9180
-3A	73	739	129	22.2	22.5	3.22	0.534	0.7275
B	73	739	129	22.2	22.5	3.00	0.490	0.6937
-4A	76	739	129	24.1	24.3	4.65	0.950	0.9777
B	76	739	129	24.1	24.3	4.64	0.942	0.9741

Table 5. (Cont'd)

Run No.	Gas Temp. °F	Column Press. mm.Hg.	Wetting Rate lb./hr.ft.	Liquid Temp. Inlet °C	Liquid Temp. Outlet °C	CO_2 absorbed lb./cu.ft. x10^2	K_L at 25°C lb. / (hr-sq.ft)(lb/cu.ft.)	$\log(K_L \times 10)$
D7-1A	78	735	159	25.0	25.3	4.17	0.979	0.9908
B	78	735	159	25.0	25.3	4.36	1.040	1.0170
-2A	76	723	159	23.2	23.5	3.90	0.830	0.9191
B	76	723	159	23.2	23.5	4.15	0.955	0.9795
-3A	76	737	159	23.1	23.4	4.45	1.030	1.0128
B	76	737	159	23.1	23.4	4.46	1.030	1.0128
D8-1A	74	739	189	22.5	22.7	3.83	0.966	0.9827
B	74	739	189	22.5	22.7	3.90	1.010	1.0043
-2A	74	739	189	22.5	22.7	3.66	0.928	0.9675
B	74	739	189	22.5	22.7	3.78	0.960	0.9823
-3A	71	739	189	21.4	21.5	4.22	1.084	1.0351
B	71	739	189	21.4	21.5	4.11	1.056	1.0237
-4A	76	742	189	24.4	24.5	4.50	1.248	1.0958
B	76	742	189	24.4	24.5	4.33	1.180	1.0719
-5A	78	737	189	25.4	25.5	3.60	0.942	0.9741
B	78	737	189	25.4	25.5	4.22	1.170	1.0682
-6A	76	722	189	23.1	23.3	3.90	1.045	1.0191
B	76	722	189	23.1	23.3	4.14	1.130	1.0531
-7A	76	722	189	22.3	22.6	4.10	1.105	1.0433
B	76	722	189	22.3	22.6	4.30	1.180	1.0719
D9-1A	80	730	173	27.0	27.1	4.01	1.048	1.0203
B	80	730	173	27.0	27.1	4.15	1.090	1.0374
-2A	70	727	173	22.0	22.0	4.51	1.130	1.0531
B	70	727	173	22.0	22.0	4.13	1.000	1.0000
-3A	75	737	173	24.1	24.2	4.22	1.052	1.0220

Table 6. Absorption data of CO_2 - H_2O system in the packed column.

Run No.	Gas Rate cu.ft./hr.	Gas Temp. °F	Column Pressure mm.Hg.	Liquid Rate lb./hr.	Liquid Mass Vel. lb./hr-sqft	Liquid Temp. Inlet °C	Liquid Temp. Outlet °C	CO_2 absorbed lb./cu.ft. x10^2
R00-1A	1.55	78	743	13.0	596	30.8	28.2	3.97
B	1.55			13.0	596	31.6	29.2	4.00
-2A	1.55	75	736	13.0	596	29.6	27.5	4.28
B	1.55			13.0	596	30.1	28.7	4.08
R01-1A	5.42	76	747	13.0	596	30.2	27.5	4.16
B	5.42			13.0	596	30.7	28.8	4.00
-2A	5.42	78	739	13.0	596	30.0	28.1	4.35
B	5.42			13.0	596	30.5	29.2	4.07
R02-1A	10.6	75	741	13.0	596	29.5	27.2	4.12
B	10.6			13.0	596	30.7	28.7	3.82
-2A	10.6	73	745	13.0	596	29.1	27.1	4.72
B	10.6			13.0	596	29.5	28.0	4.49
R10-1A	1.55	80	741	24.0	1100	29.4	28.7	3.66
B	1.55			24.0	1100	29.6	29.2	3.96
-2A	1.55	76	733	24.0	1100	27.8	27.2	3.58
B	1.55			24.0	1100	27.9	27.4	3.87
R11-1A	5.42	80	745	24.0	1100	29.4	28.8	3.73
B	5.42			24.0	1100	29.6	29.2	3.76
-2A	5.42	74	739	24.0	1100	26.9	26.9	4.06
B	5.42			24.0	1100	26.8	26.6	3.77
R12-1A	10.6	80	755	24.0	1100	30.8	29.7	4.42
B	10.6			24.0	1100	30.6	30.3	4.02
-2A	10.6	78	748	24.0	1100	28.2	28.0	3.98
B	10.6			24.0	1100	28.2	28.0	3.88
R20-1A	1.55	80	741	37.8	1730	28.3	28.3	3.80
B	1.55			37.8	1730	28.3	26.3	4.01
-2A	1.55	77	733	37.8	1730	26.5	26.7	3.46
B	1.55			37.8	1730	26.5	26.6	3.52

Table 6. (Cont'd)

