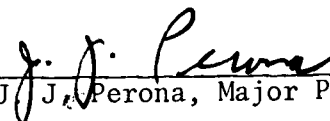
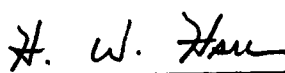


To the Graduate Council:

I am submitting herewith a thesis written by Gary Wayne Holden entitled "Mass Transfer in Gas-Liquid Cocurrent Downflow in a Pipeline Contactor." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Chemical Engineering.


J. J. Perona, Major Professor

We have read this thesis and
recommend its acceptance:




Accepted for the Council:


Vice Chancellor
Graduate Studies and Research

MASS TRANSFER IN GAS-LIQUID COCURRENT
DOWNFLOW IN A PIPELINE CONTACTOR

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Gary Wayne Holden

August 1980

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ABSTRACT

Mass transfer behavior was investigated in gas-liquid cocurrent downflow in a one-inch I.D. pipeline. The contactor, constructed of pyrex glass pipe had a test section length of 8.125 ft. Liquid phase mass transfer coefficients and interfacial areas were measured separately by the chemical absorption of carbon dioxide from an air-CO₂ gas stream into solutions of sodium hydroxide. Volumetric mass transfer coefficients were measured by physical absorption of carbon dioxide from an air-CO₂ mixture into water. Experimental data was collected in falling-film, bubbly-slug, falling bubbly-film, annular flow and froth flow regimes, which are five of the six flow regimes established for cocurrent downflow. Liquid velocities ranged from 0.06 to 1.5 ft/sec and gas velocities from 1.5 to 20.0 ft/sec.

Interfacial areas and mass transfer coefficients were affected by changes in liquid and gas velocities. Interfacial areas decreased with liquid velocity in the transition from falling film to bubbly-slug. In the transition from annular flow to froth flow, interfacial area increased with liquid velocity, while only a slight increase was noted within the falling bubbly-film regime. A large increase in interfacial area was observed with increase in gas velocity in the transition from falling film, bubbly-slug to falling bubbly-film. Interfacial area increased with gas velocity in the transition from falling bubbly-film to froth flow but decreased in the transition from falling bubbly-film

to annular flow. Interfacial areas obtained in this study fall into the broad range of values in other works. Interfacial areas for cocurrent upflow are up to five times larger.

The liquid phase chemical mass transfer coefficient increased with liquid velocity. With increase in gas velocity in the transition from falling film, bubbly-slug to falling bubbly-film, it experienced a sizable decrease. The volumetric physical mass transfer coefficient increased with liquid velocity but generally remained unchanged with increase in gas velocity. The physical mass transfer coefficient measured in this study compared closely with mass transfer coefficients reported in the literature. The chemical mass transfer coefficient however exceeded these values by a factor of 10 to 50.

The mass transfer results follow the flow regime boundaries of the flow regime map by Oshinowo and Charles very closely.

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NOMENCLATURE

- a = interfacial area, cm^{-1} .
 A = constant in Equ. (C11), 1/mole.
 A_t = cross-sectional area of tube, cm^2 .
 C = concentration in liquid phase, mole/cm^3 or mole/l .
 C' = concentration obtained from regression, mole/cm^3 or mole/l .
 $\bar{C}$ = average concentration or Laplace transform of concentration, mole/cm^3 .
 C^* = concentration of dissolved gas at interface, in equilibrium with gas at interface, mole/cm^3 .
 d = column internal diameter, ft.
 D = diffusivity in the liquid, cm^2/sec .
 E = enhancement factor, i.e., factor by which rate of absorption is increased by reaction.
 Fr = Froude number.
 h = constant(s) in Equ. (C5).
 H = Henry's law constant, atm/mole fraction or atm-l/mole.
 H^0 = Henry's law constant in water, atm/mole fraction or atm-l/mole.
 I = ionic strength, mole/l .
 k = first order rate constant, sec^{-1} .
 k_G = gas phase mass transfer coefficient, $\text{mole}/\text{cm}^2\text{-sec-atm}$.
 k_L = liquid phase chemical mass transfer coefficient, cm/sec .
 k_L^0 = liquid phase physical mass transfer coefficient, cm/sec .
 $k_L a$ = volumetric chemical mass transfer coefficient, sec^{-1} .

- $k_L^0 a$ = volumetric physical mass transfer coefficient, sec^{-1} .
 K_L = overall mass transfer coefficient based on the liquid film,
 cm/sec .
 k_2 = second order rate constant, $\text{cm}^3/\text{sec-mole}$.
 k_2^0 = second order rate constant at infinite dilution, $\text{cm}^3/\text{sec-mole}$.
 L = length of absorption column test section, ft .
 P = partial pressure in gas phase, atm .
 P_t = total pressure, atm .
 Q = volumetric flowrate, ft^3/sec .
 r = rate of reaction, $\text{mole/cm}^3\text{-sec}$.
 R = rate of absorption, $\text{mole/cm}^2\text{-sec}$.
 R_v = delivered gas to liquid volumetric ratio.
 s = fractional rate of surface renewal, sec^{-1} .
 t = time, sec .
 T = temperature, $^{\circ}\text{F}$.
 v^0 = superficial velocity, i.e., $4Q/\pi d^2$, ft/sec .
 x = distance from interface into liquid film, cm .
 Y = mole fraction in the gas phase.
 $\bar{Y}$ = average mole fraction.
 Z = ionic charge.
 ρ = density, mole/cm^3 .
 Λ = dimensionless parameter containing specific physical properties
of the liquid with reference to water.
 ϕ = average rate of absorption over time t , $\text{mole/cm}^2\text{-sec}$.
 ψ = surface age distribution function defined by Equ. (10).

Subscripts

- A = component A, CO_2 .
 B = component B, OH^- .
 CO_2 = carbon dioxide.
 G = gas phase.
 HCO_3^- = bicarbonate ion.
 H^+ = hydrogen ion.
 i = condition at the interface, component i .
 in = inlet condition.
 L = liquid phase.
 Na^+ = sodium ion.
 OH^- = hydroxide ion.
 $\text{CO}_3^{=}$ = carbonate ion.
 o = condition in the bulk liquid.
 TP = two-phase mixture.
 1 = condition at sample port 1.
 2 = condition at sample port 2.
 $+$ = refers to positive ion.
 $-$ = refers to negative ion.

