Absorption of Ammonia by Acetic Acid Solutions

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Absorption accompanied by rapid, second order, irreversible reaction was studied in a disk column. The chemical system used involving absorption of ammonia by acetic acid has not been reported on before. Results confirm the prediction of two-film and unsteady state theories for this class of two phase reaction; that is the liquid film absorption coefficient is a linear function of ratio of acid normality to interfacial concentration of ammonia. At high acid concentrations the liquid film resistance disappears. In preliminary studies an abrupt transition between laminar and turbulent liquid flow was noted, and as predicted by the unsteady state theory the liquid film coefficient in the laminar region was proportional to the 0.33 power of the liquid flow rate.

Various investigators have proposed theoretical predictions for the kinetics of simultaneous absorption and chemical reaction. Hatta (*1*) and other investigators based their theories on the assumption that resistance to diffusion is mainly within a thin liquid film adjacent to the gas-liquid interface. This film is proposed as having a negligible capacity for holding the solute as compared with the bulk of the liquid where no concentration gradient exists because of complete intermixing.

For a rapid, second order, irreversible chemical reaction in the liquid phase of the type $A + B \rightarrow AB$, a modification of the Lewis-Whitman theory (by Hatta) predicts (*2*) the rate of absorption in such a system after the equilibrium has been established and the process is occurring on a steady state basis as

$$k'_L = (D_A/x_L)\,[1 + (D_B/D_A)\,(C_B/C_{Ai})] \quad (1)$$

Equation (1) in effect states that for physical absorption the liquid film coefficient is equal to D_A/x_L while the quantity in parenthesis shows the effect of chemical reaction on the coefficient. Higbie (*3*) proposed the application of an unsteady state diffusion concept instead of steady state diffusion. He suggested that a better explanation of the process would be to consider the concentration gradients in the liquid phase as functions of time of exposure of the two phases. He further postulated that the liquid film was infinitely thick and capable of retaining the dissolved gas in the region near the interface.

The mathematical development of the unsteady state diffusion theory has been studied by various investigators and a detailed presentation has been made by Sherwood and Pigford (*2*). For a rapid, second order, irreversible reaction cited above the unsteady state diffusion theory leads to the following approximation:

$$k'_L = (2/\sqrt{\pi})\,(D_A/\theta)^{1/2}\,[1 + (D_B/D_A)\,(C_B/C_{Ai})] \quad (2)$$

Equation (2), like Equation (1) of the steady state diffusion theory, predicts that the liquid film coefficient in the presence of chemical reaction increases linearly with the concentration of C_B and decreases with increasing concentration of A at the interface. But Equation (2) in addition incorporates the effect of the time of exposure of the liquid surface.

Various investigators have correlated experimental data with the above Equations (1) and (2). Stephen and Morris (*4*) studied the absorption of chlorine in ferrous chloride solution. They found that the results of this fast, irreversible, second-order reaction were in excellent agreement, qualitatively, with the theory. As predicted by Equations (1) and (2) the effect of reaction on the liquid film mass transfer coefficient could be described by a linear increase in (C_B/C_{Ai}) as shown in Figure 1.

Other investigators (*5, 6, 7*) with other systems have shown that the overall coefficient increases linearly with the increase in acid normality up to a certain strength, beyond which the coefficients were found to be constant. This was assumed to support the two-film theory of Hatta in the liquid phase. If one follows Hatta's derivation, the liquid film disappears at high concentrations of the reacting solute in the liquid phase and the reaction then occurs at the gas-liquid interface. Similar behavior is predicted by the unsteady state theory. The constant value of overall coefficient beyond a certain strength of acid then would indicate that in that region there is no liquid film resistance and the overall coefficient is equal to gas-film coefficient.