Run No.	Gas Rate cu.ft./hr.	Gas Temp. °F	Column Pressure mm.Hg.	Liquid Rate lb./hr.	Liquid Mass Vel. lb./hr-sqft	Liquid Temp. Inlet °C	Liquid Temp. Outlet °C	CO_2 absorbed lb./cu.ft. x10^2
R21-1A	7.60	73	739	37.8	1730	24.7	24.5	3.80
B	7.60			37.8	1730	24.8	24.8	3.84
-2A	7.60	75	739	37.8	1730	25.3	25.2	3.66
B	7.60			37.8	1730	25.3	25.2	3.66
R22-1A	10.6	80	752	37.8	1730	28.4	28.6	4.00
B	10.6			37.8	1730	28.4	28.4	3.79
-2A	10.6	76	755	37.8	1730	26.3	26.3	3.70
B	10.6			27.8	1730	26.3	26.3	3.48
R30-1A	1.55	80	744	52.6	2410	28.4	28.4	3.88
B	1.55			52.6	2410	28.4	28.4	4.13
-2A	1.55	81	734	52.6	2410	27.5	27.4	3.75
B	1.55			52.6	2410	27.6	27.7	3.84
R31-1A	5.42	77	749	52.6	2410	26.4	26.4	3.93
B	5.42			52.6	2410	26.4	26.4	3.64
-2A	5.42	76	745	52.6	2410	25.0	25.0	3.71
B	5.42			52.6	2410	25.0	25.0	3.77
R32-1A	10.6	76	754	52.6	2410	25.3	25.3	3.73
B	10.6			52.6	2410	25.3	25.4	3.90
-2A	10.6	76	755	52.6	2410	25.3	25.4	4.04
B	10.6			52.6	2410	25.3	25.4	3.78
E00-1A	1.55	80	741	13.0	596	31.5	29.6	4.07
B	1.55			13.0	596	32.4	30.8	4.48
-2A	1.55	76	733	13.0	596	29.9	27.3	4.18
B	1.55			13.0	596	30.2	27.9	4.22
E01-1A	5.42	77	748	13.0	596	29.3	26.0	missing
B	5.42			13.0	596	30.9	28.4	4.84
-2A	5.42	76	735	13.0	596	31.1	29.3	3.99
B	5.42			13.0	596	31.1	29.7	3.84
E02-1A	10.6	76	750	13.0	596	29.4	26.7	4.10
B	10.6			13.0	596	30.2	27.9	4.30
-2A	10.6	77	747	13.0	596	29.8	27.8	4.36
B	10.6			13.0	596	30.3	28.6	4.19

Table 6. (Cont'd)

Run No.	Gas Rate cu.ft./hr.	Gas Temp. °F	Column Pressure mm.Hg.	Liquid Rate lb./hr.	Liquid Mass Vel. lb./hr-sqft	Liquid Temp. Inlet °C	Liquid Temp. Outlet °C	CO_2 absorbed lb./cu.ft. x10^2
E10-1A	1.55	78	737	24.0	1100	26.7	26.6	4.12
B	1.55			24.0	1100	26.9	26.8	3.98
-2A	1.55	81	734	24.0	1100	30.2	29.7	3.68
B	1.55			24.0	1100	30.4	30.0	3.64
E11-1A	5.42	80	747	24.0	1100	30.8	30.3	4.02
B	5.42			24.0	1100	30.9	30.5	4.20
-2A	5.42	78	739	24.0	1100	27.0	26.9	3.95
B	5.42			24.0	1100	27.1	27.0	3.68
E12-1A	10.6	78	752	24.0	1100	28.6	27.3	3.77
B	10.6			24.0	1100	28.6	27.3	3.55
-2A	10.6	78	748	24.0	1100	27.8	27.7	3.86
B	10.6			24.0	1100	27.8	27.7	3.84
E20-1A	1.55	76	742	37.8	1730	25.8	25.8	4.03
B	1.55			37.8	1730	35.8	35.8	3.83
-2A	1.55	78	737	37.8	1730	25.6	25.7	3.92
B	1.55			37.8	1730	25.6	25.7	4.14
E21-1A	5.42	79	746	37.8	1730	28.6	28.5	4.00
B	5.42			37.8	1730	28.7	28.6	3.74
-2A	5.42	76	747	37.8	1730	26.5	26.5	3.67
B	5.42			37.8	1730	26.5	26.5	3.44
E22-1A	10.6	80	750	37.8	1730	28.2	28.2	3.83
B	10.6			37.8	1730	28.2	28.2	3.73
-2A	10.6	78	736	37.8	1730	25.1	25.4	4.17
B	10.6			37.8	1730	25.1	25.4	3.85
E30-1A	1.55	77	746	52.6	2410	26.6	26.7	3.62
B	1.55			52.6	2410	26.6	26.6	3.60
-2A	1.55	81	734	52.6	2410	28.3	28.3	3.94
B	1.55			52.6	2410	28.3	28.3	3.75
E31-1A	5.42	80	747	52.6	2410	28.3	28.3	missing
B	5.42			52.6	2410	28.3	28.3	3.92
-2A	5.42	78	745	52.6	2410	26.5	26.5	3.62
B	5.42			52.6	2410	26.5	26.5	3.78
E32-1A	10.6	76	754	52.6	2410	25.3	25.4	3.72
B	10.6			52.6	2410	25.3	25.4	3.87
-2A	10.6	81	742	52.6	2410	28.1	28.3	3.58
B	10.6			52.6	2410	28.1	28.2	3.82

Table 7. Liquid film coefficient for CO_2-H_2O absorption in the packed column.