Mathematical Terminology

- $\frac{d}{dx_i}$ = ordinary derivative
 $\frac{\partial}{\partial x_i}$ = partial derivative
 $\frac{D}{Dt}$ = substantial derivative
 ∇^2 = Laplacian operator

I. INTRODUCTION

There are a variety of gas-liquid contacting devices. One of the simplest that has received attention recently is the cocurrent pipeline contactor. Applications where such a contactor might be advantageous include absorption operations which require only one equilibrium stage or a reactor where mass transfer and chemical reaction occur simultaneously. In many industrial operations it may be desirable to utilize such systems having high mass transfer coefficients as contacting stages, even though the overall staged operation is countercurrent. Also, consider the case of cocurrent gas-liquid multicomponent flow in heat exchanger tubes, which cool reactor effluent streams. The process engineer would like to estimate the amount of absorption taking place in such tubes in order to plan for subsequent processing operations. There are many other examples in the chemical process industries where mass transfer in two-phase cocurrent flow is important.

The application of gas-liquid cocurrent flow in mass transfer operations and gas absorption in particular, holds several potential advantages. The primary advantage is the absence of flooding, even at high gas and liquid flow rates, which allows for high mass transfer rates per unit volume. Also, high flow rates prevent caking or settling of precipitated reaction products. Other advantages include the freedom to orient the device at any angle between horizontal and vertical, simplicity of design and simple temperature control.

Cocurrent contactors are in use in the chemical process industries only in special cases because of lack of data. Before they can be fully implemented on an industrial scale, reliable models must be developed to resolve the dependencies of both the liquid phase mass transfer coefficient and the interfacial area on contactor hydrodynamics. The design problem is complicated by the fact that one would expect different mass transfer efficiencies for the different flow regimes. Each regime must be investigated separately.

In view of the potential advantages and probable applications of two-phase flow for mass transfer operations, the goal of this work was to measure mass transfer coefficients and interfacial areas in as many flow regimes in cocurrent downflow as possible.

II. BACKGROUND

Mass transfer is directly dependent, in part, on the hydrodynamics of two-phase flow. In 1974, Oshinowo and Charles (24, 25) published a two part paper on flow pattern, holdup and pressure drop correlations. They investigated both upflow and downflow using an air-water system. A flow pattern classification with six regimes was established for downflow. The flow regimes are illustrated in Figure 1. No independent literature data was available to test the correlation for downflow systems. Another study on two-phase flow hydrodynamics was published later by Thwaites et al. (35). Liquid film properties in downward annular flow were investigated. They are base film thickness, wave frequency of the liquid film, pressure gradient and wave velocity. It is the wave structure that presents the greatest problems in any theoretical attempt at a complete understanding of the hydrodynamics of the liquid film.

In recent years several papers have been published on mass transfer in gas-liquid flow in pipeline contactors. Most work has been concerned with horizontal flow with only a few publications on vertical upflow. Only one study has been done on cocurrent downflow.

Heuss et al. (14) reported on liquid side controlled absorption of oxygen and gas side controlled absorption of ammonia into water in horizontal flow under froth conditions. Scott and Hayduk (30) obtained data on the liquid side controlled absorption of carbon dioxide into water,

