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The effect of varying surface tension on the rate of carbon dioxide absorption in water.

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UNIVERSITY OF LOUISVILLE

THE EFFECT OF VARYING SURFACE
TENSION ON THE RATE OF
CARBON DIOXIDE ABSORPTION IN WATER

A Thesis

Submitted to the Faculty
of the Graduate School
of the University of Louisville
in Partial Fulfillment of
the Requirements
for the Degree of
MASTER OF CHEMICAL ENGINEERING

Department of Chemical Engineering

Sheldon Hutchison Butt

1941

THE EFFECT OF VARYING SURFACE
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CARBON DIOXIDE ABSORPTION IN WATER

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May 26, 1941

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LIST OF SYMBOLS

A	Area measured perpendicular to direction of diffusion
B_f	Thickness of film
C	Proportionality constant
c	Concentration
D_M	Molar diffusivity
H	Henry's law constant
I	Contact factor
K	Overall coefficient of gas absorption
k	Film coefficient of gas absorption
N	Quantity of material, moles
n	Inverse Henry's law constant
P	Partial pressure
R	Film resistance
s	Density of liquid
T	Absolute temperature
u	Molecular velocity
V	Liquid velocity
sub A	component A
sub AB	A through B
sub BA	B through A
sub B	component B
sub g	Gas
sub i	Interface
sub l	Liquid

LIST OF SYMBOLS CONTINUED

- β Coefficient of resistance
 μ Viscosity of liquid
 θ Time
 ω Partial molal volume

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ABSTRACT

Although there has been a great deal of work done in the past on gas absorption, a thorough literature search failed to reveal any previous quantitative work done on the effect of surface tension on absorption rates. A batch absorption system using the carbon dioxide water system was investigated. The surface tension was varied using n-butanol, iso-pentanol, Santomerse D, and Aerosol. The first two were shown to produce a marked increase in absorption rate with decrease in surface tension, while the last two were shown to produce a varying amount of decrease in absorption rate with decrease in surface tension. The effect of varying speeds of agitation of the batch system was also investigated. No theoretical correlation has resulted from the experimental data obtained. This was due to the complexity of the effect of the wetting agents used, which would require a large amount of data to obtain a correlation.

INTRODUCTION

The process of gas absorption was of great interest because of its many important industrial applications. Many previous investigators have studied the process of gas absorption, obtaining a large amount of data which was of practical and theoretical interest.

The various absorption systems have been generally divided into four classifications which were based upon the factors that have been found to control absorption rate. The first were those in which the liquid film was found to be controlling. The second were those in which the gas film was found to be controlling. The third were those in which both films were found to be controlling, while the fourth were those in which the absorbed gas reacts with the solvent and in which the speed of the reaction was found to be controlling.

Among the various factors whose effects on the rate of gas absorption have been studied in great detail, were the effects of the velocity of the absorbing liquid and the effects of the viscosity of the absorbing liquid.

The purpose of this investigation was to determine the effect of varying surface tension on absorption rate of gas in liquid in systems in which the liquid film was controlling.

The specific problem investigated was the effect of varying surface tension on the absorption rate of carbon dioxide in water.

HISTORICAL

The development of a theory of gas absorption which was of sufficient practical value to be of much use in chemical engineering design and calculations was rather recent. The first theory of such practical value was that developed in 1923 by Whitman. (28). The fundamentals of the theory of the physical process of gas absorption had been recognized by Maxwell. (26). He recognized that gas absorption was a diffusional process, and that the rate of gas absorption was dependent upon the partial pressure difference across the liquid-gas interface. An example of the early attempts to develop an equation which could be applied to the actual operation of engineering equipment was the work done by Baker. (4).

Baker noted that the force causing a gas to be absorbed by a liquid was the difference between the partial pressure of the gas in the gas mixture and the vapor pressure exerted by the gas dissolved in the liquid. He also stated that the rate of absorption depended upon the intimacy of contact between the liquid and the gas mixture and that this factor was dependent upon the design and operation of the particular equipment under consideration. A theoretical equation was then derived from these fundamental concepts and applied to the available data. He proposed the following equation:

$$\frac{dN_A}{dA} = (P_{AG} - P_{A1}^*)$$

$$\frac{dN_A}{dA}$$

Absorption rate

$$(P_{AG} - P_{A1}^*)$$

Difference in partial and vapor pressure of gas

C

Proportionality constant

I

Factor representing the intimacy of contact of gas and liquid phases

He further recognized that the percent of theoretical absorption obtained under actual conditions of operation depended upon this rate of absorption and upon a factor which represented the efficiency of the system. From these concepts he developed the equation:

$$\frac{dN_A}{dA} = C_2 C' (P_{Ag} - P_{A1}^*) I \Theta$$

C_2 Proportionality constant

C' Efficiency factor

Θ Time of contact

It was apparent that although this equation was theoretically sound, it was of little practical value. Each particular set of process equipment and each particular variation of the physical conditions under which the equipment was operating required a new determination of the various factors included in the equation.

A further and somewhat more advanced application of these same theoretical concepts was made by Van Arsdel. (24). He proposed as a fundamental equation the following:

$$\frac{dN_A}{dA} = CA(nc_{Ag} - c_{A1})$$

A Area of contact

n Henry's law constant evaluated so that $nc_{Ag} = c_{A1}$

c_{Ag} Concentration of A in gas phase

c_{A1} Concentration of A in liquid phase

C Proportionality constant

Van Arsdel then proceeded to adapt this equation to a packed tower obtaining the following expression:

$$\frac{dN_A}{dA} = AK(nc_{Ag} - c_{A1})_{av.}$$

K Transfer coefficient

This equation still suffered from the disadvantage of containing a

factor, K , which had to be experimentally determined for any change in the physical conditions of operation of the apparatus or for any change in the components of the system.

Van Arsdell (25) also made an attempt at correlation of data such that the effect of variation of superficial gas velocity could be taken into account. He arrived at the conclusion that, up to a certain critical gas velocity, the transfer coefficient, K , was roughly proportional to the liquid velocity. He also came to the conclusion that this same transfer coefficient varied inversely as the viscosity of the liquid phase.

The most important single advance in the study of the theory of gas absorption was the postulation of the double film concept of gas absorption. This concept the basis for modern gas absorption theory, was first advanced by Whitman. (28). Whitman stated that the overall coefficient of material transferred could be defined according to the following equation:

$$K_A = \frac{1}{R_g + R_l}$$

K_A Overall coefficient of material transfer

R_g Resistance of gas film

R_l Resistance of liquid film

This two film concept of gas absorption will be dealt with further in the section of this thesis devoted to theory.

A determination of the effect of the superficial gas velocity upon the gas film coefficient was made by Haslam, Ryan, and Weber. (11). They arrived at the conclusion that the overall coefficient was related

to gas velocity by the following expression:

$$\frac{1}{K_A} = \frac{C}{V^{0.8}} + R_1$$

V Gas velocity

Further work on the effect of the viscosity of the absorbing liquid on the rate of gas absorption by Haslam, Hershey, and Keen, (10) resulted in the conclusion that the gas film coefficient was related to velocity and viscosity by the equation:

$$k_g = cv^{0.8}(s/\mu)^{2/3}$$

s Density of the film

μ Viscosity of the film

Similarly, the liquid film coefficient was found to vary directly with the expression, $(s/\mu)^{2/3}$.