Run No.	Liquid Mass Velocity lb./hr.-sq.ht.	Absorption Rate lb./hr. x10^3	$(\Delta C)_{l.m.}$ lb./cu.ft. x10^2	k_La Liquid Film Coefficient $\frac{lb.}{(hr.-cu.ft.)(lb./cu.ft.)}$ Observed	Corrected to 25°C	log k_La
R00-1A	596	8.41	5.68	15.5	14.1	1.1492
B	596	8.48	5.50	16.1	14.2	1.1523
-2A	596	9.07	5.62	16.8	15.5	1.1903
B	596	8.65	5.55	16.3	14.6	1.1644
R01-1A	596	8.82	5.78	16.0	14.6	1.1644
B	596	8.48	5.66	15.7	14.1	1.1492
-2A	596	9.22	5.46	17.3	15.7	1.1959
B	596	8.62	5.46	16.5	14.8	1.1703
R02-1A	596	8.73	5.79	15.8	14.5	1.1614
B	596	8.09	5.69	14.9	13.4	1.1271
-2A	596	10.00	5.57	18.7	17.4	1.2405
B	596	9.51	5.55	17.9	16.3	1.2122
R10-1A	1100	14.43	5.89	25.8	23.5	1.3711
B	1100	15.61	5.64	28.8	26.0	1.4150
-2A	1100	14.10	6.15	24.1	22.8	1.3579
B	1100	15.25	5.99	26.6	24.9	1.3962
R11-1A	1100	14.70	5.87	26.2	23.6	1.3729
B	1100	14.82	5.80	26.8	24.2	1.3838
-2A	1100	16.00	6.08	27.5	26.4	1.4216
B	1100	14.85	6.32	24.6	23.6	1.3729
R12-1A	1100	17.42	5.35	34.1	30.1	1.4786
B	1100	15.85	5.54	30.0	26.5	1.4232
-2A	1100	15.68	5.98	27.4	25.6	1.4082
B	1100	15.29	6.02	26.6	24.7	1.3927
R20-1A	1730	23.14	5.93	40.8	37.9	1.5786
B	1730	24.42	5.80	44.1	40.8	1.6107
-2A	1730	21.07	6.41	34.4	33.0	1.5185
B	1730	21.44	6.41	35.1	33.7	1.5276
R21-1A	1730	23.14	6.68	36.2	26.5	1.5623
B	1730	23.39	6.75	36.2	36.2	1.5587
-2A	1730	22.29	6.71	34.8	34.8	1.5416
B	1730	24.36	6.71	34.8	34.8	1.5416

Table 7. (Cont'd)

Run No.	Liquid Mass velocity lb./hr.-sq.ft.	Absorption Rate lb./hr. x10^3	$(\Delta C)_{l.m.}$ lb./cu.ft. x10^2	k_La Liquid Film Coefficient $\frac{lb.}{(hr.-cu.ft)(lb./cu.ft.)}$ Observed	Corr. to 25°C	log k_La
R22-1A	1730	23.08	5.90	43.1	40.0	1.6021
B	1730	22.53	6.07	39.8	36.8	1.5658
-2A	1730	21.53	6.60	35.8	24.5	1.5378
B	1730	21.19	6.79	33.9	31.9	1.5038
R30-1A	2410	32.70	5.90	57.9	53.5	1.7284
B	2410	24.81	5.47	66.4	61.6	1.7896
-2A	2410	31.61	6.09	54.5	51.4	1.7110
B	2410	32.37	5.96	56.6	53.0	1.7243
R31-1A	2410	33.13	6.40	54.1	52.4	1.7193
B	2410	30.68	6.46	49.6	48.0	1.6812
-2A	2410	31.27	6.60	49.6	49.6	1.6955
B	2410	31.78	6.80	48.8	48.8	1.6884
R32-1A	2410	31.44	6.80	48.4	48.4	1.6848
B	2410	32.87	6.75	51.1	50.6	1.7042
-2A	2410	34.05	6.66	53.6	53.0	1.7243
B	2410	31.86	6.78	49.6	48.9	1.6893
E00-1A	596	8.62	5.30	17.0	15.0	1.1761
B	596	9.49	4.84	20.5	17.6	1.2455
-2A	596	8.86	5.51	16.9	15.5	1.1903
B	596	8.94	5.39	17.4	15.8	1.1987
E01-1A	596					missing
B	596	10.26	5.00	21.4	19.6	1.2923
-2A	596	8.45	5.20	17.0	15.1	1.1790
B	596	8.14	5.36	15.9	14.1	1.1492
E02-1A	596	8.69	5.87	15.5	14.5	1.1614
B	596	9.11	5.53	17.3	15.7	1.1959
-2A	596	9.24	5.53	17.5	16.1	1.2068
B	596	8.88	5.51	16.9	15.2	1.1818
E10-1A	1100	16.23	6.06	28.0	27.0	1.4314
B	1100	15.68	6.14	28.7	27.6	1.4409
-2A	1100	14.50	5.61	27.1	24.1	1.3820
B	1100	14.34	5.78	26.0	23.0	1.3617

Table 7. (Cont'd)