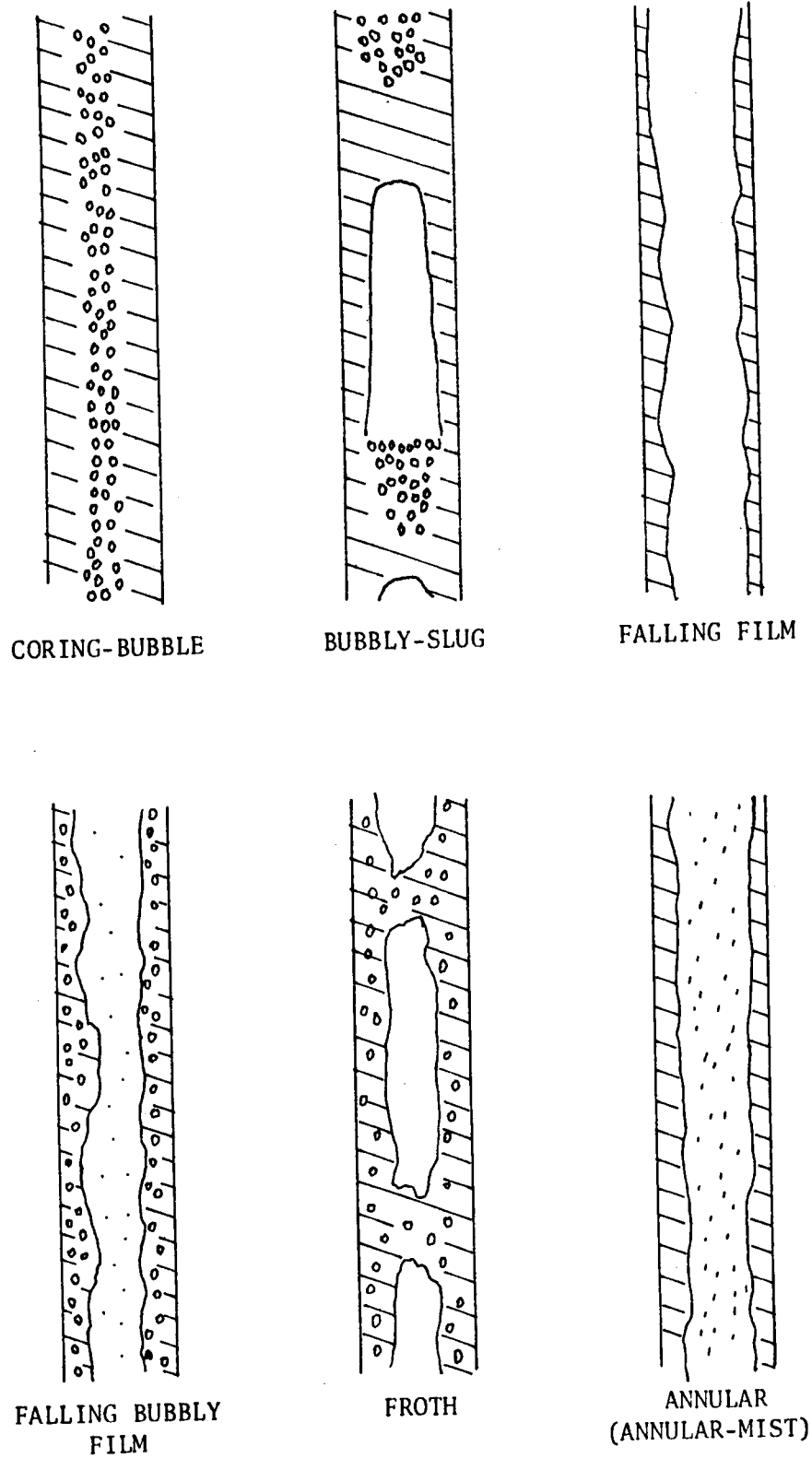


Figure 1. Flow patterns observed in vertical downflow (from Oshinowo).

ethylene glycol and ethanol. The bubble and plug flow regimes were studied in horizontal tubes of various sizes. Mass transfer in bubble flow was studied by Lamont and Scott (22). They absorbed pure carbon dioxide into water and found that the liquid mass transfer coefficient depended on the bubble frequency to a power of one-third but was almost independent of bubble size. Heuss (14) reported the opposite result. Wales (39) measured overall mass transfer coefficients and interfacial areas in annular and dispersed two-phase flow in a one-inch horizontal pipe. Doubts have been raised about the accuracy of his results by Cichy and Russel (7) and by Jepsen (17). Jepsen (17) obtained data on the absorption and desorption of oxygen in horizontal tubes of one and four-inch diameters. A general correlation was presented for $k_L a$ as a function of the two-phase frictional energy dissipation, liquid phase physical properties and pipe diameter. In 1971, Ciborowski and Rychlicki (6) absorbed carbon dioxide and ammonia into water in horizontal wavy flow. Anderson (1) investigated gas side controlled absorption of ammonia into water in a one-inch horizontal tube in annular flow. The rate of mass transfer was found to be increased by the interchange of liquid between the film and the entrained droplets. Finally, in 1975, Shah and Sharma (31) measured interfacial areas and mass transfer coefficients in horizontal tubes in the combined bubble and plug flow regimes. The volumetric mass transfer coefficients agree reasonably well with those predicted by the proposed correlation by Scott and Hayduk (30).

As mentioned, fewer papers have been published dealing with vertical upflow. In 1963, Van Heuven and Beek (37) absorbed carbon dioxide into water in gas lifts in slug flow. Later, Bannerjee (4) obtained mass transfer coefficients and interfacial areas in annular flow in helically coiled tubes. Kahol (19) obtained interfacial areas and mass transfer coefficients in the annular and froth flow regimes in a 1/2-inch column by chemical absorption into aqueous sodium hydroxide solutions. In 1974, Kasturi and Stepanek (20), using the same absorption system, presented interfacial areas for a narrow tube 6mm in diameter. Neither the Jepsen nor the Bannerjee energy dissipation parameters predicted the data very well. Good fit was possible by use of a parameter called the "rate of creation of interfacial area" against the frictional part of the pressure drop. In the fourth part of a four part series, Kasturi and Stepanek (21) presented gas and liquid side mass transfer coefficients. Recently, Shilimkan and Stepanek (34) measured interfacial areas in cocurrent upflow in tubes 10, 15 and 20mm in diameter absorbing carbon dioxide into 1N aqueous sodium hydroxide. The interfacial area showed a maximum at a different superficial velocity for different tubes, an indication that flow conditions between the different sized tubes was different. In 1979, Watson et al. (40) measured interfacial areas in a one-inch tube in the slug and froth flow regimes. The interfacial area showed a strong dependence upon the coordinates of the flow regime map proposed by Oshinowo and Charles (24). They concluded that before models could be developed correlating interfacial areas and mass transfer coefficients to frictional pressure

drop, new methods of measuring the actual frictional pressure drop must be developed.

The only study made in cocurrent gas-liquid vertical downflow was by Vavruska (38). He measured mass transfer coefficients and interfacial areas using the carbon dioxide-sodium hydroxide system. Liquid velocities in the one-inch column ranged from 0.3 to 1.5 ft./sec. while gas velocities ranged from 6 to 20 ft./sec.

III. THEORY

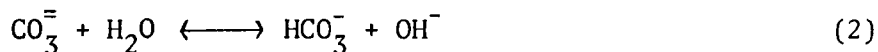
Hydrodynamics

A detailed comparison of data collected in cocurrent gas-liquid flow requires a theoretical basis for predicting what flow regime will occur under a given set of conditions. No correlation of this kind is available. In this study, the flow regime map of Oshinowo and Charles (24) was used as a guide in identifying the flow regimes in cocurrent downflow in a one-inch pipeline.

The six flow regimes are presented on the flow regime map in Figure 2. Vavruska (38) converted the coordinates of this map, $R_V^{1/2}$ and $Fr_{TP}/\Lambda^{1/2}$, to superficial gas and liquid velocities respectively. The replotted map is shown in Figure 3.

Chemical Reaction Kinetics

In this study, carbon dioxide was absorbed from air into aqueous sodium hydroxide solutions. Sodium hydroxide facilitates the absorption of carbon dioxide by reaction with it. The following reactions occur:



According to Astarita (2), if the sodium hydroxide concentration is higher than 0.01 gmole/liter the second reaction above is driven to the left.

