INTERPHASE MASS TRANSFER IN
VARIOUS TYPES OF COLUMN

by

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INTRODUCTION

The application of gas absorption accompanied by a chemical reaction in the liquid phase is attracting more and more attention today in chemical processes where higher purity of gas is demanded and where the gaseous products are to be recovered more completely. However, there are no general equations that can be used to correlate the characteristics of the absorption equipment, the properties of the gas and liquid material and the hydrodynamic conditions of the system for the purpose of design calculation.

The conventional design procedures for physical absorption stem from the two-film theory and they are essentially short range extrapolation of performance data obtained in the pilot plant under similar operating conditions as those anticipated in the full-scale installation. Hence each gas-liquid system and each piece of equipment usually has its own correlation equations describing only the performance carried out under the highly specified conditions. When the additional complication of a chemical reaction is involved, no correlation on the laboratory scale can be extrapolated to the plant conditions except in a few special cases.

The theoretical development on this subject has been difficult and slow and it still needs a great deal of experimental support. In many cases the physical constants involved in a theoretical equation are just as hard or even more difficult to obtain than the design data themselves. The Penetration theories proposed by Highie (4) and Danckwerts (2) demand such physical constants as "the fractional rate of surface renewal", "the transient absorption rate" and a knowledge of the distribution of local liquid film coefficient k_L, etc. It is obvious that such kind of treatment is still far from the practical application.

The purpose of the present investigation is to find some general, although empirical, correlation between the purely physical absorption and the absorption processes followed by chemical reaction. Only a few investigators have attempted this problem, but all followed different approach and no previous work has appeared in the literature that can be used for comparison. Roper (10, 11) has made a study of the effect of the concentration of the absorbent solution on the fractional increase of the liquid film coefficient due to chemical reaction. Data obtained from the absorption of chlorine gas in olefins with dissolved iodine as catalyst can be described by the equation

$$\phi - 1 = 39 \left\{ \frac{(C_c + 0.00005)\, C_B}{C_i} \right\}^{0.5}$$

Where ϕ = the ratio of the liquid film coefficients $\frac{k'_L}{k_L}$, primed value refers to the case when chemical reaction is involved.

C_c = Concentration of catalyst (iodine) lb - mole/ft^3

C_B = Log-mean concentration of the liquid phase reactant lb - mole/cu ft

C_i = Concentration of dissolved, but unreacted, chlorine at the gas-liquid interface lb - mole/cu ft

Stephens and Morris (15) also studied the effect of concentration in the absorption of chlorine in aqueous solutions of ferrous chloride and ferric chloride. Danckwerts (2) attempted a theoretical treatment of the absorption process accompanied by an irreversible chemical reaction and it is from this theoretical analysis that the ideas of the present experimental approach evolved.

It is deduced, qualitatively, that perhaps the ratio of the absorption rate with chemical reaction to that without chemical reaction could be correlated to the "types" of column operating under "similar" conditions. Stated in a different way, the immediate problem is to obtain the necessary experimental data in order to see whether or not the effect of chemical reaction on absorption rate could be correlated between different types of columns and what would be the proper criterion for the "similarity" of operating conditions.

To achieve this object, three types of columns: a wetted-wall column, a disc column and a packed column were used in the present investigation. They constituted a series of flow patterns of progressing complexity. The CO_2 - H_2O and the CO_2 - NaOH systems were chosen because of the rapid irreverible (pseudo first order) reaction between CO_2 and NaOH and because of the well-established fact that the absorption rate is liquid-film controlling. In the experimental runs with either of the two systems, all the variables except the liquid rate were maintained as nearly constant as possible so that the effect of the chemical reaction could be readily detected in the result.

EXPERIMENTAL

Equipment

Three types of columns were used in the present investigation. They were a disc column, a wetted-wall column and a packed column. A description of each is given below under separate paragraphs.

The wetted-wall column was designed and assembled by Lin (8). The short height of the side wall was designed purposely to eliminate the rippling effect. The Pyrex glass column was mounted between stainless steel end plates with Tygon sheet as gaskets. The absorbing liquid was introduced through two small glass tubes and it overflowed along the knife edge of the inner tube where the absorption takes place. The close-up view of the column and the detailed dimensions were shown in Fig. 1 and Fig. 2 in the Appendix.

The disc column consisted of a 1-1/8 inch Pyrex glass tube and 35 ceramic discs which were threaded on a fiberglass cord held in tension in the center of the tube. The discs were threaded in such a way that the successive discs were at right angle to each other.

The absorbing liquid was introduced at the top through a jet and it flowed downward over the surfaces of the discs. The distance between the jet and the first disc was 1 inch. The diameter and thickness of the disc and other principal constants of the column were given in the appendix and the general arrangement and the accessories were shown in Fig. 3 (Appendix).

The packed column was constructed with a 2-inch inside diameter pyrex glass tube packed with 1/4 inch glass Raschig rings. The total length of the column was 24 inches while the packed portion was 6.5 inches in height. A perforated stainless steel plate was used to support the packings. In order to insure uniform distribution, the gas from the cylinder was split by a glass tee tube into two streams which were then introduced into the column at two different points on the diameter of the column. Also, the liquid was distributed over the packings by a Tygon distributor. A close-up view was given in Fig. 4 (Appendix).

Procedure

Liquid Stream. Distilled water was stored in a 50 gallon stainless tank and pumped to the top of each column by a 1/30 hp centrifugal pump. The flow rate was controlled and regulated by a calibrated C-clamp rotameter. Care must be taken to insure that no air bubbles were rising together. Entrained air bubbles in the liquid line leading to the column inlet could usually be eliminated by filling the pump with water before it was switched on. Before each run the absorbing surfaces would be completely wetted either by running the liquor through the column at its maximum flow rate or by filling up the entire column and then draining the liquor off. Incomplete wetting would cause serious error in the results.

The output of the centrifugal pump in the range of higher flow rates required frequent adjustment of the needle valves to keep the liquid flow rate constant.

Gas Stream. The CO_2 gas was withdrawn from the gas cylinder at a controlled rate and measured by a Brooks rotameter. Problems of stoppage of flow due to expansion of CO_2 gas in reducing valves were readily overcome. Even minor fluctuations in gas flow rate would not be serious, since it has been firmly established that the CO_2 - H_2O system is liquid-film controlling so that variation of gas flow rate over a moderate range would not have any effect on the gas absorption rate.

Before entering the column the CO_2 gas was saturated with water by bubbling through two flasks in series. Two monometers connected to the inlet and outlet ends of the column were employed to measure the pressure difference of the entering and exit gas streams respectively.

Liquid Sampling. It took from 35 to 40 minutes to ensure that the steady state equilibrium conditions have been reached for each run. Samples were then taken at 10 to 15 minutes intervals until the last two samples gave identical chemical analyses.

Special techniques were developed for taking the liquid samples. The sampling device is shown in Plate I. It was necessary that the liquid sample be trapped as soon as it left the column. For the CO_2 - H_2O system, $Ba(OH)_2$ was used as the trapping solution; for the NaOH - CO_2 system, $BaCl_2$ was used. The tip of the sampling tube was submerged in the excess $Ba(OH)_2$ solution in a volumetric flask so that the liquid sample from the absorption column would have no chance to come into contact with the atmosphere. Just a short time of contact with the atmosphere could have resulted in a considerable loss of CO_2 from the sample. For the NaOH - CO_2 system, the sampling technique was not as critical as in the case of CO_2 - H_2O system as the gas had been reacted with NaOH solution to form Na_2CO_3.

Temperature, Barometric Pressure, etc. In addition to the room temperature the inlet and outlet temperatures of the gas and liquid streams were carefully measured with mercury thermometers. The location of the thermometers are indicated in the schematic diagram, Plate III. Usually one barometric reading would be sufficient for an operation of not more than five or six hours.

Chemical Analysis

For the CO_2 - H_2O system, the absorbed carbon dioxide was precipitated as barium carbonate, then the excess barium hydroxide was determined by back titration against hydrochloric acid using phenolphthalein as indicator. For the CO_2 - NaOH system, the total amount of CO_2 absorbed was determined by two titrations. The liquid sample was divided into two equal portions. The first portion was titrated against sulfuric acid using methyl orange as indicator while the second portion was titrated against the same acid using phenolphethalein as indicator. The difference of the amount of acid used in these two titrations determines the quantity of CO_2 absorbed.

The detailed procedures and principles of the chemical analysis are discussed in the appendix.

EXPLANATION OF PLATE I

A: Sample liquid stream from the absorption column

B: Three-way stopcock

C: Sampling bottle

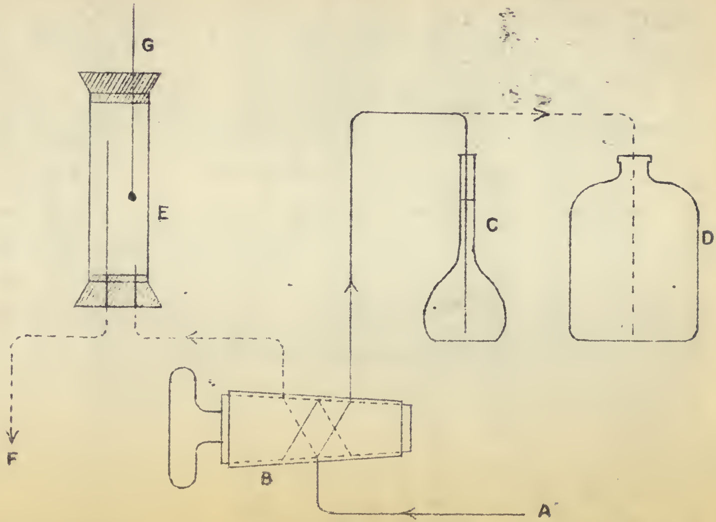
D: Receiving bottle used to drain off the liquid in the hose before sampling

