ABSORPTION OF CO_2 BUBBLES BY AQUEOUS MONOETHANOLAMINE SOLUTIONS

A THESIS

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SUMMARY

Studies were made on the absorption of carbon dioxide bubbles into aqueous monoethanolamine (MEA) solutions. Determinations were made from experimental data of the area and mass of the CO_2 bubbles as a function of time. This work was done in support of a Ph.D. thesis investigation by J. W. Mottern. Results of the calculations are presented in Figures 2 and 3 and Tables I through VI.

An equation giving the cube root of the mass of a CO_2 bubble as a linear function of time was used and found to be valid,

$$N^{1/3} = N_o^{1/3} + C_2 t$$

The N_o constant depended on the initial mass of the bubble, and the C_2 constant on temperature and pressure of the system. Rate of absorption is associated with C_2.

In the development of the above equation, the bubbles were assumed spherical and a correction was applied to account for the deviation of the actual oblate spheroid shape from the assumed spherical shape.

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CHAPTER I

ABSORPTION OF CO_2 BUBBLES BY AQUEOUS MONOETHANOLAMINE SOLUTIONS

INTRODUCTION

Extraction of acidic components such as CO_2 from gas streams with aqueous solutions of monoethanolamine is becoming increasingly important in industry. At present, the amount of technical data available on this absorption process is limited. During the last decade, however, several investigations have been carried out to determine the mechanism for absorption in this system.

This investigation is part of a research program concerned with bubble dynamics and gas-liquid interface mass transfer being carried out in the Department of Chemical Engineering at the University of Tennessee.

Previous theses on this work have been presented by Atadan (1), Griffith (2) and (3), and Mottern (5). The author's work is presented as was that of Groves and Hawkins (4) in support of a doctoral dissertation, "Interface Phenomenon is Gas-Liquid Mass Transfer Operations," by J. W. Mottern.

It is the specific objective of the present work to develop a quantitative description for the absorption of CO_2 bubbles by aqueous MEA solutions. This will involve the determination of an equation giving the mass of a CO_2 bubble as a function of absorption time in the CO_2 - MEA system.

Chapter II is devoted to the development of the equations describing

the absorption process. Chapter III gives a description of the experimental procedure used. The results, conclusions, and recommendations are given in Chapters IV and V. The Appendix contains tabulations of the mass and area of the CO_2 bubbles as a function of time, sample calculations, and a summary of the notation used.

CHAPTER II

THEORY

In order to present a discussion of the theory applicable to the present investigation, it is desirable to briefly give the scope of Mottern's work. In his Master's thesis, Mottern determined a steady-state rate equation for CO_2 transfer in the CO_2 - MEA system. Transfer was across a horizontal interface into a stirred aqueous phase. The rate was expressed in terms of the bulk liquid composition (MEA normality and degree of carbonation) and bulk gas-phase composition. The steady state gas absorption rate was found to vary with both MEA normality and degree of carbonation. It was found that the results could be explained in terms of a laminar film diffusion mechanism with an infinitely fast second-order chemical reaction.

Mottern has continued the investigation of absorption in the CO_2 - MEA system in his doctoral dissertation, "Interface Phenomenon in Gas-Liquid Mass Transfer Operations." This investigation includes two methods of measuring the absorption rate for the CO_2 - MEA system. The methods are: (1) Continuation of experimental work performed in the Master's investigation; and (2) Measurement of the absorption rate of CO_2 bubbles by experimental determination of the size of the CO_2 bubbles as a function of time during the absorption process. The CO_2 bubbles are suspended in a downward moving stream of MEA solution.

The second method is the one studied in this investigation. Before going into the theory, it is desirable to consider some general cases of gas absorption. In this consideration, possibilities for the mechanism of absorp-

tion are cited and discussed.

Two possibilities for the mechanism of absorption in the system are a modification of the Lewis-Whitman Stagnant Film Theory by Hatta and the surface renewal theory. Hatta's modification of the Lewis-Whitman Film Theory (see Sherwood and Pigford (8)) is based on the assumption that, in a gas-liquid contacting system, there exists a stagnant film of liquid adjoining the gas-liquid interface. It is assumed that the liquid outside of this film is well mixed so that the resistance to mass transfer within the liquid phase is confined to the liquid film. An infinitely fast, second order, irreversible chemical reaction occurs between the liquid and gas. After the reaction starts at the liquid-gas interface, the region of film nearest the gas side becomes depleted of MEA. This makes it possible for the CO_2 to move through part of the liquid film before meeting the MEA diffusing in from the opposite direction. The zone of reaction of gas and liquid therefore moves away from the interface and assumes a stationary position at steady state. At this position, the diffusion of the gas to the liquid is equal to the rate of diffusion of the liquid in the opposite direction. During the time required for the reaction to reach this steady-state position, the absorption rate falls rapidly.

The surface-renewal theory gives two models that possible explain the absorption phenomenon in gas-liquid systems. The models also may be applied to the problem in this investigation somewhat more readily than the previous theory.

In discussion of the first surface-renewal model, it is convenient to

picture a droplet of liquid falling vertically, and coming in contact with a gas bubble. The liquid droplet is then assumed to adhere to the bubble, and to move around half the circumference of the bubble. During this time, the liquid is absorbing and reacting with the gas. When the liquid has moved to the bottom of the gas bubble, it drops off, and the process is repeated.

The second surface-renewal model is concerned with packing material in a column. The packing material may be beryl saddles, raschig rings, or other suitable materials. Each piece of packing is covered with a thin film of liquid. Gas moving up through the column contacts the liquid film. During this time, a reaction occurs between the liquid and gas on the packing. However, the liquid moves down over the packing unit very fast; so unsteady state exists. As the liquid moves from one packing unit to another, it becomes well mixed before the process is repeated.