APPARATUS

An apparatus which was used by Stephen and Morris (*4*) was also found suitable for the present work. Basically this apparatus consisted of a number of disks of equal size joined to each other at right angles over which the fluid flowed. This arrangement of disks was roughly equivalent to a grid packing. Each time the fluid flowed from one disk to the other there was intermixing within the fluid which roughly reproduced the behavior of fluids in a packed tower. Moreover the coefficients determined in such a column were found to be independent of the length of the column. Another factor favoring the selection of the above equipment was that since the size of the disks was known, the absorption surface could be calculated and the results reported independent of the absorption surface.

The absorption surface in the tower consisted of forty equal sized disks of stainless steel. The disks were 0.57 in. in diam. and 0.155 in. in thickness, and were threaded edge-by-edge on a vertical wire (about 1.6-mm. diam.) The successive disks were maintained at right angles by solder. The threading wire was held tight externally while the disks were enclosed in a glass tube of 1 in. I.D.

The entire length of the glass tower was 78 in., which left a distance of 21 in. as calming sections between the lowermost disk and the gas inlet, and the uppermost disk and the gas exit. The gas inlet and exit were of the same bore, 1 in. I.D., as the tower itself.

A schematic plan of the apparatus is shown in Figure 2. Liquid was supplied from a 15 gal. capacity reservoir (1) which was equipped with a stirrer and constant temperature controller, and was pumped (2) into the constant head vessel (5) after passing through a flask (4) where the inlet temperature of the fluid

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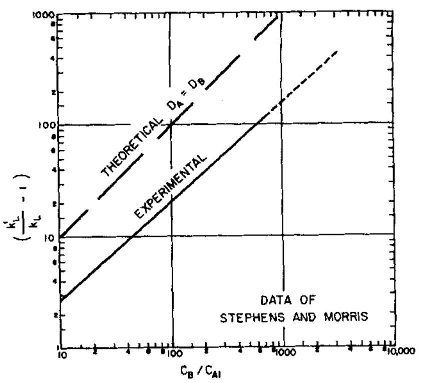

Fig. 1. Experimental correlation of effect of gas and liquid compositions for absorption of chlorine in ferrous-ferric-chloride solution.

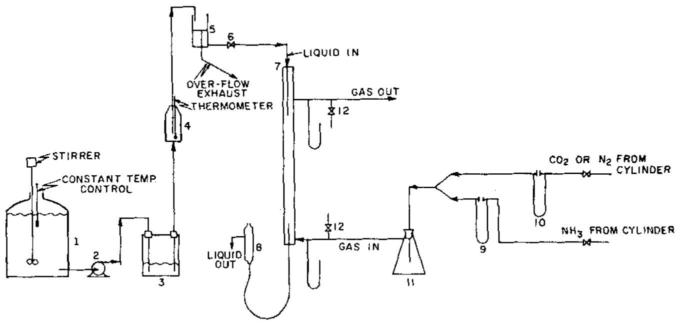

Fig. 2. Schematic of experimental apparatus.

was measured. A flask (3) was provided to compensate for pressure fluctuations from the pump. The liquid level was maintained constant in the constant head vessel (5) by an overflow exhaust tube through which a small amount of liquid overflowed constantly. The liquid from the bottom of this vessel was fed to the feed tube (7) after passing through a control valve (6). This control valve and the constant head vessel maintained a constant flow of fluid. The rate of fluid flow was however measured at the liquid exit from the lute vessel (8) during each experiment by weighing the fluid collected during a known time.

Nitrogen (as the inert gas) and ammonia or carbon dioxide were supplied from cylinders and metered by the capillary flow meters (9) and (10). The two streams of gases were mixed in the empty vessel (11) before being fed to the column.

Inlet and outlet gas samples were taken at the sampling points (12).

EXPERIMENTAL RESULTS

Liquid Film Coefficients—Carbon Dioxide—Water System

Experimental procedure. Carbon dioxide (99 + % pure) was fed into the tower at a rate of approximately 10 st. cu. ft./hr. At such a rate there was always sufficient gas to insure rapid removal of displaced air from the solution.

Distilled water was used to minimize introduction of dissolved carbon dioxide. The water rate was varied from 3.5 lb./hr. to 63 lb./hr. At flow rates lower than 3.5 lb./hr., a considerable amount of incomplete wetting of the disks was encountered.