E: Glass tube for the measurement of exit liquid temperature

F: Drain Stream

G: Thermometer

PLATE I



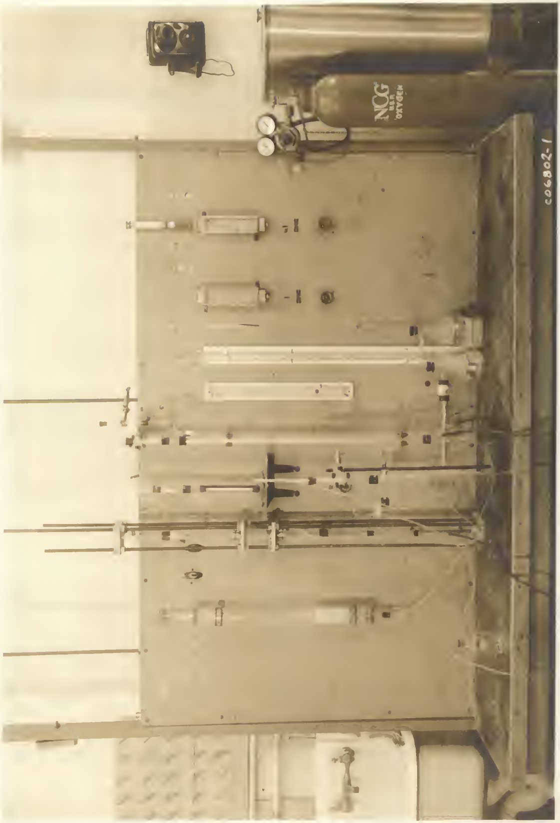
EXPLANATION OF PLATE II

A Picture of the Schematic Diagram

of

Plate III

PLATE II



EXPLANATION OF PLATE III

Schematic Diagram of Experimental Layout

L: Liquid Tank

P: Liquid pump

LRRV: Liquid rate regulating valve

LF: Liquid flowmeter

LIT: Liquid inlet temperature measuring thermometer

DC: Disc column

WWC: Wetted-wall column

PC: Packed column

LOV: Liquid outlet valve

DV: Drain valve

LLR: Liquid level regulator

LOT: Liquid outlet temperature measuring thermometer

OSV: Outlet liquid sampling valve

LIV: Liquid inlet valve

ISV: Inlet liquid sampling valve

S: Sampling bottle

G: Cylinder gas

PR: Pressure regulator

GRRV: Gas rate regulating valve

GF: Gas flowmeter

GS: Gas saturator

GIT: Gas inlet temperature measuring thermometer

GIV: Gas inlet valve

GIM: Gas inlet pressure measuring manometer

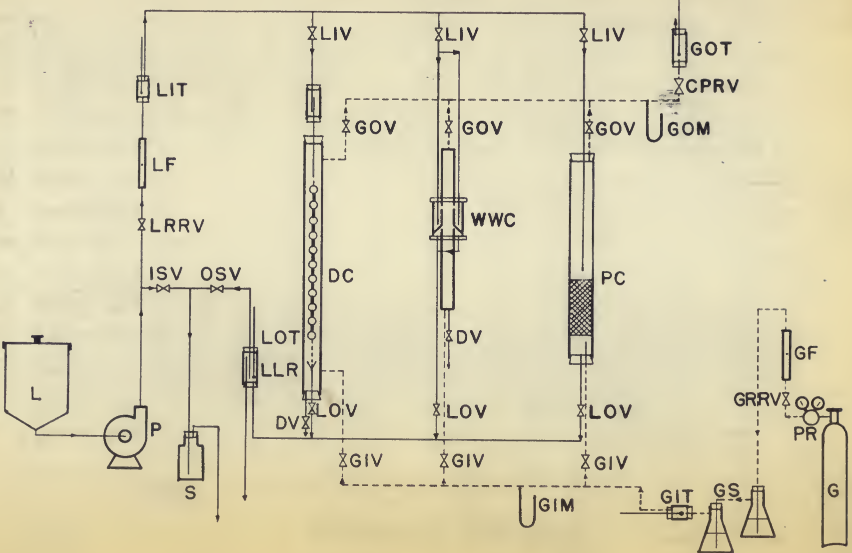
GOV: Gas outlet valve

GOM: Gas outlet pressure measuring manometer

CPRV: Column pressure regulating valve

GOT: Gas outlet temperature measuring thermometer

PLATE III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LF
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LRRV
ISV
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DC
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RESULTS AND DISCUSSION

Summary of Experimental Data

CO_2 - H_2O System. A total of 23 runs were carried out in the three columns for the absorption of carbon dioxide in water. Carbon dioxide gas from the gas cylinder was used without dilution. In all runs the flow rate of CO_2 gas was fixed at 3.1 cu. ft./hr. (at standard conditions) while the liquid rate varied from 2.0 lb./hr. to 24.8 lb./hr. During the months when these experiments were conducted, the room temperature ranged from 26° C to 30° C. In most runs there was no detectable rise in the liquid temperature as it passed through the column. In a few runs, however, the temperature did register a difference of 0.5 to 0.8° C. The carbon dioxide content of the inlet liquid was found negligible for all runs. The gas temperatures of all the runs ranged from 25° to 30° C. The absorption rates measured in these runs are given in Table 5 in the appendix. From the rate data the liquid film coefficient, k_L, was calculated for each run according to the following equation:

$$k_L = \frac{R}{\Delta C_{l.m}}$$

$$C_{l.m} = \frac{\{(Ce)_{out} - C_{in}\} - \{(Ce)_{in} - C_{out}\}}{\ln \frac{(Ce)_{out} - C_{in}}{(Ce)_{in} - C_{out}}}$$

$$(Ce)_{in} = \frac{P_{in}}{H}$$

$$(Ce)_{out} = \frac{P_{out}}{H}$$

Where R = Absorption rate lb/(hr.)(ft.^{2})

k_L = Liquid film coefficient lb/(hr.)(ft.^{2}) (lb/ft.^{3})

$\Delta C_{l.m}$ = Log mean concentration driving force lb/ft.^{3}

$(Ce)_{out}$ = Liquid concentration in equilibrium with the outgoing gas stream expressed lb./ft.^{3}

$(Ce)_{in}$ = Liquid concentration in equilibrium with the incoming gas stream lb./ft.^{3}

C_{out} = Outlet liquid concentration obtained from chemical analysis

C_{in} = Inlet liquid concentration obtained from chemical analysis (zero in the present case)

P_{in} = Partial pressure of inlet CO_2 atm

P_{out} = Partial pressure of outlet CO_2 atm

H = Henry's Law constant (available in Perry's Handbook), atm

The values of the calculated k_L range from 0.16 to 1.01 and they are given in the appendix.

CO_2 - NaOH System. A total of 27 runs were carried out under the same operating conditions as the CO_2 - H_2O system except that the distilled water in the previous absorption system was replaced by 0.92 N NaOH solution. The absorption was studied at seven different liquid rates corresponding to those conducted in the CO_2 - H_2O system. The method of calculation was the same as for the CO_2 - H_2O system. It was assumed that the solution exerted no back pressure and the concentrations of CO_2 in the solution were zero at both ends of the column. In other words C_{in} and C_{out} were both zero.

The heat of reaction between NaOH and CO_2 caused the outlet liquid temperature to increase by 2° to 6° C above the inlet temperature depending on the type of column. The liquid temperatures ranged from 27° C to 31° C for the wetted-wall column, from 26.7° C to 34.6° C from the disc column. The CO_2 content of the inlet NaOH solution was again found to be negligible.

Absorption rates measured in these runs are also given in the appendix.

Discussion of Experimental Results

Correlation of absorption rate with chemical reaction in the liquid phase from the rate of physical absorption.

In Plate III, k_L represents a correlation of the measured absorption rates of CO_2 in water and CO_2 in NaOH, respectively, in different columns. This graph was constructed from the experimental data for the disc and the wetted-wall columns as follows: In Tables 11 and 13 in the appendix, for each value of k_L, read off the corresponding value of liquid flow rate Γ and physical absorption rate R. Then in Tables 8 and 10 in the appendix, locate the identical flow rate Γ and read off the chemical absorption rate R'. The ratios between R' and R thus obtained at the same flow rate are given in Table 1 and plotted versus k_L in Plate IV.

The value of k_L in the wetted-wall column ranges from 0.174 to 0.660 lb./(hr.)(ft.^{2}) (lb./ft.^{3}) corresponding to liquid rates from 2.0 to 24.8 lb./hr. The k_L values in the disc column are from 0.562 to 1.01 over the same range of liquid rates as above.

The two sets of data give rise to two smooth curves which overlap each other in the interval of k_L values between 0.562 and 0.66. However, upon closer inspection it is seen that the data for the two different columns can be represented by a single curve as described by the equation:

$$\alpha = 14.23\ k_L - 0.697 \text{ - - - - - - - - - - - -}(1)$$

Where $\alpha = \frac{R'}{R}$, ratio of absorption rate with chemical reaction to that without chemical reaction (or to the physical absorption rate)

k_L = Liquid film transfer coefficient for the physical absorption,

and the numerical coefficients were determined by the method of least squares. The complete data and the method of calculation are tabulated in the appendix.

This result is interpreted to mean that irrespective of the type of column in which the absorption is taking place, as long as the flow rates and other operating conditions are such that the value of k_L is the same, the effect of the chemical reaction on the absorption rate can be found either directly from the curve on Plate IV or by calculation with the empirical equation (1).

The proof of the independence of the effect of chemical reaction on the absorption rate with regard to the types of column in which the absorption process occurs would be stronger if the overlapping portion of the $\frac{R'}{R}$ versus k_L were wider than the present results. However, in view of the coincidence of the general tendency of the curves and the actual overlapping of the experimental data, it is believed that the results obtained in this investigation at least provide an indication that α (which is the ratio of the absorption rates) is independent of the two types of column used. For further study it is suggested that, at least two more columns of larger dimensions be constructed and higher liquid rates, i.e. higher k_L values, be employed.

A plot of α versus k_Ga. A similar plot with α versus k_Ga for the packed column is also presented in Plate V for comparison. The general trend of the resultant curve is nearly the same as the plot for the disc and the wetted-wall columns. However, since the data here were obtained from a single packed column the results are not conclusive by themselves. Moreover, the absorption process in a packed tower is further complicated due to the fact that k_G and "a" (interfacial area per unit volume of packing) are both varying with the liquid rate. There is no way, so far, to predict the individual contribution of k_L and "a" to the combined effect observed in the laboratory. An attempt has been made to detect the change of "a" in the packed column due to the change in the liquid rate. By assuming that k_L could be predicted with the correlation developed for the disc column it was found that the absorption area (per unit packing volume) increased appreciably as the liquid rate became higher. A plot of the calculated "a" versus liquid rate is presented in Plate VI. The explanation of this phenomenon is that at lower liquid rates the packing surfaces might not have been completely wetted and were ineffective for absorption.