A thorough search in the literature failed to reveal any evidence of a systematic attempt to determine the effect of variation of surface tension upon the rate of gas absorption. The only important reference (22) to any investigation of the use of wetting agents in absorption work that was found concerned itself principally with their use in attempting to increase the wetting of the packing in a packed absorption tower. This reference stated only that the addition of the wetting agent decreased the absorption rate, the absorption taking place in a packed tower and, the wetting agent being of the same general type as the Santomerse D and the Aerosol used in this investigation. It did not represent any systematic attempt to determine the effect of decreasing surface tension on the rate of gas absorption.

The absorption rate of carbon dioxide in water has been of

great interest (4,5,6,9,16) because of the commercial importance of carbon dioxide absorption and because of the excellent example of an absorption system in which the liquid film was controlling offered by this specific system. Accordingly, a great deal of experimental work has been done in the past on the determination of the various factors affecting this process.

THEORETICAL

The process of gas absorption was defined for the purposes of this research as that process by which a solute gas is transferred from the gas phase in which it is mixed with one or more inert gases into an absorbing liquid in which it is soluble. This definition of the process of gas absorption was quite in agreement with the generally accepted one. The most widely accepted theory which has been developed to explain the mechanism of gas absorption was the "two film" theory of gas absorption which was first developed by Whitman (28). This theory was based upon the premise that gas absorption was a diffusional process and that the material transfer took place across two films, a liquid film and a gas film, entirely by diffusion. The resistance to absorption was attributed entirely to the resistance to diffusion of these two film, and that no resistance was offered by the actual liquid-gas interface.

The mechanism of gas diffusion was found to be rather simple. The fundamentals of the mechanism were best explained by visualizing a single molecule of one component, A, diffusing unidirectionally through a two component gas mixture composed of components A and B. It has experimentally been determined (27) that the frictionally resistance to diffusion of component A varied directly as its velocity past the interfering, B. It has also been determined that the resistance to diffusion of the component A varied directly as the distance through which it is diffusing, this distance was expressed symbolically as ds . It followed logically that the resistance also varied directly as the number of molecules of the interfering gas B which lay in the path of the molecule of A. The value was proportional to the partial molal

volume of B, ω_B . By summation, the conclusion was reached that the total resistance to diffusion of component A was equal to the number of molecules of A diffusing multiplied by the resistance met by each molecule. Since the number of molecules of A was also proportional to ω_A , and the total frictional resistance to diffusion of component A was equal to $\beta_{AB} \omega_A \omega_B (u_A - u_B)$, where:

β_A Coefficient of resistance

u_A Velocity of component A

u_B Velocity of component B

To cause any flow of the component A a force that would overcome the resistance to diffusion of A had to exist. This force was supplied by an equivalent drop in the partial pressure of A,

$$-dp_A = \beta_{AB} \omega_A \omega_B (u_A - u_B) dz, \text{ or } \frac{-dp_A}{dz} = \beta_{AB} \omega_A \omega_B (u_A - u_B) \quad (E1)$$

Similarly, we may write the expression:

$$\frac{dp_B}{dz} = \beta_{AB} \omega_A \omega_B (u_A - u_B) \quad (E2)$$

It was well known that if there was no significant motion of the whole body of the gas, the total pressure, P , of the gas would remain constant throughout the system. Since the total pressure equaled the sum of the partial pressures, that is,

$$P = p_A + p_B$$

Differentiation of this equation yielded the expression:

$$dp_A + dp_B = 0$$

That is, the partial pressures of A and B when differentiated were equal but opposite in sign. By equating equations (E 1) and (E 2) it was found that:

$$\beta_{AB} = \beta_{BA}$$

or, that the coefficient of resistance to diffusion of A through B was equal to that of B through A. Therefore, it was possible for the sake of convenience and clarity to drop the subscripts and consider β as the common resistance coefficient. For the sake of convenience it was more convenient to substitute molar quantities for volume quantities,

$$w_{A^uA} = \frac{dN_A}{dA} \quad \text{and} \quad w_{B^uB} = \frac{dN_B}{dA} \quad \text{Also,}$$

$$w_B = \frac{p_B}{RT} \quad w_A = \frac{p_A}{RT}$$

T Absolute temperature

R Universal gas constant

Rewriting equations (E 1) and (E 2) the expression

$$\frac{-dp_A}{ds} = \frac{dp_B}{ds} = \frac{1}{D_M} \frac{p_B dN_A}{dA} - \frac{p_A dN_B}{dA} \quad (E 3)$$

$$D_M \quad \text{Diffusivity} = \frac{p_B}{RT}$$

For the sake of simplicity in gas absorption work, the small amount of inert gas, B, which diffuses was neglected. If there was no net diffusion of the component B, then the value of dN_B was zero and equation (E 3) could be written:

$$\frac{dN_A}{dA} = \frac{D_M dp_A}{p_B ds} \quad (E 4)$$

In the case of systems which contained only small percentages of the solute gas, the value of p_B varied only slightly, and p_B was considered constant at the average value, $(p_B)_{av}$. By integrating equation (E 4) across the true gas film from 0 to B_f and from p_{A1} to p_{Ag} the expression obtained was:

$$-\frac{dN_A}{dA} = \frac{D_M(P_{A2} - P_{A1})}{(P_B)_{av.} B_f} \quad (E 5)$$

In the other case where a large percentage of the solute was present in the gas mixture, the partial pressure of B, p_B , varied significantly across the film. It has been previously established that,

$$-dp_A = dp_B$$

therefore substituting in equation (E 4) the equation obtained was:

$$\frac{dN_A}{dA} = \frac{D_M dp_B}{P_B dz} \quad (E 6).$$

By integrating (E 6), the expression obtained was:

$$\frac{-dN_A}{dA} = \frac{D_M}{B_f} \ln \frac{P_{B1}}{P_B} \quad (E 7).$$

Since $dp_A = P_{A2} - P_{A1}$ and $-dp_B = P_{B1} - P_{B2}$, then

$$\frac{P_{A2} - P_{A1}}{P_{B1} - P_{B2}} = 1 \quad (E 8).$$

When equation (E 7) was multiplied by equation (E 8) the equation obtained was:

$$-\frac{dN_A}{dA} = \frac{D_M (P_{A2} - P_{A1})}{B_f (P_B)_{l.m.}} \quad (E 9).$$

$(P_B)_{l.m.}$ Logarithmic mean of P_{B1} and P_{B2}

For engineering purposes it was convenient to determine B_f as a part of a film coefficient, which was defined as:

$$k_g = \frac{D_M}{(P_B)_{l.m.} B_f} \quad .$$

Substituting this coefficient in equation (E 9) the expression obtained was:

$$-\frac{dN_A}{dA} = k_g (P_{A2} - P_{A1}) \quad (E 10).$$

By means of a similar derivation it was established that,

$$-\frac{dN_A}{dA} = k_1 (c_{A1} - c_{Al}) \quad (E 11).$$

k_1 Liquid film coefficient defined similarly to k_g

c_{A1} Concentration of A at the interface

c_{Al} Concentration of A in the liquid

Inspection of equation (E 10) and (E 11) showed that at equal conditions of concentration of solute in the gas and in the solvent liquid, the rate of absorption was determined by the gas film coefficient, k_g and the liquid film coefficient k_1 .