The amount of carbon dioxide absorbed was determined from a sample taken from the exit liquid.

Inasmuch as pure carbon dioxide gas was passed through the tower no inlet or exit gas samples were taken or were necessary.

A total of 153[*] experimental runs were made in seven sets over a period of one and a half months. In addition to the main variable, the liquid flow rate, other variables were introduced to test their effects, if any. For example the distance between the jet and the first disk was varied from 2.5 to 6 cm., but no significant effect of this variable was observed. Nor did the size of the jet effect the determinations. As the authors had expected the rate of gas flow through the column did not affect the liquid film coefficients either.

Inlet temperature of the liquid was varied from 23° to 33°C.; however the change in temperature between the inlet and the outlet streams was never greater than a fraction of a degree. The coefficients were corrected to a constant temperature of 20°C. by means of the empirical equation $k_L \propto e^{0.023t}$ reported by Sherwood and Halloway (8) based on experiments in packed towers.

The liquid film coefficient, which for this system equals the overall coefficient, was computed from the rate of carbon dioxide absorbed and the log mean driving force in terms of a concentration difference at each end of the column. This was based on the difference between the equilibrium and actual concentrations of the dissolved gas. Data reported in "International Critical Tables" were used to determine equilibrium concentrations for carbon dioxide.

Results. Figure 3 is a graphical plot of liquid film coefficient vs. the wetting rate Γ (defined as the liquid flow rate in pounds per hour divided by the mean perimeter for liquid flow in feet).

It was reported previously by Stephen and Morris that k_L was proportional to $(\Gamma)^{0.7}$ over the range of Γ from 60 to 400 lb./hr. ft. However the present work limits such a correlation to wetting rates equal to or greater than 290 lb./hr. ft. At such flow rates the liquid film coefficient is indeed proportional to the 0.7 power of the wetting rate:

$$k_L = 0.039\ (\Gamma)^{0.7} \qquad (3)$$

Figure 3 shows however that for wetting rates below 180 lb./hr. ft. the coefficients are proportional to 0.33 power of the wetting rate:

$$k_L = 0.197\ (\Gamma)^{0.33} \qquad (4)$$

This checks with the theory for streamline flow of liquid layers where the surface velocity varies as $(\Gamma)^{2/3}$, and the time of exposure varies as $(\Gamma)^{-2/3}$ In accordance with Equation (4) k_L should therefore vary as $(\Gamma)^{1/3}$. It is therefore reasonable to assume that the liquid flow is streamline between the wetting rates of 32 and 180 lb./hr. ft. and in this region

$$k_L \propto (\Gamma)^{0.33} \qquad (5)$$

in accordance with the theory. However with flow rates above 290 lb./hr. ft. there are turbulent effects resulting in k_L varying as $(\Gamma)^{0.7}$. The higher coefficient of 0.7 is most easily explained as an effect of turbulence in the liquid layer with a resultant change in effective diffusivity.

Sherwood and Halloway (8) derived an equation from their experiments with packed towers in terms of liquid film coefficient and the liquid rate

$$\frac{k_L a}{D} = C\left(\frac{L}{\mu}\right)^m \left(\frac{\mu}{\rho D}\right)^n \qquad (6)$$

where C is a constant depending upon the character of packing. The magnitude of the exponent (m) varied from 0.54 to 0.78 for different packings. They recommended a value of 0.5 for (n) based on a general correlation and the prediction of Higbie (3) for unsteady state diffusion between the liquid layer and the gas.

Equation (6) may be rewritten as

$$\frac{k'}{D} = C'\left(\frac{4\Gamma}{\mu}\right)^m \left(\frac{\mu}{\rho D}\right)^{0.5} \ldots\ \text{ft.}^{-1} \qquad (7)$$

Equations (3) and (4) are of the same form as Equation (7) of Sherwood and Halloway, and the exponential variation of k_L with Γ found by both Stephen and Morris and the authors is in the range reported by Sherwood and Halloway. Thus the flow characteristics of the disk tower are similar to those of packed towers, and coefficients derived from a laboratory disk tower may be used as a predictive aid in the design of packed towers.