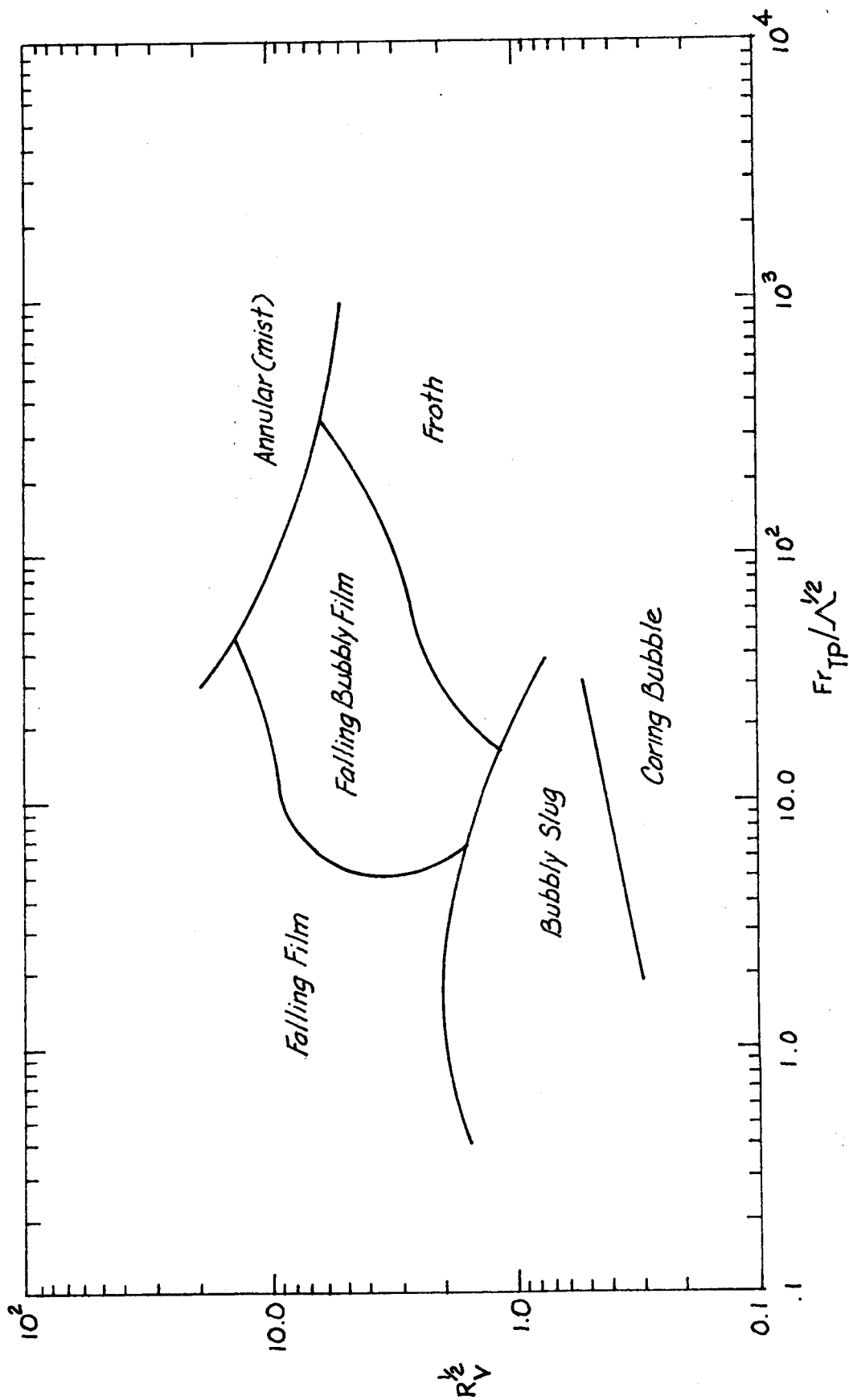


Figure 2. Proposed general flow pattern map for two-phase gas-liquid vertical downflow (from Oshinowo).

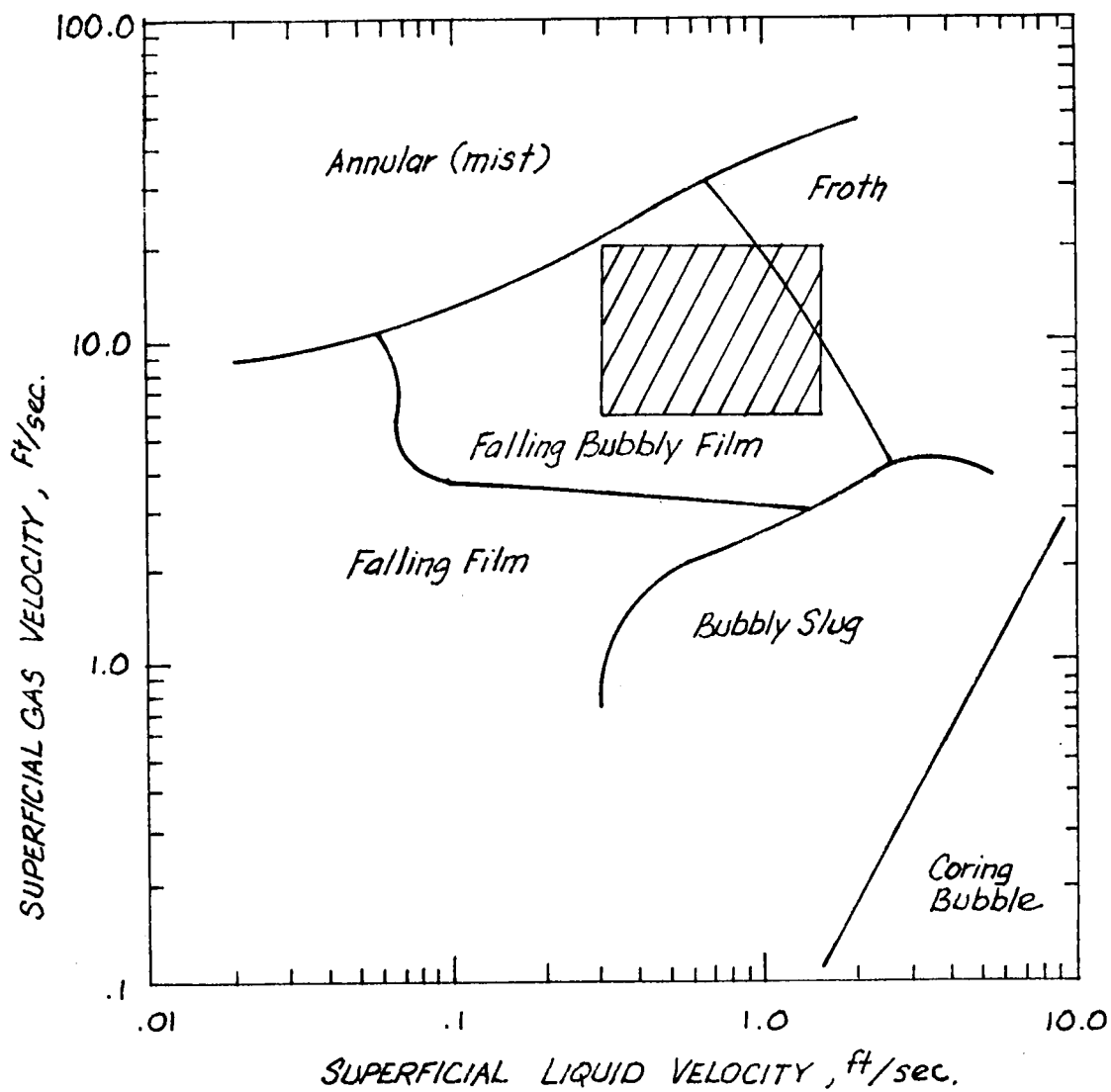
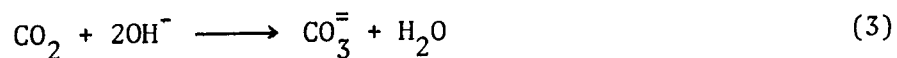