<u>The Effect of Liquid Rate on the Ratio of Liquid Film Coefficient</u>. To show the effect of liquid rate, ϕ, the ratio of the liquid film coefficient with chemical reaction to that without, is plotted against the liquid rate for each column as shown in Plates VII, VIII, and IX. The complete data for these plots are given in Tables 2, 3, and 4 in appendix, respectively. All three curves show a negative slope, which can be interpreted to mean that the film coefficient of physical absorption is increasing faster with the liquid rate than that of the chemical absorption. Furthermore, the viscosity of 0.92N NaOH solution at the average operating temperature was 1.2 times as much as that of water. Therefore in the chemical absorption case where NaOH solution is used instead of water, the liquid film thickness, hence the observed coefficient k_L should be even less sensitive to any change in liquid rate.

Another significant feature of Plates VII, VIII, and IX is that the value of $\phi = (\frac{k'_L}{k_L})$ varies from column to column depending on its type. In the wetted-wall column, the value of k'_L (film coefficient with chemical reaction) is on the average about 30 times greater than that of k_L (film coefficient of physical absorption); in the disc column, the ratio of k'_L to k_L is about 11; while in the packed column, about 10.

Note that the wetted-wall column, the disc column and the packed column all together constitute a series of flow patterns of progressing complexity. For a given liquid rate, the ratio of the two coefficients (ϕ) is much higher in the wetted-wall column than in the other two. The corresponding values of ϕ in the disc and the packed columns are approximately the same, which is also to be expected because of their resemblance in flow pattern.

For the range of the liquid rate studied, k_L value varies from 0.16 to 0.66 in the wetted-wall column and from 0.56 to 1.01 in the disc column. The lower value of k_L in the wetted-wall column would account for the higher ratio of k'_L to k_L.

The quantity $\frac{k'_L - k_L}{k_L}$ was used by Roper (10, 11) to represent the fractional increase in the liquid film coefficient due to chemical reaction. As the k_L value is continuously increasing with the liquid rate, the effect of chemical reaction, under the same operating conditions as that of the physical absorption, would become less important and finally as a limiting case at extremely high liquid rate, the value of k'_L (absorption with chemical reaction) would practically be the same as k_L (physical absorption). Then the fractional increase would become zero. On the other hand, if the k_L value for the physical absorption or the solubility of the solute gas in the absorbent liquid is so small that only a trace of the solute gas could be absorbed into the liquid, then the chemical reaction would bear a much more pronounced effect on the liquid film coefficient. The absorption process carried out in the wetted-wall column provides a direct experimental proof of the above statement because, again using Roper's terminology, the "fractional increase" in this case is expected to be a large number.

Effect of Liquid Rate on k_L in the Disc Column. The present data of the absorption of CO_2 in water can be correlated by the method of least squares as follows:

$$k = 0.123\,\Gamma^{0.37} \qquad \text{for } 16 < \Gamma < 73 \text{ ef/hr. ft.}$$

$$k = 0.0386\,\Gamma^{0.644} \qquad \text{for } 73 < \Gamma < 200 \text{ lb/hr. ft.}$$

A plot of k_L versus Γ is shown in Plate IX.

Only a limited amount of data in the literature is available for comparison. These are plotted also in Plate IX. It shows that the present data are comparable to those obtained by Taylor and Robert (16) which are represented by the equations

$$\text{(i)} \quad k = 0.124\,\Gamma^{0.4} \qquad \text{for } \Gamma < 155 \text{ lb/hr. ft.}$$

$$\text{(ii)} \quad k = 0.0056\,\Gamma^{1.0} \qquad \text{for } \Gamma > 155 \text{ lb/hr. ft.}$$

Note that the break point on the curve occurs at a different liquid rate. This also agrees with Taylor and Robert's own observation that this critical flow rate where the break in the curve occurs varies with the dimensions of the discs used in each particular column.

The data of Stephens and Morris (15) are represented by the equation

$$k = 0.048\,\Gamma^{0.7}$$

Again the apparent discrepancy may be attributed to the difference in the dimensions and the wetting properties of the discs used.

When the column used in the present study was first constructed by Hwu (6), it was tested at a higher liquid rate range. The equation $k = 0.0075\,\Gamma^{0.97}$ was tentatively proposed. The experimental points are also plotted in Plate XI.

Plate X is a plot of C, the concentration of CO_2 in the exit liquid sample, versus the liquid rate. Hwu (6) explained that two opposing factors controlled the CO_2 concentration in the exit liquid: One is the residence time or time of contact between the liquid and gas; the other is the degree of turbulence in the liquid stream. The plot in Plate X is consistent with this explanation. At the lower liquid rates, apparently the first factor predominates. Therefore the concentration first decreases, because of the shortened time of contact, as the liquid rate increases. At the higher liquid rate range, the second factor becomes more important. Therefore, then, as the liquid rate increases further, the concentration begins to level off as the effect of increased turbulence begins to compensate and may eventually overtake the effect of shortened contact time.

CONCLUSIONS

The findings of this investigation are summarized as follows:

The effect of chemical reaction on the absorption rate was studied and found amenable to correlation of the following form

$$\frac{R'}{R} = a(k_L)^b$$

where R' = Absorption rate per unit area when the liquid contains reagent which reacts with the solute.

R = Absorption rate per unit area when the liquid contains no active reagent.

k_L = Liquid film absorption coefficient when the liquid contains no active reagent.

a, b = Empirical constants.

For the absorption of CO_2 in NaOH solutions at room temperature, it was found that a = 14.23 and b = -0.697. Furthermore, these same constants apply to both the short wetted column and the disc column within the entire flow range studied from 2 lb/hr. to 24.8 lb/hr. It is recommended that k_L for the physical absorption be used as the correlating variable, in preference to the modified Reynolds' number or the liquid flow rate itself. As long as the operating conditions (flow rates, physical properties, etc.) are such that k_L values in the two different types of columns are the same, the ratio R'/R in the two columns would be the same also. Upon further varification and modification, this method of correlation should be able to fascilitate the design procedure involving new chemical reactions as follows:

(1) Determine the constants a and b with any convenient laboratory column such as the present disc column.

(2) Estimate k_L and R for the specified equipment and operating conditions by means of the existing design equations for physical absorption.

(3) Find the rate of chemical absorption in question: $R' = (R)\ a\ (k_L)^b$.

The limitation of the proposed correlation is that it only accounts for the effect of chemical reaction. The present packed column data can not be correlated by the same constants as for the other two columns, although the form of the equation is still the same. In packed columns, in addition to the chemical effect, any change in the effective absorption area due to change in flow conditions must also be accounted for. This, apart from the chemical reaction effect, has been the topic of a great deal of study in the past by various workers without much promise of success. This limitation imposes a restriction on the choice of laboratory column in step (1) of the design procedure above. It would be necessary to choose one for which the correlation of physical absorption is well known.

ϕ, the ratio of the liquid film coefficient for the absorption accompanied by chemical reaction, k'_L, to that of physical absorption, k_L, was found to vary from column to column depending on the characteristics of each individual piece of equipment. The fractional increase of the liquid film coefficient, $\phi - 1 = \frac{k'_L - k_L}{k_L}$, was found to be higher in a column where the k_L value range was lower. In other words, the effect of chemical reaction on the liquid film coefficient is more pronounced in a column of lower k_L value than those of higher values of k_L.

The measurement of the liquid film coefficient for the absorption of carbon dioxide in water in the disc column has been extended. They are consistent with those reported in the literature. Two empirical equations were proposed:

$$k_L = 0.123\,\Gamma^{0.37} \qquad \text{for } 16 < \Gamma < 73 \text{ lb/hr. ft.}$$

$$k_L = 0.0386\,\Gamma^{0.644} \qquad \text{for } 73 < \Gamma < 200 \text{ lb/hr. ft.}$$

Table 1. Effect of Chemical Reaction on the Absorption rate in the disc and the wetted-wall columns.

Run No	R CO_2 absorbed without chemical reaction lb/hr ft^2	Run No	R' CO_2 absorbed with chemical reaction lb/hr ft^2	α	k_L Liquid absorption constant lb/hr ft^2 lbs/ft^3
$5B_4$	0.0304	$42B_1, 43B_1$	0.525*	17.3	0.582
$5B_4$	0.0304	$42B_1, 43B_1$	0.525*	17.3	0.562
$7B_1$	0.0367	$44B_1$	0.694	18.9	0.618
$7B_2$	0.0384	$44B_1$	0.694	18.1	0.650
$8B_2, B_3$	0.0472*	$45B_1$	0.959	20.5	0.756*
$8B_2, B_3$	0.0472*	$46B_1$	0.740	14.9	0.756*
$9B_1$	0.0588	$47B_1$	0.917	15.6	0.905
$9B_3$	0.0602	$47B_1$	0.917	15.2	0.935
$10B_1, B_2, B_3$	0.0682*	$48B_1$	1.11	16.3	1.011*
$22B_3, B_5, B6$	0.01395*	$66B_1$	0.686	49.2	0.174*
$21B_1, B_2$	0.0252*	$68B_1$	0.847	33.6	0.303*
$21B_1, B_2$	0.0252*	$67B_1$	0.762	30.2	0.303*
$23B_2, B_3, B6$	0.0300*	$64B_1$	0.845	28.2	0.348*
$23B_2, B_3, B6$	0.0300*	$64B_2$	0.852	28.4	0.348*
$24B_1, B_2, B_3$	0.036*	$63B_1$	1.028	28.5	0.414
$24B_1, B_2, B_3$	0.036*	$63B_2$	1.082	30.0	0.414
$24B_1, B_2, B_3$	0.036*	$63B_1$	1.028	28.5	0.400
$24B_1, B_2, B_3$	0.036*	$63B_2$	1.082	30.0	0.400
$25B_3$	0.0589	$62B_1$	0.992	16.85	0.660
$25B_4$	0.0567	$62B_1$	0.992	17.50	0.660
$26B_2$	0.0482	$61B_1$	1.111	23.0	0.547
$26B_4$	0.0462	$61B_1$	1.111	24.0	0.504
$27B_1, B_2$	0.0519*	$60B_1$	1.26	24.2	0.565
$27B_3$	0.0531	$60B_1$	1.26	23.7	0.585
$27B_1, B_2$	0.0519*	$60B_2$	1.061	20.4	0.565
$27B_3$	0.0531	$60B_2$	1.061	20.0	0.585

* Average value for those runs indicated.