Equation (7) can be used to correlate liquid film coefficients (in the absence of chemical reaction) for the

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[*] Tabular material has been deposited as document 7160 with the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., and may be obtained for $1.25 for photoprints or for 35-mm. microfilm.

present work. The resulting equations are

for $\Gamma \leq 180$ lb./hr. ft.

$$\frac{k_L}{D} = 103.2\left(\frac{4\Gamma}{\mu}\right)^{0.33}\left(\frac{\mu}{\rho D}\right)^{0.5} \ldots \text{ft.}^{-1} \quad (8)$$

for $\Gamma \geqq 290$ lb./hr. ft.

$$\frac{k_L}{D} = 17.1\left(\frac{4\Gamma}{\mu}\right)^{0.7}\left(\frac{\mu}{\rho D}\right)^{0.5} \ldots \text{ft.}^{-1} \quad (9)$$

It was not found possible to simply correlate the coefficients in the transition range of $180 \leqq \Gamma \leqq 290$ lb./hr. ft.

Gas Film Coefficients—Ammonia-Nitrogen-Water System

Experimental Procedure. The tower characteristics for gas film coefficients were determined logically by picking a system wherein the gas film resistance was the controlling factor. The system ammonia-air-water had been studied by various investigators (*4, 6, 9, 10, 11*) and was selected for the study of the gas film resistance in the experimental disk tower. Moreover the experimentally determined gas film coefficients for this system were needed for later work on absorption accompanied by chemical reaction.

Distilled water was used as the absorbant. Nitrogen was used as the inert dilutant for the ammonia. The inlet composition of the gas mixture was maintained at 3 to 6% ammonia by volume and the gas mixture rate was varied from 24 cu. ft./hr. to 54 cu. ft./hr.

Liquid rate was fixed at about 42 lb./hr. corresponding to a wetting rate of 384 lb./hr. ft. which was well within the turbulent region (as predicted by the carbon dioxide-water experiments). No attempt was made to study the effect of varying wetting rate on gas film coefficients. However Stephen and Morris (*4*) had experimentally established the nature of the variation with liquid flow rate, and thus a qualitative behavior of this variable was known.

Metered ammonia and nitrogen gas streams were joined and passed through a jet enclosed in a mixing bottle. The outlet from this bottle was gradually enlarged to the size of the tower inlet (1 in. in diam.) so the well mixed gas stream entered the tower at tower pressure and with minimum turbulence. Gas samples were collected in 500-ml. gas sample bottles at the inlet and the outlet of the tower. Since there was no dissolved ammonia in the inlet liquid stream, only the outlet liquid was analyzed.

The overall coefficients (K_G) were computed from the rate of absorption of ammonia and the log mean driving force in terms of partial pressures. Solubility data of Pigford and Colburn (*12*) were used in determining the partial pressure of ammonia in equilibrium with the exit stream.

Liquid film coefficients for this system were computed from Equation (9). A diffusivity coefficient of 6.82×10^{-5} sq. ft./hr. for ammonia gas in water and $\left(\frac{\mu}{\rho D}\right)$ value of 570 for a liquid temperature of 20°C. were used (*13*). The coefficients were corrected for the actual mean temperature of the liquid by equation $k_L \alpha e^{0.023t}$ of Sherwood and Halloway (*8*).

Gas film coefficients were computed from the relation

$$1/k_g = 1/K_G - 1/Hk_L \quad (10)$$

Results. The results are graphically presented in Figure 4 where gas film coefficients are plotted as a function of the gas velocity at a constant wetting rate of 384 lb./hr. ft.

The calculated gas velocity was based on the cross-sectional area of the tower after making allowances for the area occupied by disks, but no allowance was made for the thickness of the liquid film. It was difficult to measure or correctly estimate the variable velocity of liquid film, so the reported gas velocities are absoute velocities and are not relative to the liquid interface.