It was common engineering practice to utilize an overall coefficient, K_g or K_1 which took into account the resistance of the gas and liquid films together rather than to use the individual coefficients which took into account only the individual resistances of gas and liquid films. In order to use an overall coefficient, it was necessary to express the total difference between the concentration of the solute gas in the liquid and in the gas phases in comparable units. Accordingly, the concentration of the solute gas in the liquid was generally given as the partial pressure of solute gas in the gas phase which was in equilibrium with the given concentration of the solute in the solvent liquid. This quantity was denoted symbolically as p_1^* , when partial pressures were used in the definition of the coefficient. It was also possible to use liquid concentrations to express the relationships dealt with. When this was done, the concentration of the solute gas in the gas phase was expressed as the concentration of solute in the liquid which would be in equilibrium with the gas at that partial pressure. This quantity was denoted

symbolically as c_A^* .

Equations (E 10) and (E 11) were now written,

$$-\frac{dN_A}{dA} = K_g(P_{Ag} - P_{A1}^*) = K_1(c_{Ag}^* - c_{A1}) \quad (E 12).$$

The overall coefficients were easily obtained from the individual film coefficients. It was necessary only to set up the simple relationship, $p = n c$, where n was the proportionality constant of solubility. Equations (E 10), (E 11) and (E 12) were now expressed together as:

$$-\frac{dN_A}{dA} = K_g(P_{Ag} - P_{A1}^*) = \frac{K_1}{n'}(P_{Ag} - P_{A1}^*) = K_g(P_{Ag} - P_{A1}) = \frac{k_1}{n''}(P_{A1} - P_{A1}^*) \quad (E 13).$$

$$n' = \frac{(P_{A1} - P_{A1}^*)}{(c_{A1} - c_{A1}^*)}$$

$$n'' = \frac{(P_{Ag} - P_{A1}^*)}{(c_{Ag}^* - c_{A1})}$$

Solving, the expression obtained was,

$$\frac{1}{K_g} = \frac{1}{K_g} + \frac{n'}{k_1} = \frac{n''}{K_1} \quad (E 14).$$

In the usual case where the solubility of the solute gas followed Henry's law and $p = \frac{d}{H}$, n' and n'' were equal to $\frac{1}{H}$; hence the expression obtained was:

$$\frac{1}{K_g} + \frac{1}{H k_1} = \frac{1}{H K_1} \quad (E 15).$$

It has been found in practice that the values of K_g and k_1 as expressed in equations (E 10) and (E 11) were quite often of the same order of magnitude. (27) When this was the case, it was apparent that the relative values of gas film resistance and liquid film resistance, $\frac{1}{K_g}$ and $\frac{n'}{K_1}$ were largely controlled by the value of n' . Since the value of n' was determined by the solubility relationships of the

system, according to the equation $p = n \cdot a$, it was apparent that for gases which were highly soluble in the solvent liquid that n' would be very small and the total resistance, $\frac{1}{K_g}$, would be practically equal to $\frac{1}{K_g}$. This condition of the system was termed "gas phase controlling", or "gas film controlling". Similarly, for very slightly soluble gases, n' would be large and the total resistance, $\frac{1}{K_g}$, would be practically equal to $\frac{n'}{K_l}$. This condition was termed "liquid phase controlling", or "liquid film controlling".

The system dealt with in this research, the system carbon dioxide - water was one of the systems in which the liquid film was controlling. For that reason, only the theory of absorption systems in which the liquid film was controlling was developed further in this thesis.

Any variable which would in any way effect the liquid film coefficient, k_l , of a system in which the liquid film was controlling would have almost the same quantitative effect on the overall coefficient, K_l . Accordingly, by determining the effect of varying any condition on the absorption rate of the whole system, it was possible also to determine the effect of such variation on the liquid film coefficient and on the liquid film.

The effect of the viscosity of the solvent liquid on k_l has been determined by a number of investigators. (1, 7, 10, 14, 15, 17, 18, 19, 20, 23, 25). The conclusion generally arrived at was that the liquid film coefficient was inversely proportional to the two-thirds power of the viscosity. This effect was thought to be due to the decrease in the film thickness caused by the decrease in viscosity.

Increase in agitation, or increase in the rate of flow of the body of the fluid was a method by which the thickness of the film was reduced. In cases where the liquid was flowing down the inside walls of a tower in a smooth sheet, various investigators have quantitatively determined the effect of increase in the velocity of the liquid upon the liquid film coefficient. They have found that k_1 was proportional to the eight-tenths power of the velocity of the liquid. (1,2,3,8,11,14).

No reference to any previous investigation of the quantitative effect of variation of the surface tension upon the liquid film coefficient was found. There were found, however, two allusions to the effect of the surface tension upon the liquid film coefficient. (19,22) These references made conflicting statements as to the effect of variation of surface tension upon the absorption rate.

In any liquid there existed a certain attraction between the molecules of the liquid. The attraction manifested itself near the surface of the fluid where the molecules were subject to an unbalanced force. The molecules at the surface were pulled inward by the molecules below them in the fluid and were pulled from all sides by the attraction of the molecules surrounding them at the surface. However, there was no pull exerted upon them from the gas above the liquid surface. Therefore, the liquid tended to adjust itself to the minimum possible area. Reduction of the surface tension, therefore, meant a reduction in the surface energy, it also meant a reduction in the concentration of the molecules of the solvent liquid at the surface of the liquid, since the attraction between the molecules was

constant; and if the surface energy was reduced, then the surface concentration had to be reduced proportionally in order to give this reduction in surface energy.

The addition of various materials to the solvent liquid tended to decrease the surface tension of the liquid. This was brought about by the accumulation of the molecules of the solute material at the surface of the liquid, tending to lower the surface concentration of the solvent and thus to lower the surface energy of the solution. Very small quantities of certain wetting agents accordingly had a very decided effect on the surface tension of the water.

Since a reduction of the energy maintaining the bonds between molecules of a fluid reduced the energy necessary to displace one of the molecules from its natural position in the fluid because of the decrease in the forces holding them together it appeared that a reduction in the surface tension of a fluid would make the surface of the fluid more readily penetrated by a diffusing gas. When the region in which the molecules of the wetting agent had segregated was passed, the energy relationships of the molecules of the solvent liquid were practically the same as before except for the small effect upon them of the small amount of the wetting agent which was in solution in the interior of the fluid mass. The reduction of the surface concentration of the solvent liquid resulted in a direct reduction in the area through which the material could diffuse and resulted in a direct reduction of the rate of diffusion of the gas through the surface of the solvent fluid. However, this relationship could only apply when the solute gas was not soluble in the wetting agent used to reduce the

surface tension of the solvent. In the first case, in which the solute is insoluble in the wetting agent, it followed that the two effects of the reduction of the surface tension as explained above had a canceling effect, which varied according to the variation of the thickness of the surface film. In the second case, it followed that the effect of reduction of surface energy could disappear while the effect of reduction of surface energy would continue to make itself felt. This variation in the two cases accounted for the variation in the reported effect of wetting agents on absorption rate, since one observer (19) reported results obtained using butanol and the other observer (22) reported results obtained using a long-chain sulfonated alcohol in which the gas was insoluble.

The magnitude of the effect of the reduction of the surface energy of the solvent upon the rate of diffusion through the liquid film depended upon the number of layers of molecules of solvent liquid which were contained in the liquid film. In cases where the liquid film was exceedingly thin, i.e., when agitation was great and when viscosity was low and temperature was high, the effect of the wetting agent on the absorption rate would be more pronounced. In cases where the liquid film was thick, i.e., in fluids of high viscosity and low temperature which were almost stagnant, it seemed that the effect of the wetting agent would be minimized.