Now that a general picture of the gas absorption problem has been presented, it is necessary to determine how the findings in the CO_2 - MEA system at hand relate to it. The relation will be expressed by equations giving the mass and area of the bubble as a function of time.

Before derivations of the equations can be made, it is well to give a brief account of the experimental work in determining the dimensions of the CO_2 bubbles. The experimental procedure was as follows: MEA solution was allowed to flow downward through an absorption cell, and CO_2 bubbles were emitted from a small capillary opening at the bottom of the cell. The MEA solution flowing down through the diverging cross-section cell was adjusted such that its motion counterbalanced the rising velocity of the gas bubble.

Thus, the CO_2 bubble was held almost stationary in the cell during a run. Motion pictures were taken of the single bubbles as they were absorbed in the solution. The pictures were enlarged and determinations were made of the apparent horizontal and vertical diameters of the CO_2 bubbles. Time was directly related to the numbers of the frames on the motion picture film.

With the above information, it is possible to develop an expression for the mass of a CO_2 bubble at a given time. Peebles and Garber (6) stated that for Reynolds Numbers less than 5,000, a CO_2 bubble is generally in the shape of an oblate spheroid. This case is assumed to hold here. An oblate spheroid is a surface generated by rotating an ellipse about its minor axis. The volume for an oblate spheroid is given by (9),

(1) $V = 4/3\pi a^2 b$

where:

a = length of major axis

b = length of minor axis

In terms of the horizontal and vertical diameters of a bubble, equation (1) is:

(2) $V = 4/3\pi(\frac{HD}{2})^2 (\frac{VD}{2})$

or:

(3) $V = \pi/6 (HD)^2 (VD)$

where:

HD = horizontal diameter

VD = vertical diameter

However, apparent rather than true horizontal and vertical diameters were found by measurements from the photographs in the experimental work.

So a scale factor must be used in the actual volume calculation. The factor is obtained from the true diameter of the capillary tube and the tube's image diameter as measured. The true capillary diameter was found to be 0.2547 inches.

The next step consists of developing an equation for volume which takes into account the scale factor. Let:

V = true volume of bubble in $ft.^3$

AHD = apparent horizontal diameter

AVD = apparent vertical diameter

TCD = true capillary diameter

ACD = apparent capillary diameter

Then from equation (3):

$$(4) \qquad V = \frac{\pi}{6(1728)} \frac{(TCD)^3}{(ACD)^3} (AHD)^2 (AVD) \ ft.^3$$

where $(TCD)^3/(ACD)^3$ is the desired scale factor. Simplification of (4) leads to:

$$(5) \qquad V = 3.03 \times 10^{-4} \frac{(TCD)^3}{(ACD)^3} (AHD)^2 (AVD)$$

With this expression for volume, it is now possible to derive an equation giving the mass of a CO_2 bubble. Assume that CO_2 is an ideal gas for which mass in pound-moles is given by:

$$(6) \qquad N = \frac{PV}{R_G T}$$

where:

P = pressure, cm. of Hg

T = absolute temperature, ^oR

R_G = gas constant, cm. Hg . $ft.^3$/lb. mole . ^oR

but:

(7) $T = 460 + t$

where t = test temperature, $^{\circ}F$.

Substitution of equations (5) and (7) and the value for R into (6) gives:

$$(8) \quad N = \frac{(P)\ 3.03 \times 10^{-4}\ \frac{(TCD)^3}{(ACD)^3}\ (AHD)^2\ (AVD)}{55.45\ (460 + t)}$$

Finally, equation (8) may be simplified to:

$$(9) \quad N = \frac{9.06 \times 10^{-8}\ (P)\ (AHD)^2\ (AVD)}{(ACD)^3\ (460 + t)}$$

Up to now, enough information has been developed to plot N versus time curves from the experimental data. Now it is necessary to calculate the absorption rate (N_A), given by:

$$(10) \quad N_A = \frac{R}{A}\ \frac{\text{lb. moles}}{\text{time . area}}$$

where:

(11) $R = -dN/dt$ in lb. moles/time

A = surface area of bubble in $ft.^2$

The formula for the area of an oblate spheroid in terms of a and b as previously defined is (9):

$$(12) \quad A = 2\pi\left[a^2 + \frac{ab^2}{\sqrt{a^2-b^2}}\ \ln\left(\frac{\sqrt{a^2-b^2} + a}{b}\right)\right]$$

For the case where a = b, the formula becomes that for the area of a sphere where,

(13) $A = 4\pi b^2$

For the case of a prolate spheroid, or where b is greater than a, the area is given by:

(14) $$A = 2\pi\left[a^2 + \frac{ab^2}{\sqrt{b^2-a^2}}\sin^{-1}\frac{\sqrt{b^2-a^2}}{b}\right]$$

When equation (12) is written in terms of the quantities measured in experimental work, the new expression is:

(15) $$A = \frac{\pi (TCD)^2}{2(ACD)^2(144)}\left[(AHD)^2 + \frac{AHD(AVD)^2}{\sqrt{(AHD)^2-(AVD)^2}}\ln\frac{\sqrt{(AHD)^2-(AVD)^2}+AHD}{AVD}\right] ft^2$$

where $(TCD)^2/(ACD)^2$ is the necessary scale factor. Equation (15) reduces to:

(16) $$A = \frac{7.075 \times 10^{-4}}{(ACD)^2}\left[(AHD)^2 + \frac{(AHD)(AVD)^2}{\sqrt{(AHD)^2-(AVD)^2}}\ln\frac{\sqrt{(AHD)^2-(AVD)^2}+AHD}{AVD}\right]$$

When AHD = AVD, equation (13) is used along with the above scale factor to give:

(17) $$A = \frac{1.415 \times 10^{-3}}{(ACD)^2}(AHD)^2$$

For the case where AVD is greater than AHD, equation (14) is used along with the scale factor to give the expression:

(18) $$A = \frac{7.075 \times 10^{-4}}{(ACD)^2}\left[(AHD)^2 + \frac{(AHD)(AVD)^2}{\sqrt{(AVD)^2-(AHD)^2}}\sin^{-1}\frac{\sqrt{(AVD)^2-(AHD)^2}}{(AVD)^2}\right]$$

Equation (9) has made possible the plotting of N versus time curves. It is now convenient to derive an equation for $N^{1/3}$ as a function of t. This will lead to a method for computation of N_A.