The results were correlated by the relation

$$k_g = 5.88\ (v)^{0.50} \quad (11)$$

The exponent of 0.50 is lower than that found by Stephen and Morris (*4*) (0.67) with similar equipment. However it is within the range of exponents reported by other investigators of this system in packed towers. For instance Sherwood and Halloway (*8*) presented the correlation

$$K_G a \,\alpha\, G^{0.5} \quad (12)$$

for the above system in packed towers, but others (*10, 11*) have reported values as high as 0.8.

Absorption Accompanied by Chemical Reaction—Ammonia-Nitrogen-Dilute Acetic Acid System

The choice of the above system was based on the following considerations:

1. The reaction of ammonia with acetic acid is a fast, irreversible reaction of second order with no known side reactions. Hence the theoretical considerations for such a system could be checked experimentally.

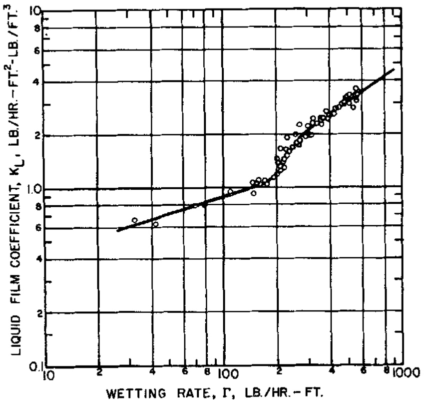

Fig. 3. Liquid film coefficients for absorption of carbon dioxide in water.

2. A similar system, ammonia-sulfuric acid, had been previously studied (*6*) in packed towers and some idea of the type of behavior expected was available for comparison.

3. The experimental techniques developed for the ammonia-water system could be used without much change.

Experimental procedure. Acetic acid solution of the desired normality was prepared in the 15-gal. reservoir and the liquid samples were taken at both the inlet and the outlet of the tower. The inlet samples were taken from the overflow stream from the constant head vessel, while the exit samples were collected from the lute vessel.

All runs were made at a constant liquid rate of 384 lb./hr. ft. (the same rate as used for the ammonia-water system). Liquid acid concentration was varied from 0.4 N to 4.4 N and the gas mixture rate was varied from 24 cu. ft./hr. to 57 cu. ft./hr. containing 5 to 53% ammonia. From two to six runs were made with varying gas composition for each concentration of the acid in the liquid, to arrive at a total of twenty-eight runs.

Wide variations were encountered between the inlet and exit liquid temperatures. These were attributed to the heat of reaction of the system.

Results. The overall mass transfer coefficient K_G was calculated from the rate of ammonia absorption by the liquid and the log mean driving force expressed in terms of partial pressures:

$$K_G = \frac{N_{NH_3}\ \text{lb./hr.}}{(a\ \text{sq. ft.})\,(P_{L.M.})} \quad (13)$$

The partial pressure of ammonia gas in equilibrium with the bulk liquid was assumed to be negligible. Gas film coefficients were taken from either Equation (11) or Figure 4 both of which were based on absorption of ammonia in water. With an overall coefficient, an overall driving force and the gas film coefficient from Equation (11) it was possible to determine the partial pressure of ammonia at the interface, P_{Ai}, from the following relation:

$$K_G\, P_{L.M.} = k_g\, (P_{L.M.} - P_{Ai}) \quad (14)$$

In the absence of any data for the equilibrium partial pressure of ammonia over ammonium acetate solution, it was assumed that it was the same as over ammonia liquor. This seems reasonable for low concentrations of the salt. Solubility data of Pigford and Colburn (*12*) were used to determine the concentration of the solution C_{Ai} of ammonia. C_{Ai} was then used as the driving force to determine the liquid film coefficient in the presence of chemical reaction k'_L from the relation

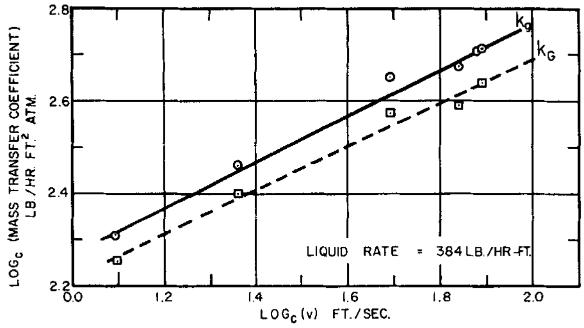

Fig. 4. Mass transfer coefficients for absorption of ammonia in water.