The experimental data accumulated during the course of this research all tends to verify the reasoning presented in the preceding paragraphs. However, the quantity of the experimental data was not such as to justify the development of any empirical relationship would

have to be somewhat complex to take into account the three factors of, film thickness, solubility of the gas in the wetting agent and reduction of surface energy.

EXPERIMENTAL

Description of Apparatus

The apparatus used in this research was a batch absorption apparatus. Absorption took place in the reaction vessel, j, which was a cylindrical battery jar of 1750 milliliters capacity. The gas and the solution were agitated by means of a stirrer, s, having one pair of blades in the solution and one pair in the gas above the solution. The stirrer was driven by a cone drive stirring motor, f, at varying speeds of rotation. Projecting into the reaction vessel was a 50 milliliter burette, e, which was used to titrate the solution. A 250 milliliter burette, j, was used to measure the CO₂ used. The burette was equipped with a leveling bottle, k. A two liter graduated cylinder, c, which was used to measure the water used was connected with the water reservoir, b. The temperature of the solution in the reaction vessel was measured by means of a thermometer, v, which read to 0.2°C. Commercial carbon dioxide was used in these experiments. The sodium carbonate used was stored in a bottle, g, which was connected with the top of the burette, e. The solution in the reaction vessel was heated by means of a heating coil, t, which was supplied with hot water by a water heater, p. The system was fitted with an observation tube, m, where the temperature of the hot water was measured. The water bottle, b, the burette, e, the sodium carbonate bottle, g, and the measuring cylinder, c, were all provided with protection tubes, a, d, h, and n. All vacuum lines were connected with a large filter flask, r, which acted as a trap. All water lines were connected with an observation tube, q. The water lines were all provided with drains, which were piped to the sink.

TABLE I
SYMBOLS USED ON DIAGRAM OF APPARATUS

- a. Protection tube
- b. Water storage bottle
- c. Measuring cylinder for water
- d. Protection tube
- e. Burette used to titrate solution
- f. Stirrer motor
- g. Sodium carbonate storage bottle
- h. Protection tube
- j. Burette for measuring carbon dioxide
- k. Level bottle
- m. Observation tube for water in heater
- n. Protection tube
- p. Water heater
- q. Observation tube for water feed
- r. Suction flask
- s. Stirrer
- t. Heater coil
- u. Reaction vessel
- v. Thermometer
- w. Release valve
- x. Drain

The experimental procedure followed in this research was a simple one designed to give as accurate a determination as possible of the overall absorption coefficients by a method sufficiently rapid to permit of the accumulation of a relatively large amount of experimental data.

The batch system of absorption was chosen in preference to a continuous system for several reasons. The primary consideration was that the batch system did not require a long period of operation during which the system was allowed to reach equilibrium before data could be taken. The batch system was also used because of the limited amount of materials available for the investigation, and it was thought that the batch system would require much less material than a continuous system.

The procedure followed in making a run with the experimental apparatus used was briefly as follows: Five hundred milliliters of water containing the wetting agent and a small amount of phenolphthalein indicator were drawn into the apparatus from the measuring cylinder by means of suction applied to the absorption vessel by an aspirator. The agitator was then started and hot water from the heater run through the small coil on the inside of the unit. When the liquid in the unit had reached a temperature of 25°C , the coil was disconnected and the agitation stopped. The liquid was then allowed to stand for one minute until it became stagnant, and a partial vacuum drawn upon the absorption vessel by means of an aspirator. The aspirator was then cut off and the line from the measuring burette opened, and 200 milliliters of carbon dioxide gas was drawn into the system. As soon as the required

amount had been added, the release valve was opened momentarily so that the gas inside of the absorption vessel could reach atmospheric pressure. The agitator was then started and the time of agitation closely controlled by means of a stop watch. Immediately upon termination of the period of agitation the release valve was opened, and a current of air was drawn through the absorption vessel by means of an aspirator. This current of air was allowed to flow through the vessel for at least one minute so that the carbon dioxide could be effectively displaced from the gas mixture in the absorption vessel. The agitator was then started again and the liquid inside the vessel titrated with tenth normal sodium carbonate solution. The end point (21) was taken to be the appearance of the first pink coloration of the liquid which would endure for a period of one minute. At the end of this time, the liquid in the system was removed and the bottom of the vessel purged with several small quantities of the same liquid as was to be used in the next run.

The surface tension of the absorbing liquid was measured by the capillary rise method using a capillary of approximately one-half millimeter bore. The capillary was calibrated against water as a standard and was kept scrupulously clean by the use of a cleaning solution composed of concentrated sulphuric acid and potassium dichromate.

The water used in the experimental work was freed from carbon dioxide by drawing carbon dioxide free air through it for a period of time of at least one hour. After this it was protected from contact with the atmosphere by a tube filled with sodium hydroxide.

The tenth normal sodium carbonate solution used to titrate the solution was carefully prepared from reagent grade sodium carbonate. During the course of the research it was carefully protected from atmospheric carbon dioxide by means of a tube filled with soda-lime. At no time during the progress of this research was it allowed to become unprotected.

The liquid held in the measuring cylinder was protected by means of a tube containing soda-lime from any contamination with atmospheric carbon-dioxide.

The solutions of the wetting agents which were used to decrease the surface tension of the absorbing liquid were carefully tested to determine that they were not acid or basic in their reaction with water.

A series of blank titrations was run to determine the amount of the standard sodium carbonate solution required to produce the standard indicator change when all parts of the procedure were carried through except for the period of agitation. A series of blanks were also run on the solutions used without allowing them to come into contact with atmospheric carbon dioxide. The two blank values were found to yield results within 0.2 cc. N/10 Na_2CO_3 titre which indicated that there was no cause to fear any measurable absorption of carbon dioxide during the period when the solution stood stagnant. This was quite as was expected from the available literature which indicated that the rate of absorption of carbon dioxide into the water when stagnant was very low.

DATA

The data obtained for each variation in surface tension and in rate of agitation were averaged and summarized. The tabulation of these summarized data was presented in Table II. The entries in this table represented the absorption rate in mols of carbon dioxide times 1000 per mol of water per minute for specific values of surface tension. They were arranged in the table according to wetting agent used and agitation rate employed. The data presented were those for n-butanol and Santomerse D. The data from the determinations using Aerosol and iso-pentanol were not presented since they were run only as checks on the data for Santomerse D and n-butanol in order to establish the fact that the curves were typical of the type of wetting agent used.

The data obtained for Aerosol yielded results similar to those obtained for Santomerse D, while those obtained for iso-pentanol gave results similar to those obtained from the determinations using n-butanol.

The data presented in tabular form in Table II were plotted in Figures 2 and 3, the data for Santomerse D being plotted on figure 2 while those for n-butanol were plotted on Figure 3. On these figures, absorption rate was plotted against surface tension of absorbing liquid.

These curves, in the case of Santomerse D showed that the absorption rate decreased with decrease in surface tension up to a value of 40 dynes per square centimeter. At this point the decrease was approximately 30%. They showed that the absorption rate increased about 40% with the first addition of butanol or iso-pentanol and con-

tinued to increase gradually with continued decrease of surface tension until an increase of approximately 60% was reached at a value of 40 dynes per square centimeter.

All the data obtained were obtained by the procedure outlined in the preceding section of this thesis.