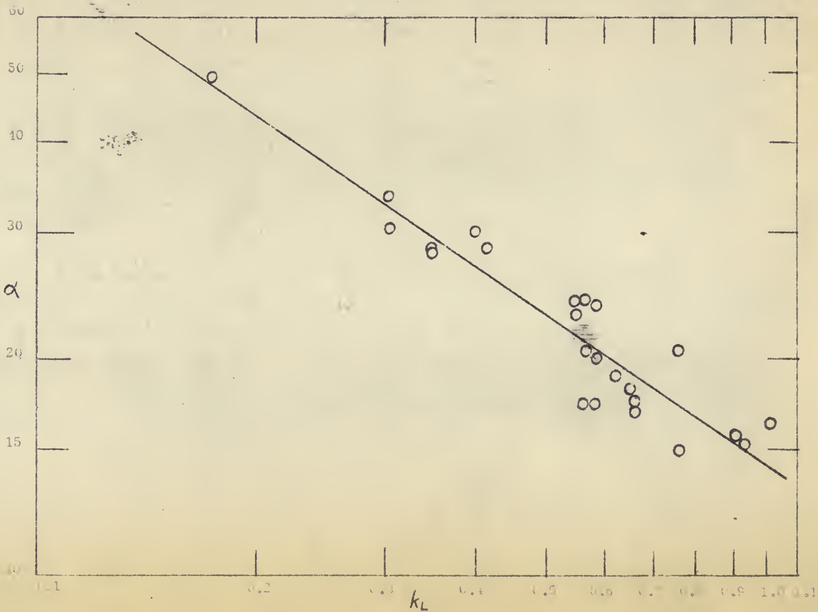
EXPLANATION OF PLATE IV

Increase of Absorption Rate due to Chemical Reaction in the disc and the wetted-wall columns at different k_L values.

Ordinate: α , $(\frac{R'}{R})$, ratio of the absorption rate with chemical reaction in the liquid
phase to that of physical absorption

Abscissa: k_L, Liquid Film Transfer Coefficient
$lbs/(hr)(ft^2)(lb/ft^3)$

PLATE IV



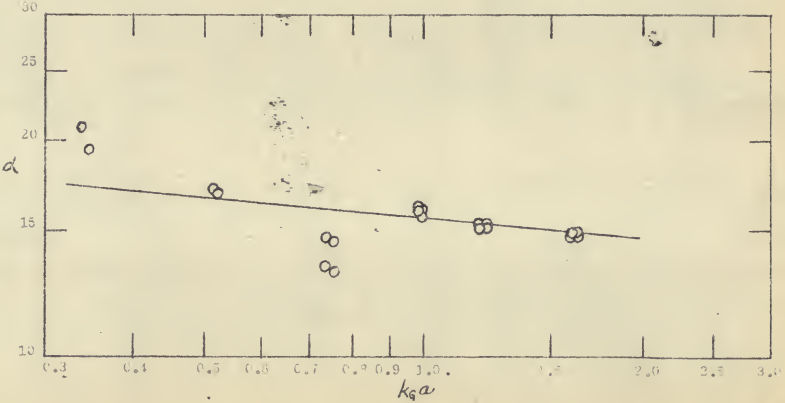
EXPLANATION OF PLATE V

Increase of Absorption Rate due to Chemical Reaction in the Packed Column at different k_Ga values.

Ordinate: α, $(\frac{R'}{R})$, ratio of the absorption rate with chemical reaction in the liquid phase to that of physical absorption

Abscissa: k_Ga, Overall transfer coefficient based on the driving force of the gas side. $lbs/(hr)(ft^2)(atm)$

PLATE [illegible]



EXPLANATION OF PLATE VI

Effect of Liquid Rate on the Wetted Surface area per unit volume of packing.

Ordinate: a, effective wetted surface area per unit volume of packing, ft^2/cu ft

Abscissa: Liquid rate G_L lbs/(hr)(ft^2)

PLATE VI

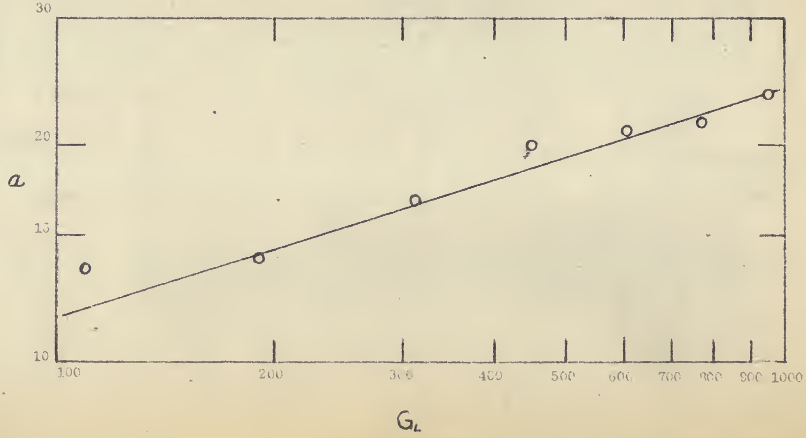


Table 2. Effect of liquid rate on the ratio of the liquid film coefficient with chemical reaction to that without in the disc column.

Run No	k_L Liquid film constant without chemical reaction $lbs/(hr)(ft^2)(lbs/ft^3)$	Run No	k'_L Liquid film constant with chemical reaction $lbs/(hr)(ft^2)(lbs/ft^3)$	∅	Γ Liquid Flow rate $lb/(hr)(ft)$
$5B_2$	0.472	$42B_2$	5.77	12.2	53.5
$5B_4$	0.582	$42B_2$	5.77	9.9	53.5
$5B_5$	0.562	$42B_2$	5.77	10.2	53.5
$5B_2$	0.472	$43B_1$	5.23	11.1	53.5
$5B_4$	0.582	$43B_1$	5.23	9.0	53.5
$5B_5$	0.562	$43B_1$	5.23	9.3	53.5
$7B_1$	0.618	$44B_1$	6.93	11.2	77.2
$7B_2$	0.650	$44B_1$	6.93	10.7	77.2
$8B_1$	0.739	$45B_1$	7.09	9.6	100.4
$8B_2, B_3$	0.756*	$45B_1$	7.09	9.4	100.4
$8B_1$	0.739	$46B_1$	10.00	13.5	100.4
$8B_2, B_3$	0.756*	$46B_1$	10.00	13.2	100.4
$9B_1$	0.905	$47B_1$	9.20	10.2	133
$9B_2$	0.912	$47B_1$	9.20	10.1	133
$9B_3$	0.935	$47B_1$	9.20	9.8	133
$10B_1$	1.023	$48B_1$	11.45	11.2	163
$10B_2$	0.955	$48B_1$	11.45	12.0	163
$10B_3$	1.011	$48B_1$	11.45	11.3	163

* Average value for Run numbers indicated.

EXPLANATION OF PLATE VII

Effect of Liquid Rate on the ratio of the liquid film coefficient with chemical reaction to that without in the disc column.

Ordinate: ϕ, $(\frac{k'}{k})$, ratio of the liquid film coefficient with chemical reaction to that without

Abscissa: Γ, liquid rate lbs/(hr)(ft)

PLATE VII

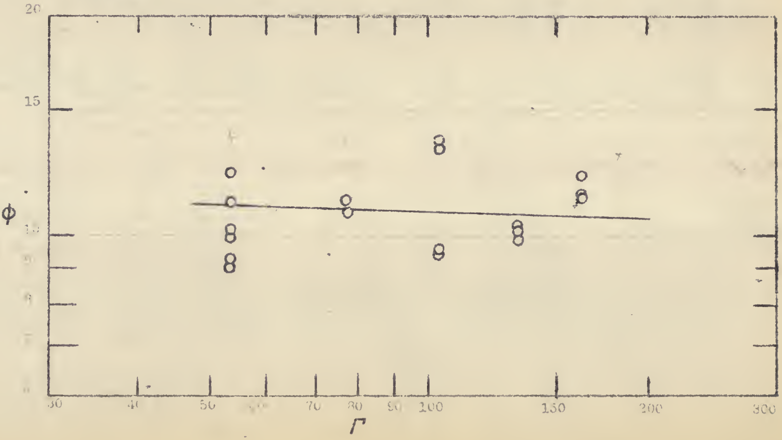


Table 3. Effect of liquid rate on the ratio of the liquid film coefficient with chemical reaction to that without in the wetted wall column.

Run No	k_L Liquid Absorption constant without chemical reaction lb/(hr)(ft^2)(lb/ft^3)	Run No	k'_L Liquid Absorption constant with chemical reaction lb/(hr)(ft^2)(lb/ft^3)	ø	G_L Mass Flow Rate lb/(hr)(ft^2)
$22B_3, B_5, B_6$	0.174*	$66B_1$	6.9	39.7	366
$21B_1$	0.311	$67B_1$	7.7	24.8	770
$21B_2$	0.2955	$67B_1$	7.7	26.1	770
$21B_1$	0.311	$68B_1$	8.56	27.8	770
$21B_2$	0.2955	$68B_1$	8.56	29.0	770
$23B_2$	0.348	$64B_1$	9.16	26.3	1245
$23B_3$	0.3415	$64B_1$	9.16	26.8	1245
$23B_6$	0.358	$64B_1$	9.16	25.6	1245
$23B_2$	0.348	$64B_2$	9.26	27.2	1245
$23B_3$	0.3415	$64B_2$	9.26	27.1	1245
$23B_6$	0.358	$64B_2$	9.26	25.9	1245
$24B_2$	0.400	$63B_1$	9.9	24.8	1795
$24B_1, B_3$	0.4155*	$63B_1$	9.9	23.8	1795
$24B_2$	0.400	$63B_2$	10.9	27.3	1795
$24B_1, B_3$	0.4155*	$63B_2$	10.9	26.2	1795
$25B_3$	0.664	$62B_1$	10.0	15.1	2420
$25B_4$	0.656	$62B_1$	10.0	15.2	2420
$26B_2$	0.547	$61B_1$	11.3	20.7	3100
$26B_4$	0.504	$61B_1$	11.3	22.4	3100
$27B_1, B_2$	0.565*	$60B_1$	12.3	21.8	3800
$27B_3$	0.585	$60B_2$	12.3	21.0	3800
$27B_1, B_2$	0.565	$60B_1$	10.7	18.9	3800
$27B_3$	0.585	$60B_2$	10.7	18.3	3800

* Average values for those runs indicated.

EXPLANATION OF PLATE VIII

Effect of Liquid Rate on the Ratio of the Liquid Film Coefficient with Chemical Reaction to that without in the Wetted-Wall Column.