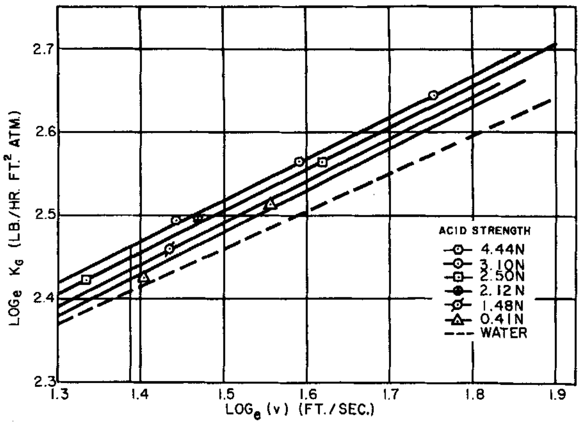

Fig. 5. Overall mass transfer coefficients for absorption of ammonia in acetic acid solution.

$$k'_L = \frac{N_A \text{ lb./hr.}}{(a \text{ sq. ft.})\,(C_{Ai} \text{ lb./cu. ft.})} \quad (15)$$

Finally liquid film coefficients for physical solution were computed from Equation (9), developed from the carbon dioxide-water experiments at the average temperature in the tower (mean of the inlet and the outlet temperature) and at the same flow rates as for the ammonia-acetic acid run in question.

It was found that the results expressed as overall mass transfer coefficients based on a gas phase driving force could be correlated with an average gas velocity in the tower and parametrically as a function of acid normality (see Figure 5). The use of an average velocity in the tower seems appropriate in view of the considerable difference between the velocities at the inlet and the outlet of the tower as a result of the rapid removal of ammonia from the gas stream.

Figure 6 is a graphical representation of the increase in the overall coefficient K_G with the increase in inlet acid concentration of the liquid. The values shown in Figure 6 are at an average velocity of 4 ft./sec. in the tower for a gas concentration of 18 to 23% ammonia. Similar behavior could be demonstrated at any other gas velocity.

In accordance with the two-film theory for simultaneous absorption and chemical reaction, as modified by Hatta, the reaction occurs at the inner boundary of the liquid film. Increasing the solute concentration in the liquid should decrease the thickness of this liquid film until it finally disappears. The chemical reaction then takes place at the gas liquid interface and the gas film resistance is thus wholly controlling.

The rate of absorption therefore should increase linearly with the concentration of reacting solute in the liquid up to some critical value, beyond which the rate should be constant. The same behavior is also predicted by the theory of unsteady state diffusion into a laminar flowing liquid.

The present data, as presented in Figure 6, support the above theories. The overall coefficient K_G increases linearly with the inlet acid strength and becomes constant at approximately 3.0 N strength of the solution. However it is doubtful if there is any critical value of solute strength where the liquid film suddenly disappears (as indicated by the broken line in Figure 6). It seems more logical to assume that the liquid film disappears gradually till it completely vanishes. Since K_G values are the average values for the tower a proper correlation would be to plot them against average concentration of the solute in the tower, that is the mean of the inlet and outlet concentrations. Such a plot is also presented in Figure 6. It may be seen that the data can be fitted by a smooth curve supporting the above reasoning of gradual disappearance of the liquid film.