TABLE II

SUMMARY OF ABSORPTION RATE DATA

A. AGITATION C, WETTING AGENT, SANTOMERSE D

Surface Tension Dynes/cm. ²	Absorption Rate Mols CO ₂ x 10 ³ /min. per mol water
70.0	0.223
57.5	0.196
49.0	0.182
46.5	0.176
45.0	0.162
39.0	0.144
27.0	0.144
23.0	0.157
22.0	0.158

B. AGITATION D, WETTING AGENT, SANTOMERSE D

Surface Tension Dynes/cm. ²	Absorption Rate Mols CO ₂ x 10 ³ /min. per mol water
70.0	0.252
61.5	0.231
50.0	0.205
34.0	0.216
31.0	0.259

TABLE II CONTINUED
SUMMARY OF ABSORPTION RATE DATA

C. AGITATION E, WETTING AGENT N-BUTANOL

Surface Tension Dynes/cm. ²	Absorption Rate Mols CO ₂ x 10 ³ /min. per mol water
70.0	0.390
65.0	0.519
57.5	0.527
52.0	0.556
48.0	0.590
38.0	0.626

D. AGITATION D, WETTING AGENT N-BUTANOL

Surface Tension Dynes/cm. ²	Absorption Rate Mols CO ₂ x 10 ³ /min. per mol water
65.0	0.344
61.0	0.344
56.0	0.358
54.0	0.363
43.0	0.389

FIG. 2. ABSORPTION RATE VS SURFACE TENSION
WETTING AGENT — SANTOMERSE D

FIG. 3 ABSORPTION RATE VS. SURFACE TENSION
WETTING AGENT N-BUTANOL

INTERPRETATION OF DATA

The experimental data obtained can be roughly classified into two groups. These are: 1. The data obtained for absorption rate using commercial wetting agents (Santomerse D and Aerosol), and, 2. The data obtained for absorption rate using the lower aliphatic alcohols (n-butanol and iso-pentanol).

The sulfonated alcohols of high molecular weight which were used commercially as wetting agents did not appear to increase the absorption rate of carbon dioxide in water. Over the higher range of surface tensions, the absorption rate decreased almost in direct proportion to the decrease in surface tension. When surface tension was further decreased, the absorption rate increased. The use of ordinary aliphatic alcohols appeared to result in an increase in absorption rate. This increase was most marked over the initial range of decrease of surface tension. Further decrease of surface tension by the further addition of wetting agent resulted in a continued rise in absorption rate.

There was not found in the literature investigated any data obtained by previous investigators with which the data obtained in this research could be quantitatively correlated. Remy and Behre (19), state that the use of certain liquids which lower the surface tension appears to increase the absorption rate. Sherwood and Holloway, (22), stated that the use of a certain commercial wetting agent decreased the absorption rate. In neither case is there any quantitative data presented.

CONCLUSIONS

It appeared that the variations in absorption rate observed depended not only upon the surface tension but also upon the nature of the wetting agent used.

No simple mathematical relationship between surface tension and absorption rate could be correlated from the data obtained.

Correlation would seem to depend on obtaining large quantities of data on several systems using the same wetting agent, since the properties of the wetting agent itself had a great effect on the absorption rate. The wetting agents in which CO_2 was insoluble lowered the absorption rate, while the wetting agents used in which CO_2 was soluble increased the absorption rate.

APPENDIX

SAMPLE CALCULATIONS

The only calculations made, other than the very simple elementary ones, were the calculations for surface tension and mols of carbon dioxide per mol water in the solution at the end of the run.

Surface Tension:

Surface tension of liquid =

$$\frac{\text{mm. capillary rise of unknown liquid}}{\text{mm. capillary rise of standard}} \times \text{surface tension of standard}$$

Mols of Carbon Dioxide per mol of Water:

Mols of carbon dioxide per mol of water =

$$\frac{(\text{ml. Na}_2\text{CO}_3 \text{ titre}) (\text{normality of Na}_2\text{CO}_3)}{(\text{mols H}_2\text{O}) (1000)}$$

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Runs 1 to 32 performed on this problem were trial runs and cannot be included with the experimental data here tabulated.

In all cases, 500 milliliters of the absorbing solution were used in the reaction vessel.

In all cases, the percentage of carbon dioxide in the gas mixture over the solution was approximately 16% (plus or minus 0.5%).

TABLE III COMPLETE DATA

Run Number	Wetting Agent	Agitation r.p.m.	Surface tension Dynes/cm. ²	Agitation Time Minutes	Temperature Degrees C.	Ml. Na ₂ CO ₃ per 500 cc.	Mols CO ₂ x 10 ³ per mol water
33A	Aerosol	500	47.0	5	21.0	7.80	0.497
34A	Aerosol	500	47.0	5	21.5	7.50	0.475
35A	Aerosol	500	47.0	4	20.5	7.50	0.475
36A	Aerosol	500	47.0	4	21.8	7.80	0.497
37A	Aerosol	This run was ruined in the preliminary manipulations					
38A	Aerosol	450	21.5	5	25.0	17.20	1.175
39C	Aerosol	100	21.5	5	25.0	14.70	1.000
40C	Aerosol	100	21.5	5	24.8	13.30	0.893
41C	Aerosol	100	21.5	5	24.5	13.30	0.893
42C	Aerosol	100	21.5	3	24.3	9.70	0.633
43C	Aerosol	100	21.5	3	24.3	9.30	0.605
44C	Aerosol	100	21.5	3	25.0	8.90	0.577
45C	Aerosol	100	21.5	3	25.2	8.90	0.577
46C	Aerosol	100	21.5	2	24.7	7.30	0.462
47C	Aerosol	100	21.5	2	24.6	7.10	0.477

TABLE III CONTINUED COMPLETE DATA

Run Number	Wetting Agent	Agitation r.p.m.	Surface tension Dynes/cm. ²	Agitation Time Minutes	Temperature Degrees C.	Ml. Na ₂ CO ₃ per 500 cc.	Mols CO ₂ x 10 ³ per mol water
48C	Aerosol	100	21.5	2	24.8	7.20	0.453
49C	Aerosol	100	21.5	1	24.8	4.00	0.223
50C	Aerosol	100	21.5	1	25.3	4.05	0.227
51C	Aerosol	100	21.5	1	25.2	2.70	0.201
52C	Aerosol	100	21.5	0	25.2	0.50	0.000
53C	Aerosol	100	21.5	0	25.2	0.65	0.000
54C	Aerosol	100	21.5	0	25.2	0.75	0.000
55C	Aerosol	100	21.5	4	24.5	9.80	0.641
56C	Aerosol	100	21.5	4	24.5	9.90	0.648
57C	Aerosol	100	21.5	4	25.8	9.40	0.613
58C	Aerosol	100	21.5	5	24.8	9.70	0.633
59C	Aerosol	100	21.5	5	25.0	11.00	0.736
60C	Aerosol	100	21.5	5	25.0	9.50	0.619
61C	Aerosol	100	21.5	4	25.0	8.60	0.554
62C	Aerosol	100	21.5	3	25.0	7.30	0.462