Ordinate: ϕ, $(\frac{k'}{k})$, ratio of the liquid film coefficient with chemical reaction to that without

Abscissa: G_L, liquid rate lbs/(hr)(ft^2)

PLATE VIII

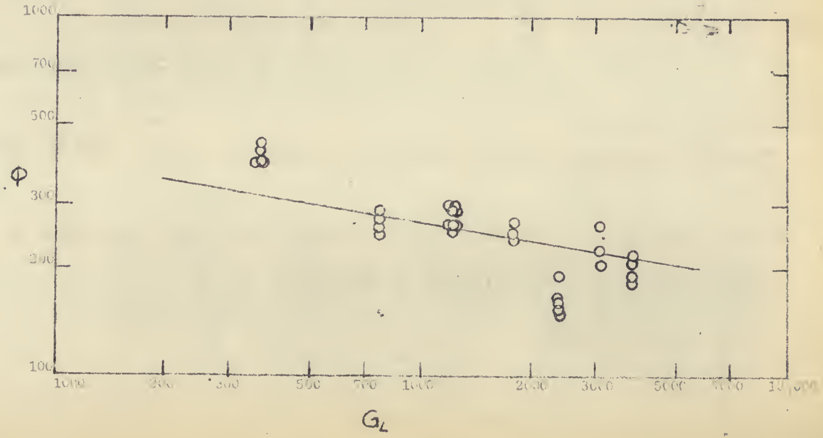

1000
700
500
300
200
100
Φ
100
200
300
500
700
1000
2000
3000
5000
7000
10,000
G_L

Table 4. Effect of Liquid Rate on the ratio of the liquid film coefficient with chemical reaction in the liquid phase to that without in the packed column.

Run No	k_La Liquid film coefficient without chemical reaction lb/(hr ft^3)(lb/ft^3)	Run No	k'_La Liquid film coefficient with chemical reaction lb/(hr ft^3)(lb/ft^3)	$\frac{k'_La}{k_La}$	G_L Liquid flow rate lb/hr ft^2
$15B_3, B_4$	5.96*	$51B_1$	74.0	12.4	192.5
$15B_5, B_6$	6.25*	$51B_1$	74.0	11.8	192.5
$14B_3, B_4$	9.45*	$49B_1, B_2$	97.55*	10.3	312
$14B_5, B_6$	9.28*	$49B_1, B_2$	97.55*	10.5	312
$13B_1, B_2$	12.95*	$52B_2$	109	8.4	449.5
$13B_3, B_4$	12.45*	$52B_2$	109	8.8	449.5
$13B_1, B_2$	12.95*	$52B_1$	116.5	9.0	449.5
$13B_3, B_4$	12.45*	$52B_1$	116.5	9.4	449.5
$17B_2$	15.69	$53B_1$	162	10.5	605
$17B_3, B_4$	16.19*	$53B_1$	162	10.1	605
$17B_6$	16.78	$53B_2$	166	9.8	605
$18B_1$	20.2	$54B_1, B_2$	201*	9.95	775
$18B_2, B_3$	19.39*	$54B_1, B_2$	201*	10.4	775
$19B_1, B_2$	23.6*	$55B_1, B_2$	218*	9.2	950

* Average value for runs indicated.

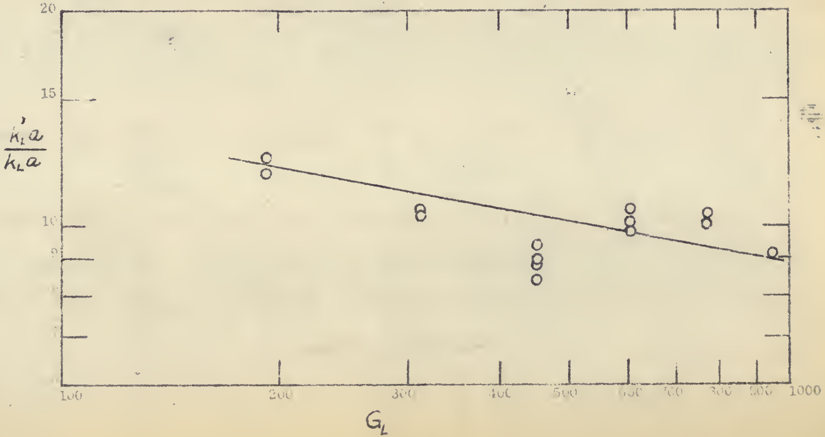
EXPLANATION OF PLATE IX

Effect of Liquid Rate on the Ratio of the Liquid Film Coefficient with Chemical Reaction in the Liquid Phase to that without in the Packed Column.

Ordinate: $\frac{(k'_L a)}{(k_L a)_{\text{without}}}$, ratio of the liquid film coefficient with chemical reaction to that without

Abscissa: G_L, liquid rate lbs/(hr)(ft^2)

PLATE IX



20
15
10
9
$\frac{k'_L a}{k_L a}$
100
200
300
400
500
600
700
800
900
1000
G_L

EXPLANATION OF PLATE X

Plot of Liquid Film Coefficient, k_L vs the liquid rate, Γ in the disc column.

Ordinate: Liquid Film Coefficient k_L lbs/hr $(ft^2)(lb/ft^3)$

Abscissa: Liquid Rate Γ lbs/(hr)(ft)

Legend:

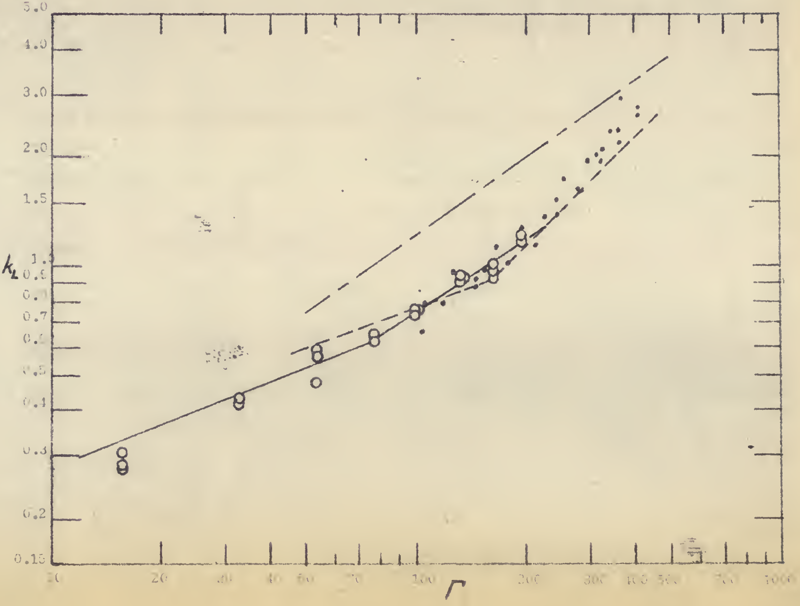
——— — ——— — Reported by Stephens & Morris (15)

— — — — — Reported by Taylor & Robert (16)

—————— Present investigation

• • • • • • • • • • • • Data reported by Hwu (6)

PLATE X


5.0
4.0
3.0
2.0
1.5
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.15
k_L
10
20
30
40
50
70
100
200
300
400
500
700
1000
Γ

EXPLANATION OF PLATE XI

Plot of Exit CO_2 concentration vs liquid rate.

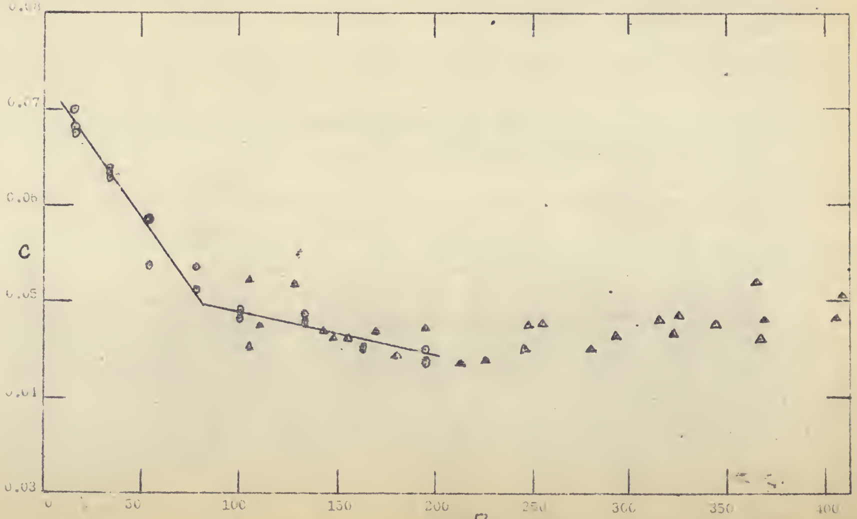
Ordinate: Exit concentration CO_2 lb/cu ft

Abscissa: Liquid rate Γ lbs/(hr)(ft)

Legend:

⊙	Data obtained from the present observation
△	Data reported by Hwu (6)

PLATE [illegible]



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APPENDIX

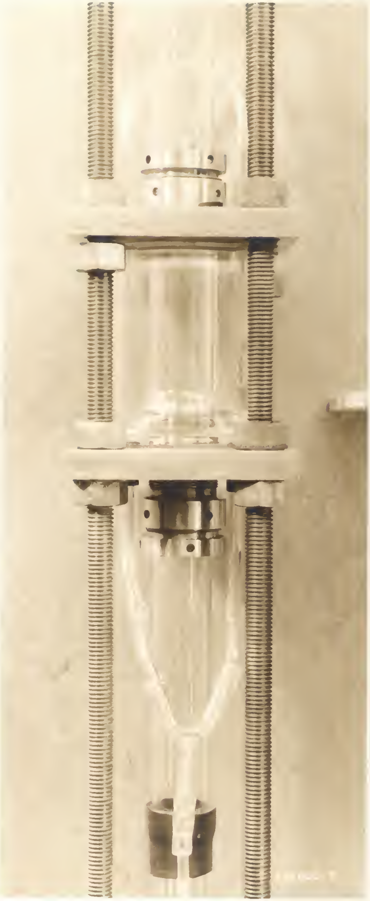

Fig. 1. Wetted-wall column.

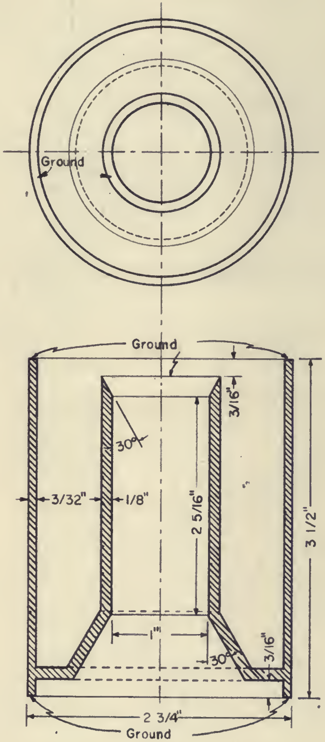

Fig. 2 Detailed Drawing of Wetted-Wall Column

Fig. 3. Disc column.