Proceeding with the development of an expression for $N^{1/3}$, equations (10) and (11) show that:

$$N_A = \frac{R}{A} \quad \frac{\text{lb. moles}}{\text{time.area}}$$

and

$$R = \frac{-dN}{dt}$$

or

(19) $R = N_A A.$

The area of a spherical bubble is given by,

$$A = 4\pi a^2$$

where:

a = bubble radius

Substitution of this expression for A into (19) gives:

(20) $R = 4N_A \pi a^2$

Furthermore, from equations (11) and (20),

(21) $\frac{-dN}{dt} = 4N_A \pi a^2$

The volume of a sphere is given by:

$$V = \frac{4}{3} \pi a^3$$

or

(22) $a^3 = \frac{3V}{4\pi}$

From equation (6),

(23) $V = \frac{NR_G T}{P}$

Then substitution of (23) into (22) gives:

$$a^3 = \frac{3NR_G T}{4\pi P}$$

or

$$(24) \quad a^2 = \left[\frac{3NR_GT}{4\pi P}\right]^{2/3}$$

When equations (20), (21), and (24) are combined,

$$(25) \quad \frac{dN}{dt} = -N_A 4\pi \left[\frac{3NR_GT}{4\pi P}\right]^{2/3}$$

Separation of the variables and integration gives:

$$(26) \quad N^{1/3} - N_o^{1/3} = -\left[\frac{4\pi}{3}\right]^{1/3} \left[\frac{R_GT}{P}\right]^{2/3} \times \int_o^t N_A dt$$

Further integration gives the expression,

$$(27) \quad N^{1/3} - N_o^{1/3} = C_1 N_A t$$

where:

$$C_1 = -\left[\frac{4\pi}{3}\right]^{1/3} \left[\frac{R_GT}{P}\right]^{2/3}$$

also let:

$$(28) \quad C_2 = C_1 N_A = -\left[\frac{4\pi}{3}\right]^{1/3} \left[\frac{R_GT}{P}\right]^{2/3} \times N_A$$

Substitution of (28) into (27) and rearrangement gives,

$$(29) \quad N^{1/3} = N_o^{1/3} + C_2 t$$

Equation (29) is an equation for a straight line plot of $N^{1/3}$ versus t where:

$N_o^{1/3}$ = intercept on vertical axis

C_2 = slope of line

Equation (29) holds if the CO_2 bubbles are spherical shaped and if N_A is constant. Since in most cases, the bubbles were actually oblate spheroids, some error is encountered in assuming that the above reasoning holds. The

amount of error for a particular experimental run may be partially accounted for in the following manner.

Consider the case of an oblate spheroid versus a sphere. Let:

A = area of oblate spheroid

A_s = area of sphere

V = volume of oblate spheroid

V_s = volume of sphere

From equation (12):

$$A = 2\pi \left[a^2 + \frac{ab^2}{\sqrt{a^2 - b^2}} \ln \frac{\sqrt{a^2 - b^2} + a}{b} \right]$$

and from equation (1),

$$V = \frac{4}{3}\pi a^2 b$$

For a sphere of radius a,

$$A_s = 4\pi a^2$$

and

$$V_s = \frac{4}{3}\pi a^3$$

as previously stated,

a = horizontal radius

b = vertical radius

For an oblate spheroid, $a > b$.

Then let:

$$\frac{a}{b} = 1 + \Delta$$

where:

$$\Delta > 0$$

When (12) is rewritten in terms of Δ,

$$(30) \quad A = 2\pi b^2 \left[1 + 2\Delta + \Delta^2 + \frac{1+\Delta}{\sqrt{2\Delta + \Delta^2}} \ln(\sqrt{2\Delta + \Delta^2} + 1 + \Delta) \right]$$

or:

$$(31) \quad A = 2\pi a^2 \left[1 + \frac{1}{(1+\Delta)\sqrt{2\Delta + \Delta^2}} \ln(\sqrt{2\Delta + \Delta^2} + 1 + \Delta) \right]$$

Now when the area of the sphere is based on a rather than b, and it is noted that $2\pi a^2 = A_s/2$,

$$(32) \quad A = \frac{A_s}{2} \left[1 + \frac{1}{(1+\Delta)\sqrt{2\Delta + \Delta^2}} \ln(\sqrt{2\Delta + \Delta^2} + 1 + \Delta) \right]$$

For convenience, define,

$$(33) \quad F = 1 + \frac{1}{(1+\Delta)\sqrt{2\Delta + \Delta^2}} \ln(\sqrt{2\Delta + \Delta^2} + 1 + \Delta)$$

With reference to equation (19), the starting point for the derivation of equation (29), and with a slight rearrangement,

$$(34) \quad \frac{dN}{dt} = -N_A \times A$$

where (34) now becomes:

$$(35) \quad \frac{dN}{dt} = -N_A \frac{4\pi a^2}{2} \times F$$

The quantity a must be in terms of volume as before. Now, however, the volume of the ellipsoid must be used. From equation (1),

$$V = \frac{4}{3} \pi a^2 b$$

while:

$$V_s = \frac{4}{3} \pi a^3$$

but:

$$\frac{a}{b} = 1 + \Delta$$

or:

$$(36) \quad b = \frac{a}{1 + \Delta}$$

Substitution of (36) into (1) gives:

$$(37) \quad V = \frac{\frac{4}{3} \pi a^2 b}{1 + \Delta} = \frac{V_s}{1 + \Delta}$$