TABLE III CONTINUED COMPLETE DATA

Run Number	Wetting Agent	Agitation r.p.m.	Surface tension Dynes/cm. ²	Agitation Time Minutes	Temperature Degrees C.	Ml. Na ₂ CO ₃ per 500 CC.	Mols CO ₂ x 10 ³ per mol water
63C	Aerosol	100	21.5	2	25.3	6.90	0.516
64C	Aerosol	100	21.5	1	25.7	5.80	0.353
65C	Aerosol	100	52.4	4	24.6	—	—
66C	Aerosol	100	52.4	4	25.0	8.80	0.569
67C	Aerosol	100	52.4	4	27.0	9.00	0.583
68C	Aerosol	100	52.4	5	25.0	11.50	0.763
69C	Aerosol	100	52.4	4	25.0	10.40	0.684
70C	Aerosol	100	52.4	3	25.0	8.00	0.439
71C	Aerosol	100	52.4	2	25.0	5.60	0.339
72C	Aerosol	100	52.4	1	25.2	3.40	0.180
73C	Aerosol	100	52.4	3	25.0	6.20	0.382
74C	Aerosol	100	52.4	2	25.0	5.50	0.331
75C	Aerosol	100	52.4	1	25.0	3.50	0.187
76C	Aerosol	100	52.4	3	25.1	8.10	0.447
77C	Aerosol	100	52.4	2	24.5	5.50	0.332

TABLE III CONTINUED COMPLETE DATA

Run Number	Wetting Agent	Agitation r.p.m.	Surface tension Dynes/cm. ²	Agitation Time Minutes	Temperature Degrees C.	Ml. Na ₂ CO ₃ per 500 ml.	Mols CO ₂ x 10 ³ per mol water
78C	Aerosol	100	52.4	1	25.2	3.10	0.158
79C	Aerosol	100	52.4	0	25.6	1.40	0.000
80C	Aerosol	100	52.4	0	25.0	0.80	0.000
81C	Aerosol	100	52.4	0	24.5	1.00	0.000
82C	Aerosol	100	52.4	1	24.5	4.30*	0.245
83C	Aerosol	100	52.4	2	24.9	7.10	0.447
84C	Aerosol	100	52.4	3	25.0	9.50	0.620
85C	Aerosol	100	52.4	2	25.0	7.00	0.639
86C	Aerosol	100	52.4	2	25.0	5.40	0.524
87C	Aerosol	100	52.4	3	24.5	7.10	0.447
88C	Aerosol	100	46.3	2	25.1	5.70	0.346
89C	Aerosol	100	46.3	1	24.9	3.60	0.194
90C	Aerosol	100	46.3	3	24.8	7.50	0.475
91C	Aerosol	100	46.3	1	25.2	3.50	0.187

* On runs 82C to 85C the depth of immersion of the stirrer was changed, this resulted in high values

TABLE III CONTINUED COMPLETE DATA

Run Number	Wetting Agent	Agitation r.p.m.	Surface tension Dynes/cm. ²	Agitation Time Minutes	Temperature Degrees C.	Ml. Na ₂ CO ₃ per 500 ml.	Mols CO ₂ x 10 ³ per mol water
92C	Aerosol	100	46.3	2	25.0	5.50	0.331
93C	Aerosol	100	46.3	3	25.2	6.80	0.425
94C	Aerosol	100	46.3	1	25.0	3.65	0.198
95C	Aerosol	100	46.3	2	25.0	5.40	0.325
96C	Aerosol	100	46.3	3	25.3	7.00	0.439
97C	Aerosol	100	46.3	0	25.0	1.40	0.000
98C	Aerosol	100	46.3	0	25.1	1.20	0.000
99C	Aerosol	100	46.3	0	25.2	1.20	0.000
100C	Aerosol	100	50.0	2	24.9	5.10	0.303
101C	Aerosol	100	50.0	1	25.2	3.80	0.209
102C	Aerosol	100	50.0	3	25.1	6.40	0.396
103C	Aerosol	100	50.0	3	25.2	7.10	0.447
104C	Aerosol	100	50.0	2	25.3	5.30	0.317
105C	Aerosol	100	50.0	1	25.3	3.40	0.180
106C	Aerosol	100	---	3	26.0	6.90	0.432

TABLE III CONTINUED COMPLETE DATA

Run Number	Wetting Agent	Agitation r.p.m.	Surface tension Dynes/cm. ²	Agitation Time Minutes	Temperature Degrees C.	Ml. Na ₂ CO ₃ per 500 ml.	Mols CO ₂ x 10 ³ per mol water
107C	Aerosol	100	—	3	25.8	6.50	0.403
108C	Aerosol	100	—	2	25.7	4.70	0.273
109C	Aerosol	100	—	1	26.5	3.30	0.173
110C	Aerosol	100	—	3	25.3	6.00	0.367
111C	Aerosol	100	—	2	25.5	3.40	0.180
112C	Aerosol	100	—	3	24.5	5.60	0.339
113C	Aerosol	100	—	2	24.6	3.90	0.216
114C	Aerosol	100	—	1	24.6	3.40	0.180
115C	Aerosol 3*	100	—	3	25.0	16.40	—
116C	Aerosol S	100	—	2	25.0	15.20	—
117C	Aerosol S	100	—	0	25.0	12.20	—
118C	Santomerse D	100	23.5	3	25.0	5.60	0.339
119C	Santomerse D	100	23.3	2	24.5	4.70	0.273
120C	Santomerse D	100	23.3	1	25.0	2.90	0.144

*, Aerosol S contained acid as a stabilizer and therefore interfered in the carbonate titration.

TABLE III CONTINUED COMPLETE DATA

Run Number	Wetting Agent	Agitation r.p.m.	Surface tension Dynes/cm. ²	Agitation Time Minutes	Temperature Degrees C.	Ml. Na ₂ CO ₃ per 500 ml.	Mols CO ₂ x 10 ³ per mol water
121C	Santomerse D	100	23.3	3	25.0	6.00	0.367
122C	Santomerse D	100	23.3	2	25.0	4.65	0.270
123C	Santomerse D	100	23.3	1	24.8	3.30	0.173
124C	Santomerse D	100	23.3	3	25.0	6.10	0.375
125C	Santomerse D	100	23.3	2	25.2	4.60	0.267
126C	Santomerse D	100	23.3	1	25.0	3.00	0.151
127C	Santomerse D	100	23.3	0	25.0	0.90	0.000
128C	Santomerse D	100	23.3	0	25.0	0.90	0.000
129C	Santomerse D	100	22.0	3	25.0	6.50	0.403
130C	Santomerse D	100	22.0	2	24.8	4.80	0.281
131C	Santomerse D	100	22.0	1	25.0	3.10	0.158
132C	Santomerse D	100	22.0	3	25.0	6.50	0.403
133C	Santomerse D	100	22.0	2	24.8	4.40	0.255
134C	Santomerse D	100	22.0	1	24.7	3.10	0.158
135C	Santomerse D	100	22.0	3	25.2	6.10	0.375

TABLE III CONTINUED COMPLETE DATA

Run Number	Wetting Agent	Agitation r.p.m.	Surface tension Dynes/cm. ²	Agitation Time Minutes	Temperature Degrees C.	Ml. Na ₂ CO ₃ per 500 ml.	Mols CO ₂ x 10 ³ per mol water
136C	Santomerse D	100	22.0	2	24.5	4.75	0.277
137C	Santomerse D	100	22.0	1	25.1	3.10	0.158
138C	Santomerse D	100	27.0	3	25.2	6.60	0.410
139C	Santomerse D	100	27.0	2	25.0	5.10	0.303
140C	Santomerse D	100	27.0	1	25.0	2.60	0.122
141C	Santomerse D	100	27.0	3	25.0	6.40	0.396
142C	Santomerse D	100	27.0	2	25.5	4.80	0.231
143C	Santomerse D	100	27.0	1	25.6	3.00	0.151
144C	Santomerse D	100	27.0	3	25.0	6.50	0.403
145C	Santomerse D	100	27.0	2	24.5	—	—
146C	Santomerse D	100	27.0	1	25.0	2.80	0.137
147C	Santomerse D	100	39.0	2	25.0	3.80	0.209
148C	Santomerse D	100	39.0	1	25.0	2.90	0.144
149C	Santomerse D	100	39.0	2	24.5	4.70	0.274
150C	Santomerse D	100	39.0	1	25.0	2.90	0.144
151C	Santomerse D	100	39.0	2	25.0	2.90	0.144