Figure 3. Vertical downward two-phase flow regimes (from Vavruska—shaded area is region covered by his work).

The following reaction results:



The rate of the reaction is expressed by the following second order rate equation:

$$r = k_2 C_A C_B \quad (4)$$

The problem can be simplified considerably by adjusting the concentration of reactants so the reaction is pseudo first order:

$$C_A \ll C_B \quad (5)$$

Satisfying the above condition, the rate equation can be written

$$r = k C_A \quad (6)$$

where $k = k_2 C_B$.

The reaction in the liquid film is fast. Danckwerts (8) proposed the following criterion for a fast, pseudo first order reaction:

$$1 < \frac{\sqrt{D_A k_2 C_B}}{k_L} \ll \sqrt{\frac{D_A}{D_B}} + \frac{C_B}{2C_A^*} \sqrt{\frac{D_B}{D_A}} \quad (7)$$

The reaction is assumed to be fast enough that it is restricted to the liquid film so that $C_A = 0$ in the bulk liquid. The concentration of sodium hydroxide is high enough that it is not significantly depleted

near the interface. Mass transfer behavior at the gas-liquid interface is illustrated in Figure 4.

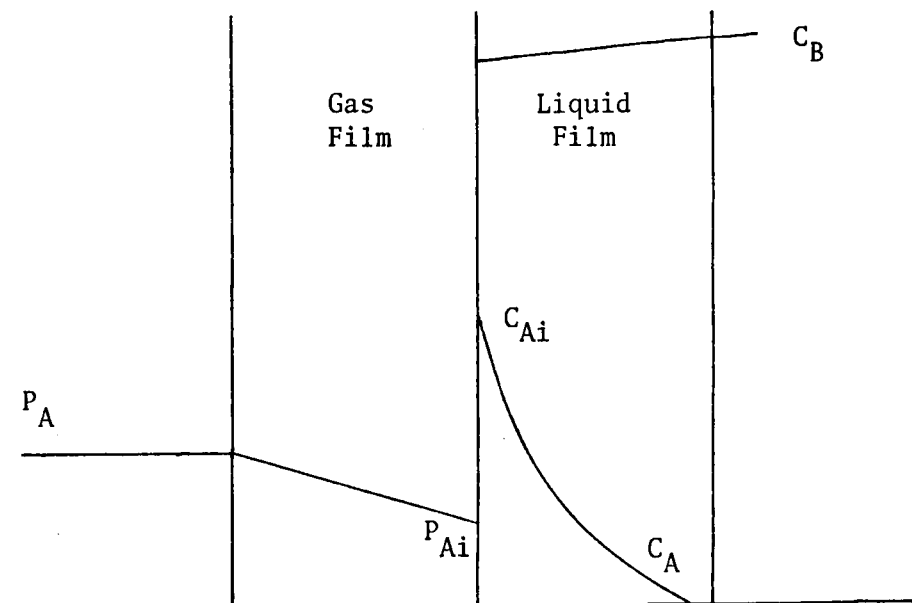


Figure 4. Mass transfer at the gas-liquid interface.

Surface Renewal Theory

Various hydrodynamic models have been proposed for the investigation of transport processes. The Danckwerts surface renewal model is the basis of the experimental method in this study.

Danckwerts (10) described the surface of the liquid as comprising a mosaic of elements which have been exposed to the gas for different lengths of time, and which themselves are replaced in due course by fresh liquid having the local average bulk composition. The rate of absorption of gas per unit area into an element of surface which has

been exposed for a length of time t is $\phi(t)$. The fraction of the surface which has been exposed for times between t and $t + dt$ is $\psi(t) dt$. The average rate of absorption is expressed by

$$R = \int_0^{\infty} \phi(t)\psi(t) dt \quad (8)$$

From Higbie (15), the average rate of absorption into a stagnant liquid of infinite depth is

$$\phi(t) = (C_{Ai} - C_{Ao}) \left(\frac{D_A}{\pi t} \right)^{1/2} \quad (9)$$

and from Danckwerts (10),

$$\psi(t) = s e^{-st} \quad (10)$$

The average rate of absorption per unit area of turbulent surface may now be expressed by the following:

$$\begin{aligned} R &= (C_{Ai} - C_{Ao}) \sqrt{D_A} \int_0^{\infty} \frac{s e^{-st}}{\sqrt{\pi t}} dt \\ &= (C_{Ai} - C_{Ao}) \sqrt{D_A s} \end{aligned} \quad (11)$$

where the time-averaged liquid film mass transfer coefficient is expressed

$$k_L = \sqrt{D_A s} \quad (12)$$

This relationship between the mass transfer coefficient k_L and the

fractional rate of surface renewal s will be used in developing the final rate equation.