When the ideal gas law is introduced into equation (37) to solve for a^2,

$$V = \frac{\frac{4}{3} \pi a^3}{1 + \Delta} = \frac{NR_GT}{P}$$

and:

$$(38) \quad a^2 = \left[\frac{NR_GT}{P}\right]^{2/3} (1 + \Delta)^{2/3} \left[\frac{3}{4\pi}\right]^{2/3}$$

Substitution of (38) into (35) gives:

$$(39) \quad \frac{dN}{dt} = -N_A 2\pi \left[\frac{NR_GT}{P}\right]^{2/3} (1 + \Delta)^{2/3} \left[\frac{3}{4\pi}\right]^{2/3} \times F$$

If the definition, $F' = (1 + \Delta)^{2/3} F$ is used, integration of (39) will give:

$$(40) \quad \frac{1}{3}(N^{1/3} - N_o^{1/3}) = 2\pi \left[\frac{R_GT}{P}\right]^{2/3} \left[\frac{3}{4\pi}\right]^{2/3} (F')(T)$$

only if F' is constant.

Table VII in the Appendix shows values of F' obtained for a set of experimental data. From these values it can be seen that the variation of F' is very small. Thus it is concluded that equation (40) holds for the data obtained in this investigation.

CHAPTER III

DESCRIPTION OF INVESTIGATION

The experimental part of this investigation was carried out by Mottern on an apparatus located in Estabrook Hall, Room 131. A flow sheet for the complete experimental process is given in Figure 1.

The experimental procedure was as follows. MEA solution was pumped from a reservoir, A to the absorption cell, E. The MEA absorbed heat as it was pumped so that it was necessary to send the solution through a heat exchanger, C, to remove the heat of pumping. A rotameter was installed at D to measure the flow rate of the MEA solution.

The MEA then was allowed to flow through the absorption cell, where it came in contact with the CO_2 bubbles emitted from the capillary tube, G. The CO_2 bubbles were produced by a CO_2 generator at I. As the MEA solution and a CO_2 bubble came into contact with one another in the absorption tube, the MEA absorbed the CO_2 bubble. The MEA velocity had been previously adjusted so that the bubble remained stationary in the diverging flow chamber of the absorber.

Motion pictures were taken of each bubble from the time it was emitted from the capillary tube until it was completely absorbed or until it was lost from the field of view. A clock was included in the picture so that the size of the bubble could be observed at known intervals of time.