TABLE III CONTINUED COMPLETE DATA

Run Number	Wetting Agent	Agitation r.p.m.	Surface tension Dynes/cm. ²	Agitation time Minutes	Temperature Degrees C.	Ml. H_2CO_3 per 500 ml.	Mols $\text{CO}_2 \times 10^3$ per mol water
152 C	Santomerse D	100	45.0	2	25.0	4.70	0.274
153C	Santomerse D	100	46.0	1	25.0	3.20	0.165
154C	Santomerse D	100	45.0	2	25.0	4.60	0.267
155C	Santomerse D	100	45.0	1	25.0	3.30	0.175
156C	Santomerse D	100	45.0	2	25.0	5.00	0.295
157C	Santomerse D	100	45.0	1	25.0	3.15	0.162
158C	Santomerse D	100	49.0	2	25.0	5.30	0.339
159C	Santomerse D	100	49.0	1	24.1	4.10	0.231
160C	Santomerse D	100	49.0	1	25.0	4.05	0.227
161C	Santomerse D	100	49.0	1	25.0	3.00	0.209
162C	Santomerse D	100	49.0	1	25.0	3.10	0.158
163C	Santomerse D	100	49.0	2	25.0	5.30	0.317
164C	Santomerse D	100	49.0	1	25.0	3.50	0.187
165C	Santomerse D	100	49.0	1	25.0	4.05	0.227
166C	Santomerse D	100	49.0	1	25.0	3.00	0.194

TABLE III CONTINUED COMPLETE DATA

Run Number	Wetting Agent	Agitation r.p.m.	Surface tension Dynes/cm. ²	Agitation time Minutes	Temperature Degrees C.	Ml. Na ₂ CO ₃ per 500 ml.	Mols CO ₂ x 10 ³ per mol water
167C	Santomerse D	100	49.0	1	25.0	4.40	0.252
168C	Santomerse D	100	49.0	1	25.0	3.15	0.162
169C	Santomerse D	100	49.0	1	25.0	3.45	0.184
170C	Santomerse D	100	49.0	1	25.0	3.50	0.187
171C	Santomerse D	100	58.0	1	25.2	3.60	0.194
172C	Santomerse D	100	58.0	1	25.0	3.70	0.201
173C	Santomerse D	100	58.0	1	25.0	3.60	0.194
174C	Santomerse D	100	40.0	1	25.0	3.10	0.158
175C	Santomerse D	100	40.0	1	25.0	3.20	0.166
176C	Santomerse D	100	40.0	1	25.0	—	—
177C	Santomerse D	100	40.0	1	25.0	3.25	0.169
178D	Santomerse D	200	40.0	1	25.0	3.70	0.201
179D	Santomerse D	200	40.0	1	25.0	3.70	0.201
180D	Santomerse D	200	40.0	1	25.0	2.75	0.205
181D	Santomerse D	200	52.0	1	24.8	4.10	0.273
182D	Santomerse D	200	52.0	1	25.0	3.70	0.201

TABLE III CONTINUED COMPLETE DATA

Run Number	Wetting Agent	Agitation r.p.m.	Surface tension Dynes/cm. ²	Agitation time Minutes	Temperature Degrees C.	Ml. Na ₂ CO ₃ per 500 ml.	Mols CO ₂ x 10 ³ per mol water
183D	Santomerse D	200	52.0	1	25.0	3.60	0.194
184D	Santomerse D	200	52.0	1	25.0	3.75	0.205
185D	Santomerse D	200	61.0	1	25.0	4.20	0.237
186D	Santomerse D	200	61.0	1	25.0	4.20	0.237
187D	Santomerse D	200	61.0	1	25.0	4.30	0.245
188D	Santomerse D	200	61.0	1	25.0	4.00	0.223
189D	Santomerse D	200	61.0	1	25.0	3.90	0.216
190D	Santomerse D	200	61.0	1	25.0	4.00	0.223
191D	Santomerse D	200	34.0	1	25.0	4.30	0.245
192D	Santomerse D	200	34.0	1	25.0	4.10	0.231
193D	Santomerse D	200	34.0	1	25.0	3.90	0.216
194D	Santomerse D	200	34.0	1	25.0	3.95	0.220
195D	Santomerse D	200	34.0	1	25.0	3.90	0.216
196D	Santomerse D	200	31.0	1	27.0	4.70	0.273
197D	Santomerse D	200	31.0	1	25.0	4.40	0.252
198D	Santomerse D	200	31.0	1	25.0	4.10	0.231

TABLE III CONTINUED COMPLETE DATA

Run Number	Wetting Agent	Agitation r.p.m.	Surface tension Dynes/cm. ²	Agitation time Minutes	Temperature Degrees C.	Ml. Na ₂ CO ₃ per 500 ml.	Mols CO ₂ x 10 ³ per mol water
199D	Santomerse D	200	31.0	1	25.0	4.60	0.266
200D	Santomerse D	200	31.0	1	25.0	4.80	0.259
201D	None	200	70.0	1	25.0	3.90	0.216
202D	None	200	70.0	1	25.0	4.10	0.231
203D	None	200	70.0	1	25.0	4.40	0.252
204D	None	200	70.0	1	25.0	4.40	0.252
205C	None	200	70.0	1	25.0	4.00	0.223
206C	None	100	70.0	1	25.0	3.50	0.187
207C	None	100	70.0	1	25.0	4.00	0.223
208E	n-Butanol	400	38.0	1	25.0	9.30	0.604
209E	n-Butanol	400	38.0	1	25.0	9.60	0.626
210E	n-Butanol	400	38.0	1	25.0	9.70	0.633
211E	n-Butanol	400	38.0	1	25.0	9.80	0.641
212E	n-Butanol	400	48.0	1	25.0	9.00	0.532
213E	n-Butanol	400	48.0	1	25.0	9.70	0.633
214E	n-Butanol	400	48.0	1	25.0	9.20	0.597

TABLE III CONTINUED COMPLETE DATA

Run Number	Wetting Agent	Agitation r.p.m.	Surface tension Dynes/cm. ²	Agitation time Minutes	Temperature Degrees C.	Ml. Na ₂ CO ₃ per 500 ml.	Mols CO ₂ x 10 ³ per mol water
215E	n-Butanol	400	48.0	1	25.0	9.20	0.597
216E	n-Butanol	400	48.0	1	25.0	8.10	0.518
217E	n-Butanol	400	52.0	1	25.0	9.00	0.583
218E	n-Butanol	400	52.0	1	25.0	8.70	0.562
219E	n-Butanol	400	52.0	1	25.0	8.65	0.567
220E	n-Butanol	400	57.5	1	25.2	8.65	0.557
221E	n-Butanol	400	57.5	1	25.0	8.20	0.526
222E	n-Butanol	400	57.5	1	25.0	8.50	0.547
223E	n-Butanol	400	57.5	1	25.0	8.30	0.533
224E	n-Butanol	400	57.5	1	25.0	8.30	0.533
225E	n-Butanol	400	65.0	1	25.0	8.30	0.533
226E	n-Butanol	400	65.0	1	25.0	8.00	0.512
227E	n-Butanol	400	65.0	1	25.0	8.10	0.517
228E	n-Butanol	400	65.0	1	25.0	8.00	0.512
229E	n-Butanol	400	70.0	1	25.0	6.30	0.389
230E	n-Butanol	400	70.0	1	25.0	6.40	0.396
231D	N-Butanol	200	43.0	1	25.0	7.00	0.439