Double Resistance Theory

Mass transferred from the gas to the liquid must pass through a gas and a liquid film resistance. It is assumed there is no resistance at the gas-liquid interface and that the gas and liquid are in equilibrium there. Concentrations at the phase boundary may be expressed by the following:

$$P_{Ai} = H C_{Ai} \quad (13)$$

where H is the Henry's Law constant.

The rate of absorption of mass may be expressed by the following for the gas and liquid films:

$$R_a = k_G a (P_A - P_{Ai}) = E k_L a (C_{Ai} - C_{Ao}) \quad (14)$$

E is the enhancement factor which is included in the presence of chemical reaction given as

$$E = \frac{\text{rate of absorption with reaction}}{\text{rate of absorption for mass transfer only}} \quad (15)$$

The rate of absorption may be expressed in terms of the overall resistance given by

$$R_a = K_L a (C_A - C_{Ao}) \quad (16)$$

The following expression relates the overall mass transfer resistance to the individual resistances obtained by combining Equations (13), (14) and (16):

$$\frac{1}{K_L a} = \frac{1}{E k_L a} + \frac{1}{H k_G a} \quad (17)$$

In this study, H is large since the gas is only slightly soluble in the liquid. Thus, the gas-side resistance is negligible and the liquid-film resistance controls absorption.

Danckwerts Rate Equation for Diffusion with Chemical Reaction

The mass balance for diffusion with chemical reaction leads to the following differential equation:

$$\frac{DC_A}{Dt} = D_A \nabla^2 C_A + r_A \quad (18)$$

where $r_A = -kC_A$.

If it is assumed that diffusion occurs perpendicular to the gas-liquid interface, Equation (18) may be written

$$\frac{\partial C_A}{\partial t} = D_A \frac{\partial^2 C_A}{\partial x^2} - kC_A \quad (19)$$

The boundary conditions for the differential equation are

$$\begin{array}{ll}
 x > 0, t = 0 & C_A = C_{Ao} = 0 \\
 x = 0, t > 0 & C_A = C_{Ai} = C_A^* \\
 x = \infty, t > 0 & C_A = C_{Ao} = 0
 \end{array}$$

Applying the Laplace transform to the differential equation and boundary conditions leads to the following transformed solution:

$$\bar{C}_A = \frac{C_A^*}{s} \exp\left[-\left(\frac{k+s}{D_A}\right)^{1/2} x\right] \quad (20)$$

The rate of absorption of gas per unit area at the gas-liquid interface may be expressed by Fick's first law

$$\phi(t) = -D_A \left[\frac{\partial C_A}{\partial x} \right]_{x=0} \quad (21)$$

Substitution of Equations (10) and (21) into Equation (8) gives

$$\begin{aligned}
 R &= - \int_0^\infty s e^{-st} D_A \left[\frac{\partial C_A}{\partial x} \right]_{x=0} dt \\
 &= -s D_A \frac{d}{dx} \left[\int_0^\infty e^{-st} C_A dt \right]_{x=0} \\
 &= -s D_A \left[\frac{d\bar{C}_A}{dx} \right]_{x=0} \quad (22)
 \end{aligned}$$

Substitution of Equation (20) into Equation (22) and taking the derivative yields the following result:

$$R = C_A^* [D_A(k+s)]^{1/2} \quad (23)$$

where $k = k_2 C_B$ and $s = k_L^2 / D_A$.

Multiplying both sides of Equation (23) by a gives the rate equation upon which the experimental method is based,

$$Ra = a C_A^* [D_A k_2 C_B + k_L^2]^{1/2} \quad (24)$$

Rate Equation for Diffusion without Chemical Reaction

Equation (24) may be written as follows in the absence of chemical reaction

$$Ra = k_L^o a C_A^* \quad (25)$$

where $k_L a$ is redefined as $k_L^o a$ for physical absorption.

IV. EXPERIMENTAL EQUIPMENT AND PROCEDURE

Absorption Column

The column was constructed of one-inch I.D. Pyrex glass pipe. The gas and liquid streams were combined at the top of the column in a glass tee. A five-foot calming section was installed below the mixing tee to allow flow in the column to develop before entering the test section. Sample ports were located at the top and bottom of the test section which was approximately eight feet in length. The gas-liquid stream passed from the test section into an ell-section which led to the sewer. The column was supported by a metal framework fastened to the floor, ceiling and wall of the laboratory. The absorption column is shown in Figure 5.

Gas Analysis System

Gas samples were drawn from the column at the top and bottom of the test section. For samples to be accurate it was important to draw only one phase from the column since mass transfer could occur in the tubing leading to the outside. The data by Wales (39) and Jepsen (17) has been questioned by Cinchy and Russel (7) among others and has been attributed to inadequate sampling.

A device was developed in this work which allowed reliable samples to be taken even at high liquid flow rates. At the beginning, a 1/4-inch O.D. stainless steel tube was installed with a one-inch ell pointing down the column. This proved to be ineffective. The new device was a tube within a tube arrangement. A 1/4-inch O.D. stainless steel tube