A Bell-Howell Traid 70 camera using Kodak Tri-X Negative film was

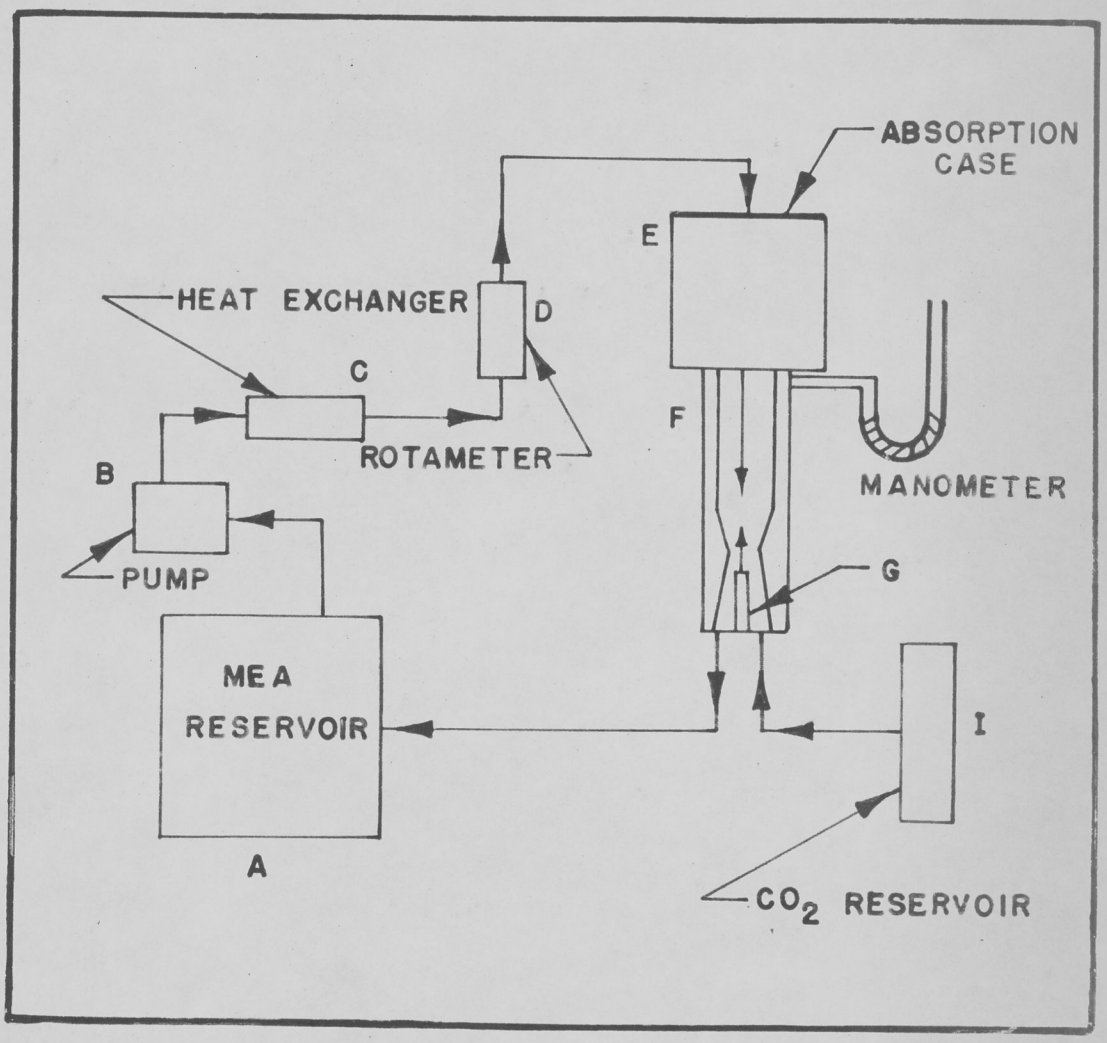

Figure 1. Flow Sheet for the CO_2 - MEA Absorption Process

used to make the pictures. The pictures of the CO_2 bubbles were enlarged and the apparent horizontal and vertical diameters measured at different intervals of absorption time.

CHAPTER IV

PRESENTATION AND DISCUSSION OF RESULTS

The experimental results included data from 5 reels of film, numbers 3, 4, 6, 7, and 8. Of the reels, numbers 3, 6, and 8 have been taken as most representative of all the data obtained. Calculations to determine the area and the mass of the CO_2 bubbles as a function of time were then made for data from the three reels.

Results of the determination of the area of the bubbles with increasing time are given in Table I of the Appendix. Take 9 of Reel 6 gave the best results while Take 3 of Reel 3 gave the worst results for the experiment as a whole.

The best and worst values for N as a function of time for the three reels are given in Tables II through VI in the Appendix. The best values of N were those which gave a uniform curve with very little scattering of points when plotted versus time. The worst values of N were those which gave a wide scattering of points when plotted.

A plot of N versus t for the best results obtained is given in Figure 2. In Figure 3 is given a plot for the worst results obtained in the determination of N. On comparison of the two plots, the variation of experimental results during the investigation may be readily seen.

In addition to the work shown in this thesis, plots of $N^{1/3}$ versus t were made for many sets of the experimental data. It was verified that the plots gave approximately straight lines, therefore supporting the theory

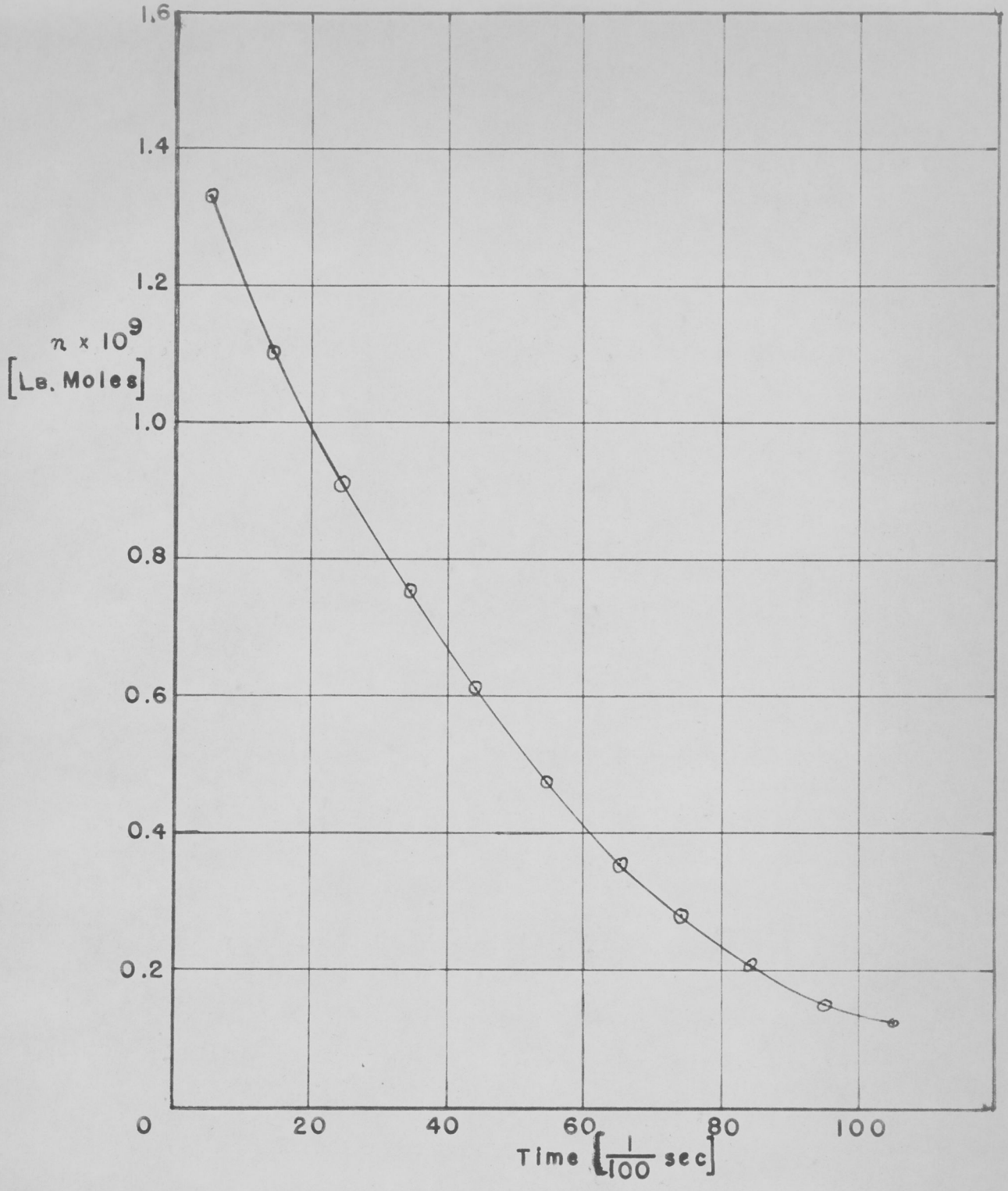

Figure 2. A Plot of N Versus t for Reel 8, Take 9 (2)