TABLE III CONTINUED COMPLETE DATA

Run Number	Wetting Agent	Agitation r.p.m.	Surface tension Dynes/cm. ²	Agitation time Minutes	Temperature Degrees C.	Ml. Na ₂ CO ₃ per 500 ml.	Mols CO ₂ x 10 ³ per mol water
232D	n-Butanol	200	43.0	1	25.0	6.60	0.375
233D	n-Butanol	200	43.0	1	25.0	6.50	0.403
234D	n-Butanol	200	43.0	1	25.0	6.40	0.396
235D	n-Butanol	200	43.0	1	25.0	6.40	0.396
236D	n-Butanol	200	54.0	1	25.0	6.80	0.425
237D	n-Butanol	200	54.0	1	25.0	6.00	0.367
238D	n-Butanol	200	54.0	1	25.0	6.10	0.375
239D	n-Butanol	200	54.0	1	25.0	5.95	0.364
240D	n-Butanol	200	58.0	1	25.0	6.20	0.382
241D	n-Butanol	200	58.0	1	25.0	6.00	0.367
242D	n-Butanol	200	58.0	1	25.0	6.00	0.367
243D	n-Butanol	200	58.0	1	26.2	5.60	0.339
244D	n-Butanol	200	58.0	1	26.2	5.60	0.339
245D	n-Butanol	200	58.0	1	26.2	5.80	0.353
246D	n-Butanol	200	58.0	1	26.2	5.90	0.361
247D	n-Butanol	200	61.0	1	26.2	5.60	0.339

TABLE III CONTINUED COMPLETE DATA

Run Number	Wetting Agent	Agitation r.p.m.	Surface tension Dynes/cm. ²	Agitation time Minutes	Temperature Degrees C.	Ml. Na_2CO_3 per 800 ml.	Mols $\text{CO}_2 \times 10^3$ per mol water
248D	n-Butanol	200	61.0	1	26.2	5.70	0.346
249D	n-Butanol	200	61.0	1	26.2	5.70	0.346
250D	n-Butanol	200	61.0	1	26.2	5.70	0.346
251D	n-Butanol	200	65.0	1	26.0	5.70	0.346
252D	n-Butanol	200	65.0	1	26.2	5.60	0.339
253D	n-Butanol	200	65.0	1	26.2	5.65	0.343
254D	n-Butanol	200	65.0	1	26.2	5.70	0.346
255C	n-Butanol	10	65.0	1	26.2	5.65	0.357
256C	n-Butanol	100	65.0	1	26.2	5.60	0.331
257C	n-Butanol	100	65.0	1	26.2	5.75	0.349
258C	n-Butanol	100	65.0	1	26.2	5.65	0.343
259C	n-Butanol	100	65.0	1	26.2	6.30	0.389
260C	n-Butanol	100	65.0	1	26.2	5.70	0.346
261C	n-Butanol	100	29.0	1	24.2	5.80	0.363
262C	n-Butanol	100	29.0	1	24.2	5.55	0.335
263C	n-Butanol	100	29.0	1	24.2	5.90	0.361

TABLE III CONTINUED COMPLETE DATA

Run Number	Wetting Agent	Agitation r.p.m.	Surface tension Dynes/cm. ²	Agitation time Minutes	Temperature Degrees C.	Ml. Na ₂ CO ₃ per 500 ml.	Mols CO ₂ x 10 ³ per mol water
264C	n-Butanol	100	29.0	1	24.2	6.10	0.375
265C	n-Butanol	100	29.0	1	24.2	6.76	0.349
266C	n-Butanol	100	45.0	1	24.3	7.50	0.475
267C	n-Butanol	100	55.0	1	24.3	6.60	0.410
268C	n-Butanol	100	45.0	1	24.4	6.80	0.424
269C	n-Butanol	100	45.0	1	24.4	6.80	0.424
270C	n-Butanol	100	49.0	1	25.0	7.20	0.453
271C	n-Butanol	100	49.0	1	25.1	7.00	0.438
272C	n-Butanol	100	49.0	1	25.1	7.15	0.450
273C	n-Butanol	100	61.0	1	25.3	6.40	0.396
274C	n-Butanol	100	61.0	1	25.3	5.70	0.346
275C	n-Butanol	100	61.0	1	25.3	6.20	0.381
276C	n-Butanol	100	61.0	1	25.3	6.30	0.389
277C	n-Butanol	100	61.0	1	25.2	6.40	0.396
278C	n-Butanol	100	54.0	1	25.0	7.00	0.439
279C	n-Butanol	100	54.0	1	25.3	6.80	0.425

TABLE III CONTINUED COMPLETE DATA

Run Number	Wetting Agent	Agitation r.p.m.	Surface tension Dynes/cm. ²	Agitation time Minutes	Temperature Degrees C.	Ml. Na ₂ CO ₃ per 500 ml.	Mols CO ₂ x 10 ³ per mol water
2800	n-Butanol	100	54.0	1	25.0	6.80	0.425
2810	n-Butanol	100	54.0	1	25.0	6.80	0.425
2820	n-Butanol	100	70.0	1	25.0	4.40	0.252
2830	n-Butanol	100	70.0	1	25.0	4.70	0.274
2840	n-Butanol	100	70.0	1	25.0	4.70	0.274
2850	n-Butanol	100	70.0	1	25.0	4.70	0.274
2860	n-Butanol	200	70.0	1	25.0	6.0	0.367
2870	n-Butanol	200	70.0	1	25.0	6.15	0.388
2880	n-Butanol	200	70.0	1	25.0	6.70	0.418
2890	iso-pentanol	200	39.0	1	25.0	6.30	0.380
2900	iso-pentanol	200	39.0	1	25.0	7.20	0.453
2910	iso-pentanol	200	39.0	1	25.0	7.30	0.452
2920	iso-pentanol	200	39.0	1	25.0	7.80	0.497
2930	iso-pentanol	200	39.0	1	25.0	7.80	0.497

VITA

Sheldon Hutchison Dutt was born in Pelham Manor, New York on August 22, 1919. In 1927, he moved to Louisville, Kentucky. He attended I. W. Bloom School and Longfellow School, graduating from the latter in 1930. He then attended Highland Junior High School in Louisville, graduating in 1933. He then entered the Louisville Male High School, from which he graduated with Honorable Mention in 1936. While in High School he was active in debating, being president of the Debate Club and captain of the Debate Team. In the fall of 1936, he entered the Speed Scientific School of the University of Louisville. While in school he was a member of the Louisville Chapter of Triangle Fraternity, of which he was House Manager in 1940 and Social Chairman in 1941. He was also a member of the A. I. Ch. E. student chapter and Secretary of that organization in 1940. He was make-up editor of the University of Louisville Annual in 1940 and Chairman of the University of Louisville Publicity League in 1940. He was a member of Theta Chi Delta, honorary chemical fraternity, and won the Chemical Engineering Faculty Senior Award in 1940. He received the degree of Bachelor of Chemical Engineering in 1940 from the University of Louisville. On July 1, 1941, he was appointed Graduate Assistant in the Department of Chemical Engineering of the University of Louisville.