Run No.	Liquid Mass Velocity lb./hr.-sq.ft.	Absorption Rate lb./hr. $\times 10^3$	$(\Delta C)_{l.m.}$ lb./cu.ft. $\times 10^2$	k_La Liquid Film Coefficient $\frac{\text{lb.}}{(\text{hr.-cu.ft.})(\text{lb./cu.ft.})}$ Observed	Corrected to 25°C	log k_La
E11-1A	1100	15.84	5.40	30.8	27.0	1.4314
B	1100	16.55	5.31	32.6	28.7	1.4579
-2A	1100	15.56	6.11	26.6	25.3	1.4031
B	1100	14.50	6.30	24.1	27.5	1.4393
E12-1A	1100	14.85	6.16	25.2	23.4	1.3692
B	1100	13.99	6.26	23.4	21.8	1.3385
-2A	1100	15.21	6.16	25.9	24.3	1.3856
B	1100	15.13	6.15	25.7	24.1	1.3820
E20-1A	1730	24.54	6.38	40.2	39.4	1.5955
B	1730	23.32	6.53	37.3	36.6	1.5635
-2A	1730	23.87	6.40	39.2	38.6	1.5866
B	1730	25.21	6.28	42.1	41.4	1.6170
E21-1A	1730	24.36	5.80	44.0	40.4	1.6064
B	1730	22.78	5.95	40.2	36.8	1.5658
-2A	1730	22.35	6.52	35.9	34.8	1.5416
B	1730	20.95	6.65	33.0	31.9	1.5038
E22-1A	1730	23.32	6.02	40.5	37.7	1.5763
B	1730	22.71	6.07	39.1	36.3	1.5599
-2A	1730	25.40	6.34	42.0	42.0	1.6232
B	1730	22.45	6.57	35.8	35.8	1.5539
E30-1A	2410	30.51	6.45	49.5	47.6	1.6776
B	2410	30.34	6.45	49.5	47.5	1.6767
-2A	2410	33.21	5.82	59.6	55.5	1.7435
B	2410	31.61	5.96	55.5	52.0	1.7160
E31-1A	2410					missing
B	2410	33.04	5.92	58.4	54.0	1.7324
-2A	2410	30.51	6.17	51.7	49.9	1.6981
B	2410	31.86	6.05	55.2	53.4	1.7275
E32-1A	2410	31.36	6.83	48.0	47.6	1.6776
B	2410	32.62	6.75	50.7	50.1	1.6998
-2A	2410	30.18	6.10	51.8	48.1	1.6821
B	2410	32.20	5.94	56.8	51.7	1.7135

IV. Statistical Analysis

PC series. Data taken from the last column of Table 4 are summarized in Table 8a. The following sums of squares are calculated from the main table and sub-tables of Table 8 a,b,c, and d.

$C.F. = (74.6514)^2/72 = 77.40043$, where 72 is the total number of observation.

(a) $0.7852^2 + \text{---} + 1.3424^2 - C.F. = 2.49332$

(b) $(1.5704^2 + \ldots\ldots + 2.6096^2)/2 - C.F. = 2.37931$

(c) $(17.8723^2 + \ldots\ldots + 19.1362^2)/18 - C.F. = 0.22781$

(d) $(35.4286^2 + \ldots\ldots + 39.2228^2)/36 - C.F. = 0.19995$

(e) $(3.2152^2 + \ldots\ldots + 5.0626^2)/4 - C.F. = 2.04449$

(f) $(6.6249^2 + \ldots\ldots + 9.9347^2)/8 - C.F. = 1.93212$

(g) $(36.6593^2 + \ldots\ldots + 37.9921^2)/36 - C.F. = 0.02467$

(h) $(9.6942^2 + \ldots\ldots + 14.9618^2)/12 - C.F. = 1.92405$

(i) $(24.4221^2 + \ldots\ldots + 24.7320^2)/24 - C.F. = 0.02553$

(j) $(11.8503^2 + \ldots\ldots + 12.3982^2)/12 - C.F. = 0.05986$

(k) $(20.0281^2 + \ldots\ldots + 29.5656^2)/24 - C.F. = 1.89697$

Sum of square for R = d , T = e , RxT = b-d-e

for main effects: F = g, L = k, G = i

for interactions: FxL = h-g-k , FxG = j-i-g , LxG = f-k-i
FxLxG = e-f-g-h-i-j-k

for observation within run: a-b

QD series. No attempt was made to test for significance of effects flow type with this experiment. The purpose of conducting this experiment was to furnish more data to determine the relationship between k_L and the liquid rate. Therefore only error of observation within run was calculated. This was done by the method as described for PC series, i.e. to find the corresponding a-b term.

RE series. Computation similar to that done in PC series was carried out. There were two missing data, E01-1A and E31-1A, due to known errors. In order to facilitate computation, these data were substituted by values that would give minimum errors. The new values were calculated with the folowing formula (5):

$$\hat{X}_{11} = \frac{nX_{.1} + (v-1)X_{1.} + X_{2.} - X_{..}}{(v-2)(n-1)}$$

$$\hat{X}_{21} = \frac{nX_{.1} + (v-1)X_{2.} + X_{1.} - X_{..}}{(v-2)(n-1)}$$

where X = value of observation

$\hat{X}_{11}$ = the estimated value of the missing one of replicate 1 and treatment 1.

$\hat{X}_{21}$ = the estimated value of the missing one of replicate 1 and treatment 2.

$X_{.1}$ = the sum of replicate 1 excluding X_{11}.

$X_{1.}$ = the sum of treatment 1 excluding X_{11}.

$X_{..}$ = the grand total excluding the missing one.

n = number of replicate.

v = number of treatment.

According to the above formula and using the first sample (a) of replicate 1 as the replicate in the formula, we can calculate the best estimate values for E01-1A and E31-1A. These are 1.2096 and 1.7221 respectively.

Since we have introduced two values with minimum error, the total number of observation for determining experimental error will thus be reduced by two. So total degree of freedom becomes 96-1-2 = 93.

Table 8. The logarithm of liquid film coefficient, log (k_L x 10), data from the absorption experiment of CO_2 - H_2O system in the disc column.

(a) Replicate versus treatment.