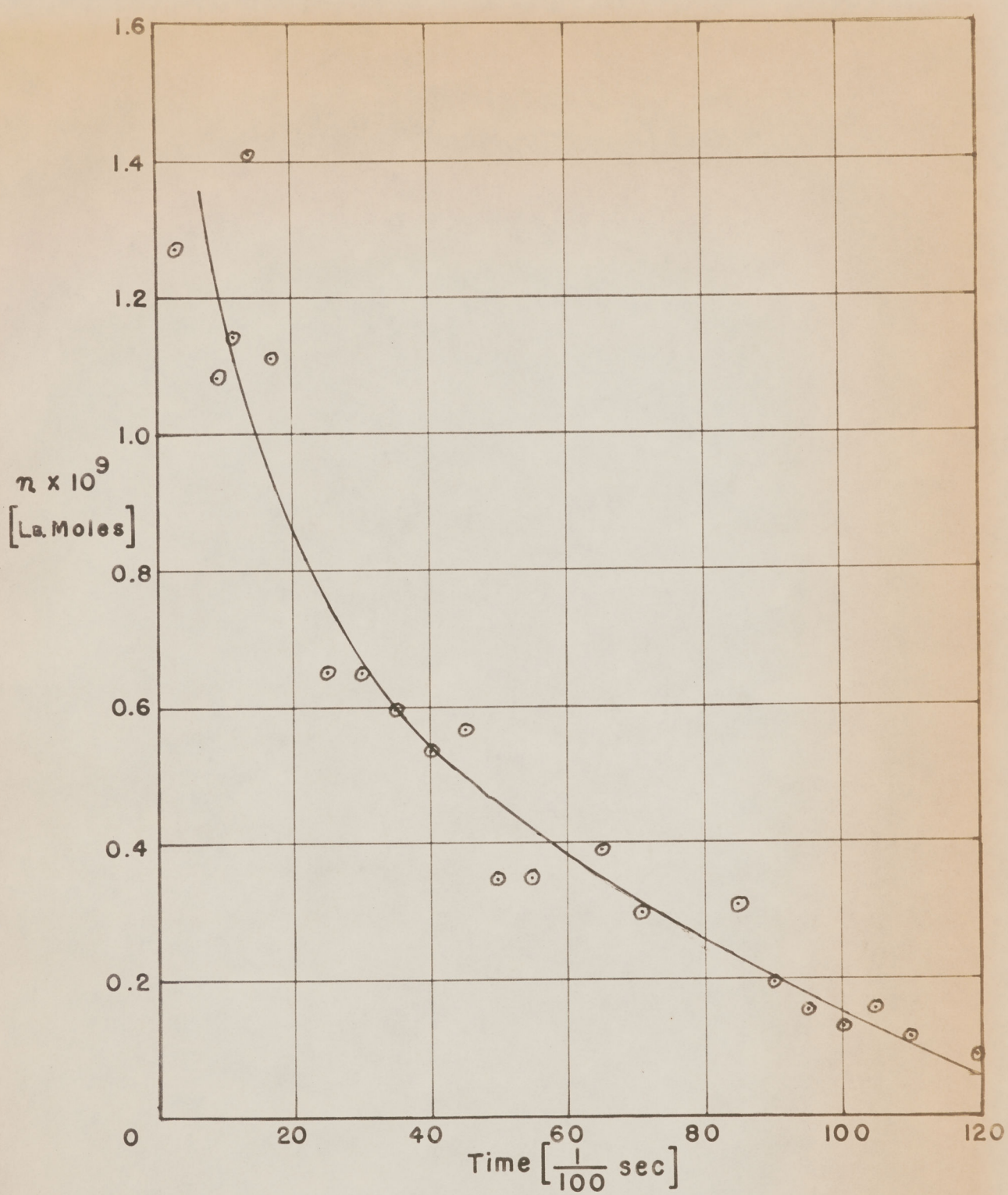

Figure 3. A Plot of N Versus t for Reel 3, Take 7

developed for such a plot in Chapter II. Straight line equations for the plots were found by the method of least squares. The equation determined was of the form:

$$N^{1/3} = mt + B$$

The above equation is analogous to equation (29) in Chapter II, where now:

$$m = C_2$$

$$B = N_o^{1/3}$$

when a comparison is made between the two equations. Plots of $N^{1/3}$ versus t and a complete discussion of the associated theory are given in Mottern's doctoral dissertation.

For an estimation of the error involved in assuming that equation (29) (see Chapter II) holds, values were found for Δ, $(1 + \Delta)^{2/3}$, and F'. It has been shown in Chapter II that F' varies only slightly for an experimental run. Therefore, it is concluded that the error involved in assuming that the CO_2 bubbles are spherical is quite small, and is constant for a given experimental run. Other errors, both systematic and random, affect the accuracy and precision obtained. However, a discussion of the latter factors is beyond the scope of this investigation.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The conclusions formed from a consideration of the experimental data obtained from the CO_2 - MEA system are as follows:

1. The CO_2 bubbles may be treated as being spherical in the development of equations descriptive of the absorption process. A constant correction factor is shown to account for the deviation of an oblate spheroid from a sphere.
2. For the CO_2 - MEA system, the expression for the mass of a CO_2 bubble as a function of time is given by:

$$N^{1/3} = N_o^{1/3} + C_2 t$$

where the constants depend on the initial mass of the bubble, temperature, pressure, and the absorption rate. The absorption rate may thus be evaluated from C_2. The fact that C_2 is constant, indicates that absorption rate is independent of bubble size.