Fig. 4. Packed column.

Chemical Analysis:

CO_2 - H_2O System

The amount of the absorbed CO_2 precipitated as barium carbonate in the barium hydroxide solution was determined by back-titration of barium hydroxide against hydrochloric acid.

The method is based on the reaction:

$$\underset{}{H_2CO_3} + \underset{\text{in excess}}{Ba(OH)_2} \longrightarrow BaCO_3\downarrow + 2H_2O + \underset{\substack{\text{remaining}\\\text{portion}}}{Ba(OH)_2}$$

the remaining portion of $Ba(OH)_2$ was then titrated against HCl (0.1N) using phenolphthalcin as indicator. The results of this back titration method were generally less than 5 per cent in error.

The amount of CO_2 absorbed was calculated by the following formula

$$CO_2 \text{ absorbed gr/c.c.} = \frac{C(Y-X) \times 0.022}{\text{Sample taken (c.c.)}}$$

where Y = HCl (number of c.c.) required to neutralize the trapping solution $Ba(OH)_2$

X = HCl (number of c.c.) required in the back titration

C = Concentration (number of normality of HCl used)

0.022 = Equivalent quantity of CO_2 (gram) for every c.c. of 1N HCl solution consumed in titration

All titrations were carried out in an Erlenmeyer flask free from carbon dioxide. A standard solution was prepared for the comparison of the color of the end point of titration.

CO_2 - NaOH System

In the present case, the sample liquid was a mixture of Na_2CO_3, $NaHCO_3$, NaOH, and H_2O. The chemical reactions upon which the method of titration was based were listed as follows:

$$\text{(A)}\quad Na_2CO_3 + H_2SO_4 \longrightarrow Na_2SO_4 + H_2O + CO_2$$

$$2NaHCO_3 + H_2SO_4 \longrightarrow NaSO_4 + 2H_2O + CO_2$$

$$2NaOH + H_2SO_4 \longrightarrow Na_2SO_4 + 2H_2O$$

Methyl orange indicator

$$\text{(B)}\quad Na_2CO_3 + BaCl_2 \longrightarrow BaCO_3 + 2NaCl$$

$$2NaOH + H_2SO_4 \longrightarrow Na_2SO_4 + 2H_2O$$

phenolphthalein indicator

To determine the total sodium ion concentration methyl orange was used as indicator as shown by the equations in group (A). To another portion of the same sample, excess $BaCl_2$ was added for the precipitation of $BaCO_3$ then the excess NaOH in the sample solution was back titrated against H_2SO_4 using phenolphthalein as indication shown by the equations in group (B). This would determine the ionic strength of the remaining NaOH after a portion of it being reacted with the absorbed CO_2.

The amount of CO_2 absorbed was then calculated by the following formula.

$$\text{Gram } CO_2 \text{ absorbed} = \frac{C(A - B) \times 0.053}{106.1} \times 44$$

where A = H_2SO_4 used in the first titration (group (A).

B = H_2SO_4 used in the second titration (group B).

C = concentration of H_2SO_4 in normality.

In both of the titrations, magnetic stirrer was used to keep the solution being titrated well mixed at all times. Sufficient stirring was extremely important in the titration of the B part since the accumulation of acid at the dead corner of the titration flask could cause reaction with the precipitated $BaCO_3$.

Sample Calculation

Run No. $6B_1$

(1) Observed data:

Liquid rate 4.2 lb/hr

Gas rate 3.093 cu ft/hr

Liquid inlet temp. 29.9° C

Liquid outlet temp. 29.2° C

Gas inlet temp. 28.9° C

Gas outlet temp. 29.9° C

Gas inlet manometer pressure 2.72 mmHg

Gas outlet manometer pressure 0.59 mmHg

Henry's Law constant H_{in} (Perry's Handbook) 1864

Henry's Law constant H_{out} (Perry's Handbook) 1830

Temperature correction coefficient, α, of barometric reading (Perry's Handbook) 0.12826

Barometric pressure 742.6 mmHg

Room temperature 29.4° C

Vapor pressure at 28.9° C - - - - 29.87 mmHg

Vapor pressure at 29.9° C - - - - 31.64 mmHg

Exit concentration of sample C_{out} 1.02×10^{-3} lb/lb or 0.0634 lb/ft^3

(2) Calculation:

Corrected barometric pressure at 0° C is obtained by the following equation:

$H_t = H'_t - \alpha(t' - t)$ where H_t is the height at the standard temperature

H'_t = the observed height at the temperature t'

$t = 0^\circ$ C

t' = the room temperature

$$H = 742.6 - 0.1283\ (294 - 0) = 738.8 \text{ mmHg}$$

$$(PCO_2)_{in} = (738.8 + 2.72) - 29.87 = 711.6 \text{ mmHg}$$

$$(PCO_2)_{out} = (738.8 + 0.59) - 31.64 = 707.8 \text{ mmHg}$$

$$C_{e_{in}} = \frac{(PCO_2)}{H} = \frac{707.8/760}{1864}\ \frac{44}{18} \times 62.2 = 0.0760 \text{ lb/ft}^3$$

$$C_{e_{out}} = \frac{(PCO_2)}{H} = \frac{711.6/760}{1830}\ \frac{44}{18} \times 62.2 = 0.0781 \text{ lb/ft}^3$$

$$\Delta C_{l.m.} = \frac{(C_e)_{out} - C_{in} - (C_e)_{in} - C_{out}}{\ln \dfrac{(C_e)_{out} - C_{in}}{(C_e)_{in} - C_{out}}} = \frac{0.0655}{\ln 6.2} =$$

$$0.036 \text{ lb/ft}^3$$

Absorption rate R lb/hr ft^2 was obtained as follows:

$$R = \frac{4.2 \times (1.02 \times 10^{-4})}{0.22} = 1.945 \times 10^{-2}$$

$$k = \frac{R}{C} = \frac{1.945 \times 10^{-2}}{0.036} = 0.54$$

k was corrected to 20° C by the following equation:

$$(k_L)_{20^\circ\ C} = (k_L)_{t^\circ\ C}\ \frac{e^{0.023 \times 20}}{e^{0.023t}}$$

$$= 0.54\ \frac{e^{0.023 \times 20}}{e^{0.023 \times 29.55}} = 0.43$$

Empirical Equation by Least Square Method

Data from Tables 5 to 16 show a straight line relationship on a full log scale.

It suggests that the empirical equation takes the form

$$\alpha = ak^{b}{}_{L} \quad \text{or}$$

$$\log \alpha = \log a + b \log k_L$$

The least square method requires that the sum of the squares of the difference of the observed values α' and calculated values α (where $\alpha = a\ k^{b}{}_{L}$) be minimum.

The empirical constants a and b are obtained by solving the following two equations simultaneously

$$\log \alpha = n \log a + b \sum \log k \qquad (1)$$

$$\sum \log \alpha \ \log k = a \sum \log k + b \sum (\log k)^2 \qquad (2)$$

where n = the number of points taken into calculation

log	log k	log log k	$(\log k_2)^2$
35.129	-7.355	-10.456	2.8249

substituting in (1) and (2) and solve for a and b

$a = 14.23$

$b = -0.697$

Therefore, the empirical equation is $\alpha = 14.23\ k_L^{-0.697}$

Table 5. Absorption data of CO_2 - H_2O system in disc column.

Run No	Barometric Pressure mmHg	Room Temperature °C	Liquid Rate lb/hr	Liquid Temperature-°C		Manometer Reading - mmHg		Gas Temperature-°C		C_{out} lbs CO_2/ lb H_2O
				Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	
$5B_2$	742.4	28	6.8	28.9	28.9	1.84	0	28.3	29.9	8.62×10^{-4}
$5B_4$	742.4	28	6.8	28.9	28.9	1.84	0	28.3	30	9.40×10^{-4}
$5B_5$	742.4	28	6.8	29.2	29.2	1.84	0	28.3	30	9.40×10^{-4}
$6B_1$	742.6	29.4	4.2	29.9	29.2	2.72	0.59	28.9	29.9	1.02×10^{-3}
$6B_2$	742.6	29.4	4.2	30.3	29.4	2.72	0.59	28.9	29.9	1.01×10^{-3}
$6B_3$	742.6	29.4	4.2	30.3	29.4	2.72	0.59	28.9	29.9	1.022×10^{-3}
$7B_1$	742.6	29.4	9.8	28.6	28.9	2.72	0.59	28.9	29.9	8.24×10^{-4}
$7B_2$	742.6	29.4	9.8	28.6	28.6	2.72	0.59	28.6	29.2	8.63×10^{-4}
$8B_1$	742.6	29.4	13.2	27.8	27.8	2.72	0.59	28.3	29.2	7.75×10^{-4}
$8B_2$	742.6	29.4	13.2	27.8	27.8	2.72	0.59	28.3	29.2	7.88×10^{-4}
$8B_3$	742.6	29.4	13.2	27.8	27.8	2.72	0.59	28.3	29.2	7.85×10^{-4}
$9B_1$	741.5	25.6	16.9	26.6	26.6	2.2	0.44	25.6	26.6	7.66×10^{-4}
$9B_2$	741.5	25.6	16.9	26.6	26.6	2.2	0.44	25.6	26.6	7.67×10^{-4}
$9B_3$	741.5	25.6	16.9	26.6	26.6	2.2	0.44	25.6	26.6	7.84×10^{-4}
$10B_1$	741.5	26	20.7	26.4	26.6	2.2	0.44	25.6	26.6	7.25×10^{-4}
$10B_2$	741.5	26	20.7	26.4	26.6	2.2	0.44	25.6	26.6	7.27×10^{-4}
$10B_3$	741.5	26	20.7	26.4	26.6	2.2	0.44	25.6	26.6	7.24×10^{-4}
$11B_1$	741.5	26	24.8	26.6	26.1	2.2	0.44	26.6	27.8	7.03×10^{-4}
$11B_2$	741.5	26	24.8	26.6	26.6	2.2	0.44	26.6	27.8	7.24×10^{-4}
$11B_3$	741.5	26	24.8	26.4	26.6	2.2	0.44	26.6	27.8	7.00×10^{-4}
$12B_1$	728.9	28	2.0	29.4	27.8	2.2	0.44	27.2	28.3	1.122×10^{-3}
$12B_2$	728.9	28.5	2.0	30.6	28.9	2.2	0.44	27.8	28.9	1.085×10^{-3}
$12B_3$	728.9	29	2.0	31.1	28.9	2.2	0.44	27.8	28.9	1.096×10^{-3}