Treatment	Replicate						Total
	1A	1B	sum 1	2A	2B	Sum 2	
P00	.7852	.7852	1.5704	.8129	.8319	1.6448	3.2152
1	.6693	.6857	1.3550	.9420	.8976	1.8396	3.1946
2	.7679	.7135	1.4814	.9165	.8865	1.8030	3.2844
P10	.9689	.8597	1.8286	.9768	1.0043	1.9811	3.8097
1	1.0835	1.0588	2.1423	1.1732	1.0588	2.2320	4.3743
2	1.0835	.9786	2.0621	1.1673	.9479	2.1152	4.1773
P20	1.2041	1.3181	2.5222	1.1761	1.1271	2.3032	4.8254
1	1.1461	1.2095	2.3556	1.2742	1.2765	2.5507	4.9063
2	1.1072	1.1173	2.2245	1.3444	1.3032	2.6476	4.8721
C00	.8463	.8351	1.6814	.8710	.8573	1.7283	3.4097
1	.8129	.8195	1.6324	1.1673	.9217	2.0890	3.7214
2	.7404	.6911	1.4315	.8893	.8820	1.7713	3.2028
C10	1.0730	1.0550	2.1280	1.1959	1.1139	2.3098	4.4378
1	.9643	.9800	1.9443	1.1265	1.0550	2.1815	4.1258
2	.9380	.9253	1.8633	1.1761	1.0934	2.2695	4.1328
C20	1.1430	1.0792	2.2222	1.2279	1.2742	2.5021	4.7243
1	1.3032	1.2272	2.5304	1.3820	1.2625	2.6445	5.1749
2	1.2355	1.2175	2.4530	1.2672	1.3424	2.6096	5.0626
Total	17.8723	17.5563	35.4286	20.0866	19.1362	39.2228	74.6514

Table 8. (Cont'd)

(b) Flow type versus flow rates.

Rates	Flow type				Total
	P		C		
00	3.2152		3.4097		6.6249
1	3.1946		3.7214		6.9160
2	3.2844	9.6942	3.2028	10.3339	6.4872
10	3.8097		4.4378		8.2475
1	4.3743		4.1258		8.5001
2	4.1773	12.3613	4.1328	12.6964	8.3101
20	4.8254		4.7243		9.5497
1	4.9063		5.1749		10.0812
2	4.8721	14.6038	5.0626	14.9618	9.9347
Total	36.6593		37.9921		74.6514

(c) Flow type versus gas rate.

Gas Rate	P	C	Total
0	11.8503	12.5718	24.4221
1	12.4752	13.0221	25.4973
2	12.3338	12.3982	24.7320
Total	36.6593	37.9921	74.6514

(d) Gas rate versus liquid rate.

Liquid Rate	Gas Rate			Total
	0	1	2	
0	6.6249	6.9160	6.4872	20.0281
1	8.2475	8.5001	8.3101	25.0577
2	9.5497	10.0812	9.9347	29.5656
Total	24.4221	25.4973	24.7320	74.6514

Table 9. The logarithm of liquid film coefficient, log (k_L x 10), data from the absorption experiment of CO_2 -H_2O system in the disc column at gas rate of 5.42 cu.ft./hr.

Run No.	Sample			Run No.	Sample		
	A	B	Sum		A	B	Sum
Q5-1	0.9135	0.8949	1.8084	D5-1	0.9031	0.8921	1.7952
-2	0.8543	0.8555	1.7098	-2	0.8982	0.8751	1.7733
-3	0.8482	0.9085	1.7567	-3	0.9004	0.8842	1.7846
Q6-1	0.8663	0.9170	1.7833	-4	0.8075	0.8035	1.6110
-3	0.6946	0.7126	1.4072	D6-1	0.8949	0.9004	1.7953
-4	0.9754	0.9566	1.9320	-2	0.9370	0.9180	1.8550
Q7-1	1.0656	1.0622	2.1278	-3	0.7275	0.6937	1.4212
-2	0.9791	1.0212	2.0003	-4	0.9777	0.9741	1.9518
-3	1.0043	0.9814	1.9857	D7-1	0.9908	1.0170	2.0078
-4	1.0407	1.0212	2.0619	-2	0.9191	0.9795	1.8986
Q8-3	1.0577	1.0607	2.1184	-3	1.0128	1.0128	2.0256
-4	1.0690	1.0645	2.1335	D8-1	0.9827	1.0043	1.9870
-5	1.0278	1.0203	2.0481	-2	0.9675	0.9823	1.9498
-6	0.9991	1.0755	2.0746	-3	1.0351	1.0237	2.0588
-7	1.0577	1.0382	2.0959	-4	1.0958	1.0919	2.1677
-8	1.1038	1.1106	2.2144	-5	0.9741	1.0682	2.0423
Q9-1	1.0068	1.0076	2.0154	-6	1.0191	1.0531	2.0722
-2	1.0237	1.0395	2.0632	-7	1.0433	1.0719	2.1152
				D9-1	1.0203	1.0374	2.0577
				-2	1.0531	1.0000	2.0531
Total							73.7596

Table 10. The logarithm of liquid film coefficient, log k_L, data from the absorption experiment of CO_2 - H_2O system in the packed column.

(a) Replicate versus treatment.