If one assumes, by the above argument, that the constant value of K_G of 11.75 represents only the gas film coefficient the gas film resistance then is 1/11.75 = 0.0852, while the overall resistance in the absence of chemical reaction as indicated by the intercept at zero acid strength is 1/11.175 = 0.0895. It will be recalled that all of the ammonia acetic acid data were taken at a constant liquid flow rate of 384 lb./hr. ft. in the disk tower. At this liquid rate the above numbers show that the gas film represents about 95% of the total resistance and the liquid film represents the remaining 5%. These results check well with those obtained from ammonia-water experiments wherein the gas film resistance was found to be 94% of the total resistance.

Both Hatta's modified two-film theory for steady state diffusion and the theory of unsteady state diffusion in a laminar flowing liquid further predicted that the liquid film coefficient, in the presence of a fast, second order, irreversible reaction was a function of the residual concentration of the solute B in the liquid and of the interfacial concentration of the diffusing gas A.

Hatta's two-film theory is

$$k'_L = \frac{D_A}{x_L}\left[\left(1 + \frac{D_B}{D_A}\frac{C_B}{C_{Ai}}\right)\right] \quad (1)$$

Unsteady state diffusion theory:

$$k'_L = 2\sqrt{\frac{D_A}{\pi\theta}}\left[\left(1 + \frac{D_B}{D_A}\frac{C_B}{C_{Ai}}\right)\right] \quad (2)$$

Since both D_A/x_L and $2\sqrt{D_A/\pi\theta}$ are equal to k_L (liquid film coefficient for physical absorption) for each of the respective theories the above equations may be written in the identical form:

$$k'_L = k_L\left[\left(1 + \frac{D_B}{D_A}\frac{C_B}{C_{Ai}}\right)\right] \quad (16)$$

or

$$\frac{k'_L}{k_L} - 1 = \left(\frac{D_B}{D_A}\right)\left(\frac{C_B}{C_{Ai}}\right) \quad (17)$$

Equation (17) states that the fractional increase in the liquid film coefficient in the presence of chemical reaction is a linear function of (C_B/C_{Ai}) if a fast, irreversible reaction occurs in a narrow zone within the liquid film and if the rate of absorption is controlled by diffusion of the reactants.

That the present data indeed lend support to the above theories is seen

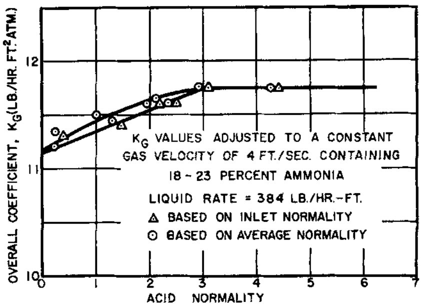

Fig. 6. Effect of acid strength on mass transfer coefficients for absorption of ammonia.

from Figure 7, where $(k'_L/k_L - 1)$ is plotted against (C_B/C_{Ai}). The dotted line indicates the theoretical prediction for $D_B/D_A = 1$ with a slope of unity. The actual slope based on data is 0.77 and the coefficient is given by:

$$k'_L = k_L \left[1 + 0.22 \left(\frac{C_B}{C_{Ai}} \right)^{0.77} \right] \quad (18)$$

The fractional value of 0.22 for the ratio D_B/D_A indicates that the diffusion of ammonia in the liquid is much greater than that of the solute.

In accordance with the data of Sherwood and Pigford (*2*) it seems plausible to assume that the low exponent on (C_B/C_{Ai}) in the empirical Equation (18) is due to the fact that the second order reaction is not instantaneous and that the reaction goes on to a certain extent deep into the liquid. This would result in a lesser influence of (C_B/C_{Ai}) on the coefficients.

A different explanation was offered by Perry (*14*) on data on the carbon dioxide-potassium hydroxide system. The experimentally determined lower values of liquid film coefficient to those predicted by the theory were explained on the basis of an interfacial resistance, that is that no thermodynamic equilibrium existed at the gas liquid interface.

It was difficult to correlate the results of four runs at very low concentrations of the gas (less than 10% ammonia). The results were erratic and tended to give low values of k'_L at high values of (C_B/C_{Ai}), contrary to the prediction of Equation (17). This unexpected dependence of liquid film coefficient k'_L on the concentration of the gas stream and thus C_{Ai}, under conditions such that the rate of absorption was small, would be predicted if the reaction was relatively slow and effectively first order.