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

Run No	Barometric Pressure mmHg	Room Temperature °C	Liquid Rate lb/hr	Liquid Temperature-°C Inlet	Liquid Temperature-°C Outlet	Manometer Reading – mmHg Inlet	Manometer Reading – mmHg Outlet	Gas Temperature-°C Inlet	Gas Temperature-°C Outlet	C_{out} lbs CO_2/ lb H_2O,10^4
13B1	736	25.8	9.8	27.8	27.2	2.6	0.44	25.6	26.1	7.76
$13B_2$	736	25.8	9.8	27.8	27.2	2.6	0.44	25.6	26.1	7.86
$13B_3$	736	25.8	9.8	27.8	27.2	2.6	0.44	25.6	26.1	7.62
$13B_4$	736	25.8	9.8	28.3	27.2	2.6	0.44	25.6	26.6	7.64
$14B_3$	736	26.1	6.8	28.9	28.3	2.6	0.44	26.6	27.2	7.95
$14B_4$	736	26.1	6.8	28.9	28.3	2.6	0.44	26.6	27.2	8.00
14B6	736	26.1	6.8	28.9	28.3	2.6	0.44	26.6	27.2	7.86
$15B_3$	731.4	24.5	4.2	28	26.6	2.6	0.44	24.4	25.6	8.09
$15B_4$	731.4	24.5	4.2	28.3	26.6	2.6	0.44	24.4	25.6	8.10
$15B_5$	731.4	24.5	4.2	28.3	26.9	2.6	0.44	24.4	26.1	8.35
15B6	731.4	24.5	4.2	28.9	27.8	2.6	0.44	25.0	26.6	8.40
16B	731.4	26	2.0	28.9	26.1	2.9	0.59	25.6	26.6	9.22
16B	731.4	26	2.0	28.9	26.1	2.9	0.59	25.6	26.6	9.51
$17B_2$	728.4	25.3	13.2	26.6	26.6	2.9	0.74	25.6	26.4	7.34
$17B_3$	728.4	25.3	13.2	26.6	26.6	2.9	0.74	25.6	26.4	7.48
$17B_4$	728.4	25.3	13.2	26.6	26.6	2.9	0.74	25.6	26.4	7.46
$17B_6$	728.4	25.3	13.2	26.6	26.6	2.9	0.74	25.6	26.1	7.39
$18B_1$	731	25	15.8	24.4	24.4	3.2	0.59	25.6	26.6	7.95
$18B_2$	731	25	15.8	24.4	24.7	3.2	0.59	25.6	26.6	7.76
$18B_3$	731	25	15.8	24.4	24.7	3.2	0.59	25.6	26.6	7.85
$19B_1$	731	24.4	20.7	24.2	24.3	3.2	0.59	25.0	25.6	7.45
$19B_2$	731	24.4	20.7	24.2	24.3	3.2	0.59	25.0	25.6	7.29
$20B_1$	731	24.8	24.8	23.9	24.3	3.2	0.59	25.0	26.6	7.31
$20B_2$	731	24.8	24.8	23.9	24.3	3.2	0.59	25.0	26.6	7.31

Table 7. Absorption data of CO_2-H_2O system in wetted-wall column.

Run No	Barometric Pressure mmHg	Room Temperature °C	Liquid Rate lb/hr	Liquid Temperature-°C		Manometer Reading - mmHg		Gas Temperature-°C		C_{out} lbs CO_2/ lb H_2O,10^4
				Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	
$21B_1$	741	27.5	4.2	30	28.9	2.2	0.44	27.8	28.3	3.32
$21B_2$	741	27.5	4.2	30	28.9	2.2	0.44	27.8	28.3	3.16
$22B_3$	740.5	27.5	2.0	30	27.8	2.5	0.44	26.6	27.8	3.766
$22B_5$	740.5	27.5	2.0	30.6	28	2.5	0.44	27.2	28.3	3.78
$22B_6$	740.5	27.5	2.0	30.6	28	2.5	0.44	27.2	28.3	3.76
$23B_2$	740.5	27.5	6.8	29.4	29.2	2.2	0.44	27.8	28.3	2.38
$23B_3$	740.5	27.5	6.8	29.4	29.2	2.2	0.44	27.8	28.6	2.35
$23B_6$	740.5	27.5	6.8	29.4	29.2	2.2	0.44	27.8	29.2	2.44
$24B_1$	739.4	28.6	9.8	28.3	28.6	2.2	0.66	27.8	29.2	2.04
$24B_2$	739.4	28.6	9.8	28.3	28.6	2.2	0.66	27.8	29.2	1.98
$24B_3$	739.4	28.6	9.8	28	27.8	2.2	0.66	27.8	29.4	1.95
$25B_3$	734.5	27.5	13.2	27.5	27.5	2.6	0.29	27.2	28.3	2.41
$25B_4$	734.5	27.5	13.2	27.5	27.7	2.6	0.29	27.5	28.6	2.32
$26B_1$	730	29.2	16.9	27.2	27.2	2.2	0.59	28	28.9	1.34
$26B_2$	730	29.2	16.9	27.2	27.2	2.2	0.59	28	28.9	1.54
$26B_3$	730	29.2	16.9	27.2	27.2	2.2	0.59	28	28.9	1.30
$26B_4$	730	29.2	16.9	27.2	27.8	2.2	0.59	28.6	29.4	1.476
$27B_1$	730	30	20.7	27.2	27.2	2.2	0.59	28.9	29.4	1.37
$27B_2$	730	30	20.7	27.2	27.2	2.2	0.59	28.9	28.9	1.34
$27B_3$	730	30	20.7	27.2	27.2	2.2	0.59	28.9	28.9	1.385
$28B_2$	730	30	24.8	27.6	27.2	2.2	0.59	28.9	28.9	1.32

Table 8. Absorption data of CO_2 - NaOH system in disc column.

Run No	Barometric Pressure mmHg	Room Temperature °C	Liquid Rate lb/hr	Liquid Temperature-°C		Manometer Reading - mmHg		Gas Temperature-°C		C_{out} lbs CO_2/ lb H_2O
				Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	
$42B_2$	734	27.2	6.8	26.7	33.6	2.06	0.514	26.7	27.2	0.01865
$43B_1$	734.3	26.1	6.8	26.7	33.3	2.06	0.514	26.7	27.2	0.01698
$44B_1$	734.3	26.1	9.8	27.2	34.6	2.06	0.514	26.7	27.7	0.01569
$45B_1$	734.3	26.1	12.5	27.2	34.4	2.06	0.514	26.7	27.7	0.01687
$46B_1$	734.3	26.1	11.8	27.2	35	2.06	0.514	26.7	27.8	0.01312
$47B_1$	734.3	26.1	16.9	26.7	33.9	2.06	0.514	26.9	27.8	0.01192
$48B_1$	734.3	26.1	20.4	26.7	33	2.06	0.514	27.2	28.3	0.01209

Table 9. Absorption data of CO_2 - NaOH system in packed column.

Run No	Barometric Pressure mmHg	Room Temperature °C	Liquid Rate lb/hr	Liquid Temperature-°C		Manometer Reading - mmHg		Gas Temperature-°C		C_{out} lbs CO_2/ lb H_2O
				Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	
$49B_1$	734.6	27.8	6.3	26.7	32.6	2.64	0.294	26.1	27.2	0.01455
$49B_2$	734.6	27.8	6.6	27.2	32.2	2.64	0.294	26.1	27.2	0.01386
$51B_1$	734.6	27.8	3.7	28.9	33.2	2.94	0.514	26.7	28.3	0.01955
$52B_1$	734	26.1	9.8	26.7	32.2	2.94	0.514	26.7	27.2	0.01117
$52B_2$	734	26.1	9.8	26.7	31.9	2.94	0.514	26.0	27.2	0.01042
$53B_1$	734	25	13.2	26.7	32.2	2.94	0.514	26.7	27.2	0.01196
$53B_2$	734	26.1	13.2	26.7	32.3	2.94	0.514	26.7	27.8	0.01170
$54B_1$	734	25.6	16.9	26.7	32.8	2.82	0.368	26.7	27.8	0.01103
$54B_2$	734	25.6	16.6	26.7	32.8	2.82	0.368	26.7	27.8	0.01223
$55B_1$	734	27.8	20.7	27.2	33.2	2.35	0.294	27.8	28.9	0.01094
$55B_2$	734	27.8	20.7	27.2	33.2	2.35	0.294	27.8	28.9	0.01084

Table 10. Absorption data of CO_2 - NaOH system in wetted-wall column.

Run No	Barometric Pressure mmHg	Room Temperature °C	Liquid Rate lb/hr	Liquid Temperature-°C		Manometer Reading - mmHg		Gas Temperature-°C		C_{out} lbs CO_2/ lb H_2O
				Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	
$60B_1$	735.4	28.3	20.7	27.2	28.7	2.2	0.368	28.3	28.9	0.0033
$60B_2$	735.4	28.3	20.7	27.2	28.7	2.2	0.368	28.3	28.9	0.00277
$61B_1$	735.4	28.9	16.6	27.2	29.3	2.2	0.368	28.3	28.9	0.00361
$62B_1$	735.4	28.9	13.2	27.8	29.7	2.06	0.44	28.3	28.9	0.00406
$63B_1$	735.4	29.1	9.6	27.8	31.1	2.06	0.44	28.3	28.9	0.00577
$63B_2$	735.4	28.9	9.6	28.1	30.9	2.06	0.44	28.3	28.9	0.00609
$64B_1$	735.4	28.9	6.6	27.8	31	2.06	0.44	28.3	28.9	0.00691
$64B_2$	735.4	28.9	6.0	27.8	31	2.06	0.44	28.3	28.9	0.00768
$65B_1$	735.4	28.1	1.0	27.8	28.6	2.2	0.44	27.8	28.3	0.01931
$66B_1$	735.4	28.3	2.0	28.3	29.4	2.2	0.44	28.3	28.9	0.01854
$67B_1$	735.4	28.9	3.3	28.6	32.2	2.2	0.514	28.3	29.4	0.01247
$68B_1$	735.4	28.9	4.0	28.6	32.2	2.2	0.514	28.3	29.4	0.00677
$69B_1$	735.4	28.9	8.0	28.6	30.9	2.06	0.514	28.3	29.4	0.00677

Table 11. Liquid film coefficient for the absorption of CO_2 in water in the disc column.