Treatment	Replicate						Total
	1A	1B	sum 1	2A	2B	sum 2	
R00	1.1492	1.1523	2.3015	1.1903	1.1644	2.3547	4.6562
1	1.1644	1.1492	2.3136	1.1959	1.1703	2.3662	4.6798
2	1.1614	1.1271	2.2885	1.2405	1.2122	2.4527	4.7412
R10	1.3711	1.4150	2.7861	1.3579	1.3962	2.7541	5.5402
1	1.3729	1.3838	2.7567	1.4216	1.3729	2.7945	5.5512
2	1.4786	1.4232	2.9018	1.4282	1.3927	2.8009	5.7027
R20	1.5786	1.6107	3.1893	1.5185	1.5276	3.0461	6.2354
1	1.5623	1.5587	3.1210	1.5416	1.5416	3.0832	6.2042
2	1.6021	1.5658	3.1679	1.5378	1.5038	3.0416	6.2095
R30	1.7284	1.7896	3.5180	1.7110	1.7243	3.4353	6.9533
1	1.7193	1.6812	3.4005	1.6955	1.6844	3.3839	6.7844
2	1.6848	1.7042	3.3890	1.7243	1.6893	3.4136	6.8026
E00	1.1761	1.2455	2.4216	1.1903	1.1987	2.3890	4.8106
1	(a = 1.2096)	1.2923	2.5019	1.1790	1.1492	2.3282	4.8301
2	1.1614	1.1959	2.3573	1.2068	1.1818	2.3886	4.7459
E10	1.4314	1.4409	2.8723	1.3820	1.3617	2.7437	5.6160
1	1.4314	1.4579	2.8893	1.4031	1.4393	2.8424	5.7317
2	1.3692	1.3385	2.7077	1.3856	1.3820	2.7676	5.4753
E20	1.5955	1.5635	3.1590	1.5866	1.6170	3.2036	6.3526
1	1.6064	1.5658	3.1722	1.5416	1.4038	3.0454	6.2176
2	1.5763	1.5599	3.1362	1.6232	1.5539	3.1771	6.3133
E30	1.6776	1.6767	3.3543	1.7436	1.7160	3.4595	6.8138
1	(b = 1.7221)	1.7324	3.4545	1.6981	1.7275	3.4256	6.8801
2	1.6776	1.6998	3.3774	1.6821	1.7135	3.3956	6.7730
Total	35.2077	35.3299	70.5376	35.1650	34.9281	70.0931	140.6307

Table 10. (Cont'd)

(b) Flow type versus flow rates.

Rates	Flow Type R		Flow Type E		Total	
00	4.6562		4.8106		9.4668	
1	4.6789		4.8301		9.5099	
2	4.7412	14.0772	4.4759	14.3866	9.4871	28.4638
10	5.5402		5.5160		11.1562	
1	5.5512		5.7317		11.2829	
2	5.7027	16.7941	5.4753	16.8230	11.1780	33.6171
20	6.2354		6.3626		12.5980	
1	6.2042		6.2176		12.4218	
2	6.2095	18.6491	6.3133	18.8935	12.5228	37.5426
30	6.9533		6.8138		13.7671	
1	6.7844		6.8801		13.6645	
2	6.8026	20.5403	6.7730	20.4669	13.5756	41.0072
Total	70.0607		70.5700		140.6307	

(c) Flow type versus gas rate.

Gas Rate	R	E	Total
0	23.3851	23.6030	46.9881
1	23.2196	23.6596	46.8791
2	23.4560	23.3075	46.7635
Total	70.0607	70.5700	140.6307

(d) Gas rate versus liquid rate.

Liquid Rate	Gas Rate 0	Gas Rate 1	Gas Rate 2	Total
0	9.4668	9.5099	9.4871	28.4638
1	11.1562	11.2829	11.1780	33.6171
2	12.5980	12.4218	12.5228	37.5426
3	13.7671	13.6645	13.5756	41.0072
Total	46.9881	46.8791	46.7635	140.6307

V. Derivation of Equations

(4) $k_L = 0.0203\,\Gamma^{0.745}$

(5) $k_La = 0.0655\,L^{0.85}$

Selection of data. All data from RE series were used to derive equation (5), but data from PC series were examined carefully, because the analytical result (Table 1) showed the significance of variation due to replicate in PC series. There are two possibilities; (a) the experiment is irreproducible in the disc column, or (b) some unnoticed error has been introduced in either of the two replicates.

Though the performance in different disc columns may give different results (20), it is not plausible that the experiment is irreproducible in the same column. The changable de-wetting phenomenon will definitely increase the experimental error to a considerable degree, but it will not introduce any systematical error. Therefore, the irreproducibility of the experiment will not be considered.

The detail of experimental procedure was exactly the same for both replicates. The HCl solution used belonged to the same batch and was analysed from time to time for check. The only difference between the replicates was the NaOH solution used. In replicate 1 a batch of NaOH solution of concentration 0.0465N was used, and in replicate 2 another batch of 0.0510N was used. Two samples of NaOH solution were determined for effective concentration for each batch, and one check was made during the experiment (For QD and RE series, the concentration of CO_2 in inlet water and the effective concentration of NaOH were checked every six runs. The three series were performed in the order of PC, QD and RE.). Thus the concentration determination would not be the source of error. Since the record did not show any perceivable mistake, a comparison of data from replicate 1 and 2 of PC series with those from QD series was made.

The total of 164 k_L data for the disc column were separated into three groups, PC-1 (for rep. 1), PC-2 and QD. Every observation was compared with the mean value of the observations that belonged to the same group and had the same liquid rate (ignoring the flow type and gas rate difference). If that observation had a deviation more than 20 percent from the mean, it was discarded. The rejected observations were P10-1B, P12-2B, P20-1B, P20-2B, P22-2A, C02-1B, C20-1B, C21-1A, C10-1A, C01-2A, C21-2A, Q6-3A and B, D6-3A and B, a total number of 15 observations. The resulting means after these observations were rejected, were plotted on Plate IX. It is obvious from the plot that data from PC-1 are consistent with those from QD, while data from PC-2 give higher k_L values. Therefore, all data from PC-2 were not used in correlation.