CONCLUSIONS

The experimental investigation of simultaneous absorption and chemical reaction involving rapid, second order reaction kinetics resulted in the following conclusions:

As predicted by the theory of unsteady state diffusion into a laminar film, the liquid film coefficient for physical absorption of carbon dioxide in water is proportional to 0.33 power of the liquid rate.

However for the rates where the flow is turbulent the liquid film coefficient is proportional to 0.7 power of the wetting rate. This was attributed to the change in effective diffusivity of the dissolved gas because of turbulence effects in the liquid.

As predicted by the alternate theories of absorption accompanied by chemical reaction, the liquid film coefficient for a rapid, second order, irreversible reaction, such as ammonia in acetic acid, is indeed a linear function of the ratio (C_B/C_{Ai}), that is the absorption is controlled by diffusion only.

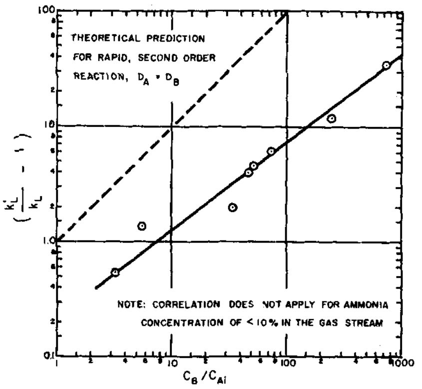

Fig. 7. Experimental correlation of effect of gas and liquid compositions for absorption of ammonia in acetic acid solution.

It has also been experimentally established that the liquid film resistance decreases as the acid strength (C_B) is increased until it essentially vanishes and the process then is completely controlled by gas film resistance.

An interesting point established is the unique dependence of the liquid film coefficient on the concentration of the gas, and hence the absorption driving force, when second order reaction of finite speed occurs in the liquid phase. This would happen when the concentration of the solute is very low in the gas phase and the reaction is slow and therefore essentially first order. The liquid film coefficient was found to decrease with the increasing concentration of the ratio (C_B/C_{Ai}) when the concentration of the solute was less than 10% in the gas phase.

NOTATION

a = absorption surface, sq. ft.
A = solute component in the gas phase
B = reaction component in the liquid phase
C_A = concentration of component A, lb./cu. ft.
C_B = concentration of component B, lb./cu. ft.
D = diffusivity, sq. ft./hr.
d_e = equivalent diameter of the disks
D_e = equivalent diameter of the tower for gas flow
e = base of natural logarithms, 2.718
G = superficial velocity, lb./hr. sq. ft.
H = Henry's law constant, lb./cu. ft. atm.
i = interface (subscript)
K_G = overall gas phase coefficient, lb./hr. sq. ft. atm.
k_g = gas film coefficient, lb./hr. sq. ft. atm.
K_Ga = overall coefficient, lb. mol./hr. cu. ft. atm.
k_L = liquid film coefficient for physical absorption, lb./hr. sq. ft. —lb./cu. ft.
k'_L = liquid film coefficient for absorption accompanied by chemical reaction, lb./hr. sq. ft.—lb./cu. ft.
k_La = liquid film coefficient, lb. mol./hr. cu. ft.—lb. mol./cu. ft.
L = liquid rate, lb./hr. sq. ft.
N = normality
N_A = rate of absorption of solute A, lb./hr.
P = barometric or total pressure, atm.
$P_{L.M.}$ = log mean driving force in terms of partial pressures, atm.
p = average pressure of the solute gas, atm.
p_1 = tower inlet gas phase pressure of solute, atm.
p_2 = tower outlet gas phase pressure of solute, atm.
t = temperature, °C.
v = Average gas velocity, ft./sec.
x_L = liquid film thickness, ft.
Γ = wetting rate, lb./hr. ft.
ρ = density, lb./cu. ft.
θ = time, sec.
μ = viscosity, lb. (mass)/ft. hr.

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