3. It is recommended that further work be done to investigate the geometry of the CO_2 bubbles and the absorption rate for them while they are oscillating from the effects of breaking away from the capillary tube.

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LIST OF REFERENCES

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APPENDICES

APPENDIX A

EXPERIMENTAL DATA

TABLE I

BEST AND WORST RESULTS FOR AREA OF BUBBLES
AS A FUNCTION OF TIME

Reel 6, Take 9 (Best Results)			
Time ($\frac{1}{100}$ sec)	$Ax10^4 (ft)^2$	Time	$Ax10^4$
0	2.896	55	1.254
4	2.574	60	1.236
$9\frac{1}{2}$	2.364	64	1.139
15	2.134	69	0.9673
20	2.150	74	0.8536
27	1.970	79	0.7825
34	1.806	84	0.6738
39	1.675	89	0.5971
44	1.471	94	0.4662
$49\frac{1}{2}$	1.373	100	0.3390

Reel 3, Take 3 (Worst Results)			
Time ($\frac{1}{100}$ sec)	$Ax10^4 (ft)^2$	Time	$Ax10^4$
0	2.900	63	1.390
2	2.969	68	1.389
6	2.985	73	0.955
13	2.765	78	1.001
16	2.721	83	1.088
$22\frac{1}{2}$	2.685	88	0.908
28	2.330	93	0.733
33	1.880	98	0.785
38	2.061	103	0.472
43	2.110	108	0.772
49	1.566	113	0.589
58	1.465	118	0.761

TABLE II

BEST RESULTS FOR DETERMINATION OF N
AS A FUNCTION OF t FROM REEL 3

Take 21			
Time ($\frac{1}{100}$ sec)	$Nx10^9$(lb.moles)	Time	$Nx10^9$
0	1.42	80	0.301
5	1.035	85	0.249
15	0.943	90	0.261
20	0.982	95	0.236
25	0.834	100	0.173
30	0.725	105	0 173
35	0.585	110	0.166
40	0.543	115	0.146
45	0.520	125	0.114
50	0.520	130	0.125
55	0.446	134	0.097
60	0.417	140	0.070
65	0.419	155	0.034
70	0.376	161	0.051
75	0.346		

TABLE III

WORST RESULTS FOR N FROM REEL 3

Take 7			
Time ($\frac{1}{100}$ sec)	$Nx10^9$ (lb. moles)	Time	$Nx10^9$
0	1.025	55	0.349
3	1.27	65	0.39
9	1.08	71	0.298
$11\frac{1}{2}$	1.142	$77\frac{1}{2}$	0.274
14	1.41	85	0.308
17	1.11	90	0.192
25	0.65	95	0.151
30	0.65	100	0.128
35	0.59	105	0.159
40	0.534	110	0.116
45	0.569	115	0.081
50	0.349		

TABLE IV

BEST RESULTS FOR N FROM REEL 6

Take 13			
Time ($\frac{1}{100}$ sec)	$Nx10^9$ (lb. moles)	Time	$Nx10^9$
0	1.270	55	0.4218
4	1.085	60	0.3528
9	0.9602	$64\frac{1}{2}$	0.3083
$14\frac{1}{2}$	0.8493	69	0.2952
$19\frac{1}{2}$	0.7915	74	0.2611
25	0.7169	82	0.2007
30	0.6862	89	0.1690
39	0.5919	95	0.1223
$44\frac{1}{2}$	0.5098	99	0.1214
50	0.4850	104	0.1062
		109	0.08658

TABLE V

WORST RESULTS FOR N FROM REEL 6

Take 16 (2)			
Time ($\frac{1}{100}$ sec)	$Nx10^9$ (lb. moles)	Time	$Nx10^9$
0	1.487	70	0.3638
10	1.236	80	0.2600
20	0.8630	90	0.2054
24	1.004	95	0.1837
48	0.6145	100	0.1723
55	0.4839	105	0.1350
60	0.5170	110	0.09293
64	0.4286		

TABLE VI

BEST AND WORST RESULTS FOR N FROM REEL 8

Take 9 (2) (Best Results)			
Time ($\frac{1}{100}$ sec)	$Nx10^9$(lb. moles)	Time	$Nx10^9$
0	1.573	55	0.4787
5	1.330	$65\frac{1}{2}$	0.3547
15	1.108	75	0.2895
25	0.9153	85	0.2104
35	0.7592	$95\frac{1}{2}$	0.1507
45	0.6132	105	0.1294

Take 13 (2) (Worst Results)			
Time ($\frac{1}{100}$ sec)	$Nx10^9$(lb. moles)	Time	$Nx10^9$
0	1.612	$45\frac{1}{2}$	0.6761
5	1.495	55	0.5336
11	1.191	65	0.3682
15	1.147	75	0.2389
25	0.9040	85	0.1480
$35\frac{1}{2}$	0.8682	95	00.8466

TABLE VII

RESULTS OF CALCULATIONS OF F AND F' FOR
TAKE 4 OF REEL 6

Δ	$(1 + \Delta)^{2/3}$	F	F'
0.27	1.17	1.70	1.99
0.09	1.06	1.88	1.99
0.19	1.12	1.79	2.00
0.12	1.08	1.86	2.01
0.16	1.10	1.96	2.16
0.14	1.09	1.85	2.02
0.14	1.14	1.85	2.02
0.10	1.07	1.88	2.01
0.14	1.09	1.85	2.02
0.09	1.06	1.88	1.99
0.07	1.05	1.91	2.00
0.10	1.07	1.88	2.01
0.09	1.06	1.88	1.99
0.05	1.03	1.94	2.00
0.04	1.03	1.95	2.01
0.05	1.03	1.94	2.00

APPENDIX B

SAMPLE CALCULATIONS

Consider Take 9 of Reel 6 for a summary of the calculations involved in this investigation.