Derivation. Least square method (same as that used in linear regression determination) was used in derivation. The procedure can be found in Snedecor's Statistical Methods p.138.

The sample standard deviation from the resulting function (regression) can be evaluated by:

$$S_{y.x} = \sqrt{\frac{1}{n-2}\left(\Sigma y^2 - b\Sigma xy\right)}$$

where n is the number of data used, b is the slope (coefficient of regression), y and xy are deviation of Y (dependent variable) and XY (independent variable times Y) of a single point with the means. Since $S_{y.x}$ is expressed in the logarithmic scale, we must change it back to unit related to k_L, e.g. a 0.02 unit of $S_{y.x}$ has an anti-logarithm of 1.047. It means that the standard deviation is 4.7 percent.

Data beyond 95 percent confidence limits were rejected. For the disc

EXPLANATION OF PLATE IX

Mean value of k_L vs. Γ plot for series PC-1, PC-2, and QD

k_L —— liquid-film coefficient, lb./(hr.-sq.ft.)(lb./cu.ft.)

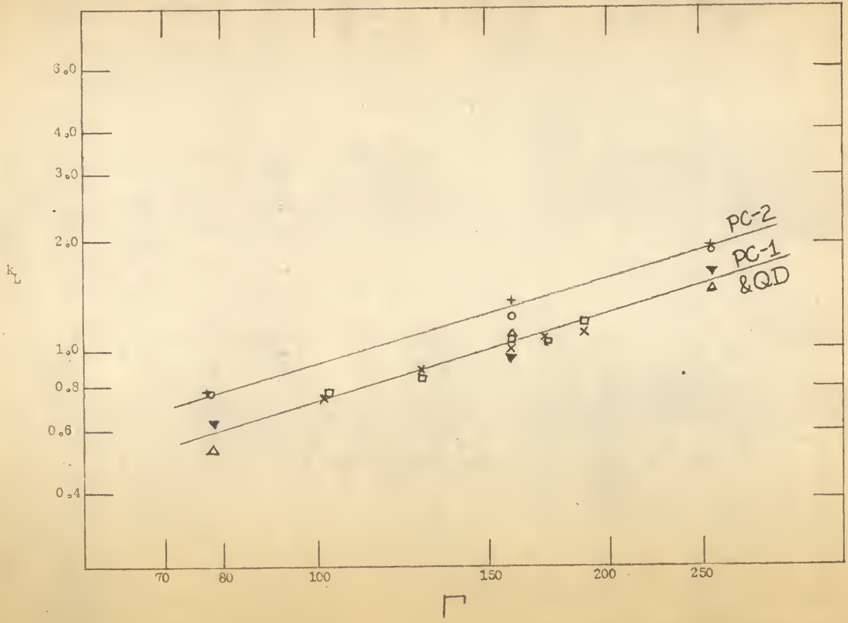
Γ —— wetting rate (liquid rate per mean wetting perimeter of disc), lb./hr.ft.

PC-1 —— replicate 1 of PC series

PC-2 —— replicate 2 of PC series

△ —— data from PC-1 for co-current flow	▼ —— data from PC-1 for countercurrent flow
+ —— data from PC-2 for co-current flow	○ —— data from PC-2 for countercurrent flow
× —— data from QD for co-current flow	□ —— data from QD for countercurrent flow

PLATE IX



column there were 20, and for the packed column 8. The remaining data were used to recalculate the equation of least deviation. The resulting equations were further transferred to that for 20°C by use of equation (3).

The final equation for the disc column, based on PC-1 and QD, is:

$$k_L = 0.0203\,\Gamma^{0.745} \qquad (4)$$

and for the packed column is:

$$k_L a = 0.0655\,L^{0.85} \qquad (5)$$

and for the disc column based on PC-2 is:

$$k_L = 0.0304\,\Gamma^{0.738} \qquad (18)$$

The last equation given is for comparison only. Equation (4) is the sole one that is considered as the result of the present experiment for the disc column, and used anywhere for interpretation and correlation. The fact that the two lines expressed by equations (4) and (18) are parallel indicated that the experimental error associated with k_L is in simple multiple form (cf. p. 11). Therefore use of logarithmic transformation is justified.

VI. Derivation of Equations (8) and (9)

Equations (8) and (9) are of the general forms for the disc column and packed column respectively. They are easy to obtain by comparing the equations (8) and (9) with the generalized equation (6) and (7) together with the following data:

μ = 2.42 lb.mass/hr.ft. (13)

ρ = 62.4 lb. mass/cu.ft. (13)

D = 7.0×10^{-5} ft^2/hr., (17)

VII. Equations for Cl_2-H_2O System in the Disc Column

Equation predicted from the result of this investigation. From the generalized equation (6), k_L is proportional to $D^{0.5}$. The equation for CO_2-H_2O system is:

$$k_L = 0.0203\,\Gamma^{0.745}$$

and the diffusivity of Cl_2 in water is 5.4×10^{-5} $ft^2/hr.$ (19). Therefore, the equation for Cl_2-H_2O will be:

$$k_L = 0.0178\,\Gamma^{0.745} \qquad (12)$$

Equation predicted by use of Chu's equation. Chu's (1) equation for CO_2-H_2O system in the same disc column is:

$$k_L = 0.0383\,\Gamma^{0.644}$$

and the resulting equation for Cl_2-H_2O system is:

$$k_L = 0.0338\,\Gamma^{0.644} \qquad (19)$$

Some particular points on lines predicted by the equations (12) and (19).