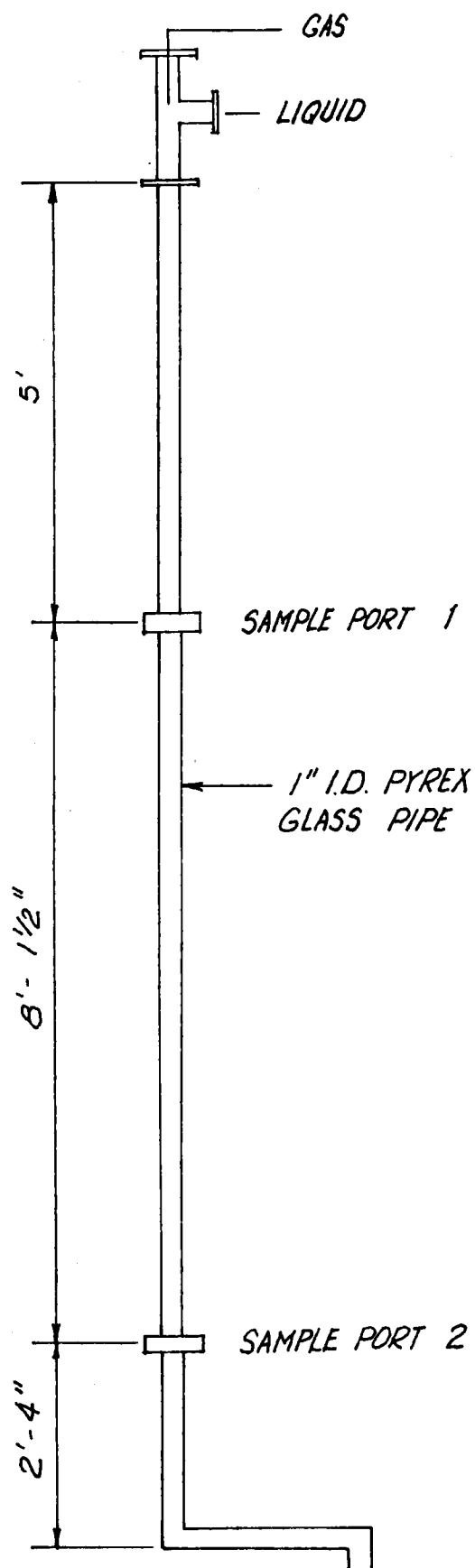


Figure 5. Absorption column.

with a cone-shaped plastic tube fit at the end, made up the inside tube. Over this was placed a 1/2-inch O.D. plastic tube which acted as a water shield. The device was installed into the plexiglas sample section with the 2 1/2-inch ell directed up the center of the column as shown in Figure 6.

Gas Analysis

Samples were drawn from the column by vacuum. A water aspirator was used as the vacuum source. The arrows in Figure 6 indicate the flow of sample from the column. Sample gas flowed through the outside tube and into the inside tube through pinholes in the cone at the top of the sampling device and then to the outside of the column. Only a trace of moisture could be seen in the flow lines after a one-hour run. To alleviate this problem, the flow lines were periodically blown dry. As a precaution, the gas sample was passed through a one-foot length of 1/4-inch I.D. plastic tubing packed with silica gel. The dried sample was metered by a Brooks rotameter at 1 ft³/hr passing from the Horiba Model PIR-2000 infrared gas analyzer. The analyzer was calibrated to read concentrations of carbon dioxide in the gas stream from 0 to 2.5%. The lower and upper range were adjusted daily using nitrogen and span gas respectively. The analyzer was connected to a Schlumberger Model SR-204 strip chart recorder. Refer to page 25.

Pressure Measurement System

It was necessary to know the total pressure in the column for mass transfer calculations. Total pressure was used to calculate gas density

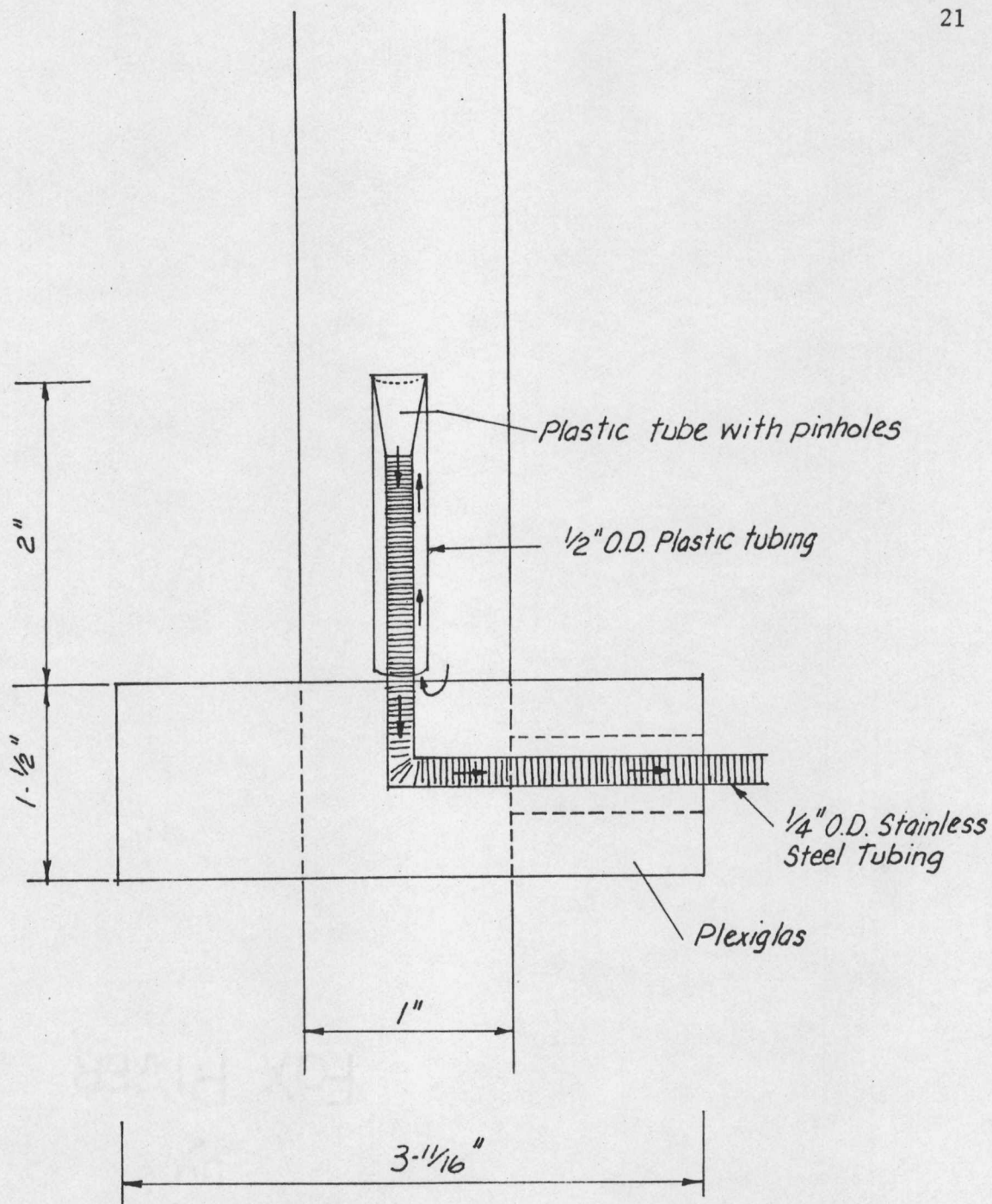


Figure 6. Gas sampling system.

as well as the equilibrium solubility of carbon dioxide in the liquid. Pressure in the column was measured with a one-meter U-tube manometer filled with 1.75 specific gravity manometer fluid. The lighter fluid was used rather than mercury due to its greater sensitivity. The manometer was connected to the gas sampling devices. To smooth out pressure pulsations, which become pronounced at high gas-liquid flows, a three-liter flask was installed as a surge chamber. To further dampen pressure fluctuation, a .6mm I.D. capillary tube was installed. Readings were easily made on the manometer. The pressure measurement system is illustrated in Figure 7.