A. Pressure Calculation:

A manometer was attached to the absorption tube of the experimental apparatus for the purpose of measuring the pressure on the CO_2 - MEA system during the absorption process. The manometer contained red oil which had a specific gravity of 2.95. The manometer readings were used along with the atmospheric pressure to calculate the total pressure in the following way.

Initial manometer reading:

left leg = 10.1 cm.

right leg = 10 cm.

Then:

ΔP_m = manometer reading due to MEA in left leg

$$= (10.1 + 10)\left(\frac{2.95}{13.5}\right) = 4.39 \text{ cm. of Hg}$$

where:

specific gravity of red oil = 2.95

specific gravity of mercury (Hg) = 13.5

Furthermore:

ΔP = manometer pressure reading during the take, cm. of red oil

P_A = atmospheric pressure, cm. of Hg

Then the total pressure on the system is given by:

$$(\alpha) \qquad P = P_A + \frac{2.95}{13.5}\Delta P - \Delta P_m + \frac{7.5}{12}\,\text{ft}\,\frac{\rho_{MEA}}{\rho_{\text{red oil}}}\left(2.54\frac{\text{cm}}{\text{in}}\right)\left(12\frac{\text{in}}{\text{ft}}\right)\left(\frac{2.95}{13.5}\right)$$

where:

ρ_{MEA} = density of MEA

$\rho_{\text{red oil}}$ = density of red oil

and:

$$\frac{\rho_{MEA}}{\rho_{\text{red oil}}} = \frac{1}{2.95}$$

Substitution and simplification of (α) gives,

$$(\alpha + 1) \qquad P = P_A + 0.218\,\Delta P - 2.98$$

In Reel 6, P_A = 74.56 cm. of Hg. For Take 9, ΔP = 48.8 cm. of red oil. Then from (α + 1),

$P = 74.56 + 0.218(48.8) - 2.98$

$P = 82.22$ cm. of Hg.

B. Calculation of N, mass of CO_2 bubble in lb. moles:

From equation (9) in Chapter II,

$$N = \frac{9.06 \times 10^{-8}(P)(AHD)^2 AVD}{(ACD)^3(460 + t)}$$

For Take 9:

$P = 82.22$ cm. of Hg.

ACD = 1.68 in.

$t = 79.7\ ^{o}F$

At the absorption time of 0.34 sec.,

AHD = 0.61 in. and AVD = 0.58 in.

By substitution into equation (9), it is found that:

$$N = 0.6274 \times 10^{-9} \text{ lb. moles}$$

C. Calculation of area of CO_2 bubble in ft^2:

From equation (16) in Chapter II,

$$A = \frac{7.075 \times 10^{-4}}{(ACD)^2} \left[(AHD)^2 + \frac{(AHD)(AVD)^2}{\sqrt{(AHD)^2 - (AVD)^2}} \ln \frac{\sqrt{(AHD)^2 - (AVD)^2} + AHD}{AVD} \right]$$

When the values for Take 9 at a time of 0.34 sec. are substituted into (16), and the equation solved,

$$A = 1.806 \times 10^{-4} \text{ ft}^2$$

D. Error Estimation:

For this part of the sample calculations, Take 4 of Reel 6 will be used.

From equation (33) in Chapter II,

$$F = 1 + \frac{1}{(1 + \Delta)\sqrt{2\Delta + \Delta^2}} \ln(\sqrt{2\Delta + \Delta^2} + 1 + \Delta)$$

In Take 4, at an absorption time of 0.20 sec., $\Delta = 0.14$. When this value is substituted into equation (33) and the calculation performed,

$$F = 1.85$$

From Chapter II,

$$F' = (1 + \Delta)^{2/3} F$$

Substitution of $\Delta = 0.14$ and $F = 1.85$ from Take 4 gives:

$$F' = 2.02$$

NOTATION

NOTATION

A = area of oblate spheroid, ft.^{2}

A_s = area of sphere, ft.^{2}

a = length of major axis of prolate or oblate spheroid

AHD = apparent horizontal diameter of CO_2 bubble, $\frac{1}{100}$ in.

AVD = apparent vertical diameter of CO_2 bubble, $\frac{1}{100}$ in.

ACD = apparent capillary diameter, $\frac{1}{100}$ in.

B = dimensionless constant

b = length of minor axis of prolate or oblate spheroid

C_1 = dimensionless constant

C_2 = dimensionless constant

F = error estimate

F' = error estimate

HD = horizontal diameter of CO_2 bubble, $\frac{1}{100}$ in.

m = dimensionless constant

N_A = absorption rate, lb. moles/ft.^{2} sec.

N = mass of CO_2 at a given time, lb. moles

P = pressure on CO_2 bubble, cm. of Hg.

P_A = barometric pressure, cm. of Hg.

R = absorption rate, lb. moles/sec.

R_G = gas constant, cm. of Hg. ft.^{3} / lb. mole. ^oR

T = absolute temperature, ^oR

t = time, sec.

TCD = true capillary diameter, $\frac{1}{100}$ in.

V = volume of oblate spheroid, ft.^{3}

V_s = volume of sphere, $ft.^3$

VD = vertical diameter of CO_2 bubble, $\frac{1}{100}$ in.

Subscripts:

0 = initial conditions

Greek Letters:

Δ = difference between horizontal and vertical diameters of a CO_2 bubble at a given time, $\frac{1}{100}$ in.

π = dimensionless constant

ρ = density of a substance