For equation (19):

Γ	$\Gamma^{0.644}$	k_L
150	25.1	0.848
200	30.3	1.03
300	39.3	1.33
400	47.5	1.61

For equation (12):

Γ	$\Gamma^{0.745}$	k_L
150	42.0	0.748
200	50.5	0.897
300	70.0	1.240
400	87.0	1.545

VIII. Gas-Film Coefficient of Ammonia-water System in the Disc Column

Equations.

(a) Predicted equation for liquid-film coefficient:

The diffusivity of NH_3 in water is given as 7.9×10^{-5} ft.^{2}/hr. (19). The equation for CO_2-H_2O system in the disc column was suggested by the present paper as:

$$k_L = 0.0203 \Gamma^{0.745}$$

and so the resulting equation for NH_3-H_2O system will be (cf. Appendix VII):

$$k_L = 0.0216 \Gamma^{0.745} \qquad (20)$$

(b) Relation between overall and film coefficients is:

$$\frac{1}{k_G} = \frac{1}{K_G} - \frac{H}{k_L} \qquad (21)$$

as given in any absorption book. The Henry constant H for ammonia in water at 20°C is taken as 0.013 atm./(lb. of NH_3/cu.ft. of H_2O), which was evaluated by Hwu (9) from Kowalke's equation.

(c) k_G vs. relative velocity:

Though Hwu's experimental result showed that the relation between k_G and relative velocity in the disc column could be represented by $k_G \propto v^{0.65}$, the following conventional relation was used:

$$k_G \propto v^{0.67} \qquad (22)$$

which has been verified by Stephens and Morris, and also by Taylor and Roberts in four different disc columns (19) (20).

Experimental Data.

The NH_3 absorption experiment in the disc column was performed by Hwu (9). Data at six different liquid rates with nearly equal interval were taken for the present correlation. These data and the corresponding k_G values calculated with equations (20) (21) and (22) are listed in the following table:

Table 11. Absorption data of NH_3-H_2O system

Run No.	Liquid rate lb./hr.ft.	Relative velocity ft./sec.	K_G at 20°C $\frac{lb.}{hr.sq.ft.atm.}$	k_G At v	k_G 5.84 ft./sec.
2	220	4.82	9.55	10.6	12.1
3	360	5.34	12.2	13.4	14.2
5	185	4.69	8.91	10.0	11.6
7	255	4.97	10.57	11.8	13.2
10	300	5.33	11.6	12.9	13.7
11	395	5.65	13.02	14.3	14.6

The first four columns were taken from Table 3 of Hwu's thesis (9).
The last two columns were calculated with equations (20)(21) and (22).

With the data given above we can derive an equation of k_G vs. through the same procedure as described in Appendix V. The resulting Equation is:

$$k_G = 3.06\,\Gamma^{0.30} \qquad (23)$$

In order to compare with other investigator's results, we transform equation (23) to satisfy the condition of relative velocity equal to 8.4 ft./sec. Thus the fanal equation becomes:

$$k_G = 3.90\,\Gamma^{0.30}$$

At two particular points, $\Gamma = 155$ lb./hr.ft. $k_G = 17.7$ lb./(hr. ft^2.atm.)

$\Gamma = 400$ lb./hr.ft. $k_G = 23.6$ lb./(hr.ft^2.atm.)

GAS ABSORPTION
IN CO-CURRENT FLOW

by

Lin-chuan Cha

B. S., National Taiwan University, China, 1954

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering

KANSAS STATE UNIVERSITY
OF AGRICULTURE AND APPLIED SCIENCE

1960

ABSTRACT

The purpose of this investigation was to study the effect of flow type on liquid film coefficient in gas absorption. Experiments under both countercurrent flow and co-current flow were carried out, and their results were compared. Experimental data of some previous workers were also recorrelated.

CO_2-H_2O system was chosen for this study. Apparatus used were 1-1/2 inch disc column with 35 pieces of 1.5 mm diameter X 0.48 th'k ceramic discs, and a 2 inch packed column with 8 mm packings. The experiments were designed and their results were analyzed statistically. The liquid rate covered a range from 10.0 lb./hr. to 52.6 lb./hr., and gas rate covered a range from 1.55 cu.ft./hr. to 10.6 cu.ft./hr.

From the results of this investigation the following conclusions were reached:

(1) Flow type has no effect on magnitude of liquid film coefficient within the range of study.

(2) Results obtained from disc column will generally vary from column to column.

(3) Data of CO_2-H_2O system for the columns used in this investigation can be correlated by the following equations:

for the disc column $k_L = 0.0203\,\Gamma^{0.745}$ at 20°C,

for the packed column $k_La = 0.0655\,L^{0.85}$ at 20°C.

(4) A general equation for liquid film coefficient in the disc column can be obtained from the present results. It is expressed as:

$$\frac{k_L}{D} = 7.44 \left(\frac{4\Gamma}{\mu}\right)^{0.745} \left(\frac{\mu}{\rho D}\right)^{0.5}$$

This equation was verified with experimental data of Cl_2-H_2O system obtained by the previous investigators.

(5) Gas film coefficient in the disc column can be predicted with considerable accuracy with the following equation:

$$\frac{k_G P}{\sqrt{\rho_L}} = 0.0326\, \Gamma^{0.30} \times \left(\frac{V d \rho}{\mu}\right)^{-0.33} \left(\frac{\mu}{\rho D}\right)^{-0.56} \frac{P}{p_{BM}}$$

which was obtained from the results of this investigation and that of another investigator.