Run No	R Absorption Rate lb/hr ft^2	$(\Delta C)_{l.m.}$ lb/ft^3	k_L Liquid Film Coefficient lb/(hr ft^2) (lb/ft^3)	(k_L) 20 C° Liquid Film Coefficient lb/(hr ft^2) (lb/ft^3)
$5B_2$	0.0278	0.0480	0.579	0.472
$5B_4$	0.0304	0.0419	0.725	0.582
$5B_5$	0.0304	0.0438	0.694	0.562
$6B_1$	0.0195	0.0360	0.540	0.430
$6B_2$	0.0193	0.0356	0.544	0.434
$6B_3$	0.0195	0.0347	0.562	0.448
$7B_1$	0.0367	0.0486	0.755	0.618
$7B_2$	0.0384	0.0486	0.790	0.650
$8B_1$	0.0465	0.0526	0.884	0.739
$8B_2$	0.0473	0.0522	0.906	0.758
$8B_3$	0.0471	0.0522	0.902	0.754
$9B_1$	0.0588	0.0559	1.052	0.905
$9B_2$	0.0589	0.0555	1.061	0.912
$9B_3$	0.0602	0.0553	1.089	0.935
$10B_1$	0.0682	0.0580	1.176	1.023
$10B_2$	0.0684	0.0618	1.107	0.955
$10B_3$	0.0681	0.0581	1.172	1.011
$11B_1$	0.0792	0.0594	1.332	1.151
$11B_2$	0.0816	0.0578	1.412	1.213
$11B_3$	0.0789	0.0581	1.359	1.170
$12B_1$	0.0102	0.0289	0.353	0.282
$12B_2$	0.00986	0.0286	0.345	0.276
$12B_3$	0.00996	0.0263	0.379	0.304

Table 12. Liquid film coefficient for the absorption of CO_2 in water in the packed column.

Run No	R Absorption Rate lb/hr ft^2	$(\Delta C)_{l.m.}$ lb/ft^3	k_La Liquid Film Coefficient lb/(hr ft^2) (lb/ft^3)	(k_La) 20° C Liquid Film Coefficient lb/(hr ft^2) (lb/ft^3)
$13B_1$	0.805	0.0532	15.32	12.9
$13B_2$	0.815	0.0528	15.436	13.0
$13B_3$	0.790	0.0537	14.711	12.39
$13B_4$	0.792	0.0527	15.028	12.5
$14B_3$	0.572	0.0500	11.440	9.4
$14B_4$	0.576	0.0498	11.566	9.5
$14B_5$	0.565	0.05045	11.192	9.21
$14B_6$	0.570	0.0501	11.377	9.35
$15B_3$	0.360	0.0515	6.990	5.93
$15B_4$	0.360	0.0510	7.059	5.99
$15B_5$	0.372	0.0501	7.425	6.25
$15B_6$	0.374	0.0496	7.540	6.25
$16B_7$	0.195	0.0453	4.305	3.62
$16B_8$	0.202	0.0406	4.975	4.18
$17B_2$	1.030	0.05647	18.240	15.69
$17B_3$	1.050	0.0556	18.885	16.20
$17B_4$	1.050	0.05575	18.82	16.18
$17B_6$	1.030	0.05624	18.35	16.78
$18B_1$	1.330	0.0596	22.3	20.2
$18B_2$	1.300	0.0601	21.3	19.38
$18B_3$	1.320	0.06151	21.45	19.40
$19B_1$	1.630	0.0620	26.3	23.8
$19B_2$	1.600	0.0626	25.6	23.2
$20B_1$	1.920	0.0627	30.65	28.1
$20B_2$	1.920	0.0627	30.65	27.65

Table 13. Liquid film coefficient for the absorption of CO_2 in NaOH solution in the wetted-wall column.

Run No	R' Absorption Rate lb/hr ft^2	$(\Delta C)_{l.m.}$ lb/ft^3	k'_L Liquid Film Coefficient lb/(hr ft^2) (lb/ft^3)	(k'_L) 20° C Liquid Film Coefficient lb/(hr ft^2) (lb/ft^3)
$60B_1$	1.260	0.0831	14.75	12.3
$60B_2$	1.061	0.0831	12.79	10.7
$61B_1$	1.111	0.0819	13.55	11.3
$62B_1$	0.992	0.0813	12.21	10.0
$63B_1$	1.028	0.0798	12.88	9.9
$63B_2$	1.082	0.0798	13.58	10.9
$64B_1$	0.845	0.0742	11.39	9.16
$64B_2$	0.852	0.0742	11.48	9.26
$65B_1$	0.358	0.0820	4.25	3.6
$66B_1$	0.686	0.0810	8.45	6.9
$67B_1$	0.762	0.0780	9.78	7.7
$68B_1$	0.847	0.0780	10.86	8.56
$69B_1$	1.001	0.0794	12.62	10.1

Table 14. Liquid film coefficient for the absorption of CO_2 in NaOH solution in the disc column.

Run No	R' Absorption Rate lb/hr ft^2	$(\Delta C)_{l.m.}$ lb/ft^3	k'_L Liquid Film Coefficient lb/(hr ft^2) (lb/ft^3)	(k'_L) 20° C Liquid Film Coefficient lb/(hr ft^2) (lb/ft^3)
$42B_2$	0.575	0.0789	7.30	5.77
$43B_1$	0.524	0.0794	6.61	5.23
$44B_1$	0.694	0.0776	8.93	6.93
$45B_1$	0.959	0.0740	12.95	10.00
$46B_1$	0.704	0.0768	9.16	7.09
$47B_1$	0.917	0.0787	11.65	9.20
$48B_1$	1.110	0.0798	14.32	11.45

Table 15. Liquid film coefficient for the absorption of CO_2 in NaOH solution in the packed column.

Run No	R' Absorption Rate lb/hr ft^3	$(\Delta C)_{l.m.}$ lb/ft^3	k'_La Liquid Film Coefficient lb/(hr ft^3) (lb/ft^3)	(k'_La) 20° C Liquid Film Coefficient lb/(hr ft^3) (lb/ft^3)
$49B_1$	9.69	0.0796	121.9	97.5
$49B_2$	9.69	0.0794	122.1	97.6
$51B_1$	7.23	0.0771	93.9	74.0
$52B_1$	11.6	0.0802	144.9	116.5
$52B_2$	10.62	0.0789	134.9	109
$53B_1$	16.6	0.0829	200.5	162
$53B_2$	16.38	0.0796	205.9	166
$54B_1$	20.00	0.0798	250.5	200
$54B_2$	20.19	0.0798	253.0	202
$55B_1$	24.01	0.0876	254.2	219
$55B_2$	23.79	0.0876	271.0	217

Table 16. Liquid film coefficient for the absorption of CO_2 in water in the wetted-wall column.

Run No	R Absorption Rate lb/hr ft^2	$(\Delta C)_{l.m.}$ lb/ft^3	k_L Liquid Film Coefficient lb/(hr ft^2) (lb/ft^3	(k_L) 20° C Liquid Film Coefficient lb/(hr ft^2) (lb/ft^3)
$21B_1$	0.0258	0.06668	0.387	0.311
$21B_2$	0.0246	0.06620	0.372	0.2955
$22B_3$	0.01395	0.06589	0.212	0.173
$22B_5$	0.0140	0.06488	0.216	0.175
$22B_6$	0.01393	0.06474	0.2155	0.174
$23B_2$	0.0300	0.06969	0.431	0.348
$23B_3$	0.0296	0.0702	0.422	0.3415
$23B_6$	0.0307	0.06932	0.443	0.358
$24B_1$	0.0370	0.07352	0.504	0.414
$24B_2$	0.0359	0.07353	0.487	0.400
$24B_3$	0.0354	0.07075	0.500	0.417
$25B_3$	0.0589	0.07478	0.787	0.664
$25B_4$	0.0567	0.07262	0.780	0.656
$26B_1$	0.0419	0.07677	0.545	0.547
$26B_2$	0.0482	0.07487	0.645	0.504
$26B_3$	0.0407	0.08059	0.505	0.429
$26B_4$	0.0462	0.07742	0.598	0.504
$27B_1$	0.0525	0.0788	0.666	0.565
$27B_2$	0.0514	0.0773	0.666	0.565
$27B_3$	0.0531	0.0768	0.690	0.585
$28B_2$	0.0606	0.0732	0.830	0.704

Principal Constants of Disc Column

Number of discs	35
Diameter of the disc	1.5 cm (0.594 inches)
Thickness of the disc	0.48 cm (0.188 inches)
Diameter of the Pyrex column	1 1/8 inches
Mean perimeter for liquid flow	0.127 ft.
Equivalent diameter for gas flow	0.059 ft.
Absorption surface (dry)	0.22 sq. ft.

Constants of Wetted-wall Column

Liquid inlet opening gas = 1/16"
Liquid outlet opening gas = 7/64"
Absorption area (dry) = 0.054 sq. ft.

INTERPHASE MASS TRANSFER IN VARIOUS TYPES OF COLUMN

by

I-cheng Chu

B. S. National Taiwan University, China, 1953

AN ABSTRACT OF A THESIS

submitted in partial fulfillment of the

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The application of gas absorption accompanied by a chemical reaction in the liquid phase is attracting more and more attention today in chemical processes where higher purity of gas is demanded and where the gaseous products are to be recovered more completely. However, there are no general equations that can be used to correlate the characteristics of the absorption equipment, the properties of the liquid and gas material, and the hydrodynamic condition of the system for the purpose of design calculations.

The purpose of the present investigation is to find some empirical correlation between the purely physical absorption and the absorption processes accompanied by a chemical reaction in different types of absorption equipment. Three columns: a wetted-wall column, a disc column and a packed column, which constitute a series of flow pattern of progressing complexity, were used and the CO_2 - H_2O and CO_2 - NaOH systems were chosen for the study because of the rapid irreversible reaction between CO_2 and NaOH and because of the well-established fact that the absorption rate is liquid-film controlling.

An empirical equation for the correlation of the effect of chemical reaction on absorption rate was developed in the following form:

$$\frac{R'}{R} = 14.23\ k_L^{-0.697}$$

It is recommended that k_L for the physical absorption be used as the correlating variable in reference to the Reynold's number or the liquid flow rate. The equation is applicable to both wetted-wall and disc columns used in this study and is independent of the individual characteristics of each column. This equation can be used for design calculations of absorption towers where a chemical reaction is involved provided that the k_L and R values for physical absorption are known.

The experimental results are also interpreted as indicating that the effect of chemical reaction on the film coefficient is more pronounced in an absorption where the range of k_L value is lower. In other words the ratio of k'_L (film coefficient with chemical reaction) to k_L is higher in a column of lower k_L value.