Experimental System-Supporting Equipment

Liquid feed solutions were made up in a 75-liter stainless steel tank. The liquid was pumped to the top of the column with an Alsop centrifugal pump driven by a 1/2 H.P. Alsop electric motor. The flow of the liquid was metered through one Fisher and Porter and two Brooks rotameters placed in parallel. The meters were calibrated by direct weighing method using a Toledo scale, 75-liter tank and a watch. Calibration curves are in Appendix E.

Air was available from a laboratory supply line at 80 psig. It was filtered by Sharpe and Speedaire filters. Air flow was measured by one Cochraine and one Fisher and Porter rotameter. Both were calibrated with a 100 CPH capacity wet test meter. See Appendix E for calibration curves.

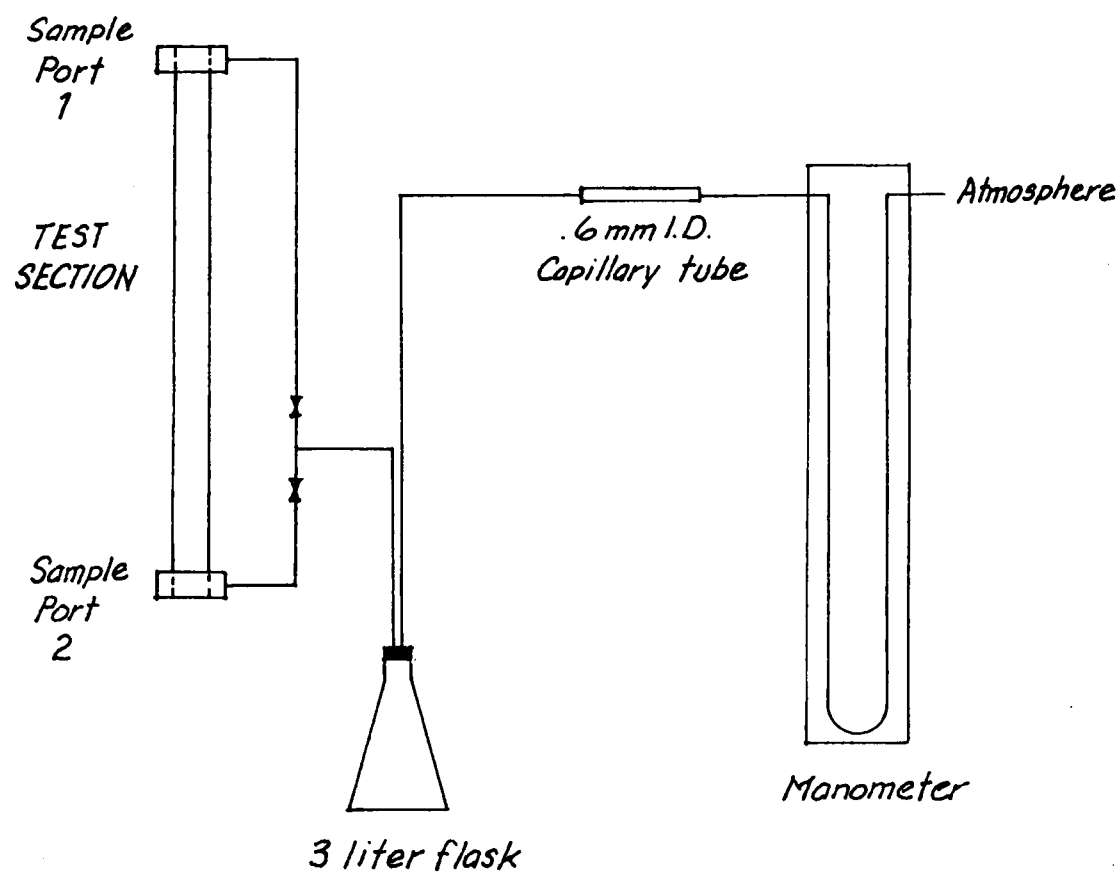


Figure 7. Pressure measurement system.

Carbon dioxide was fed from a pressurized cylinder through a heated pressure regulator to avoid the Joule-Thompson cooling effect of a rapidly expanding gas. The flow of carbon dioxide was measured using a Brooks rotameter which was calibrated with a 680 liter/hour capacity wet test meter. Calibration curves are in Appendix E.

The air and carbon dioxide streams were combined in a tee and fed to the top of the column in 3/8-inch I.D. Tygon tubing. All other gas tubing was 1/8-inch I.D. plastic. Liquid was delivered through 3/4-inch I.D. Tygon tubing. Details of the experimental system are illustrated in Figure 8.

Experimental Procedure

Runs were made at seven different gas rates. At each gas flow rate the liquid flow was varied seven times. Superficial liquid velocities ranged from 0.06 to 1.5 ft/sec and superficial gas velocities ranged from 1.5 to 20 ft/sec. Sodium hydroxide concentrations in the feed ranged from 0.05 N to 0.3 N. The concentration of carbon dioxide in the gas stream was 2.5%. The experimental procedure was as follows:

1. The feed tank was filled with 70 liters of deionized water. The desired quantity of sodium hydroxide pellets was weighed and predissolved in a two-liter beaker and then added to the tank. The liquid was thoroughly mixed. A sample was taken from the tank and titrated to determine the hydroxide ion concentration. The feed temperature was recorded and ranged from 77 to 85°F.

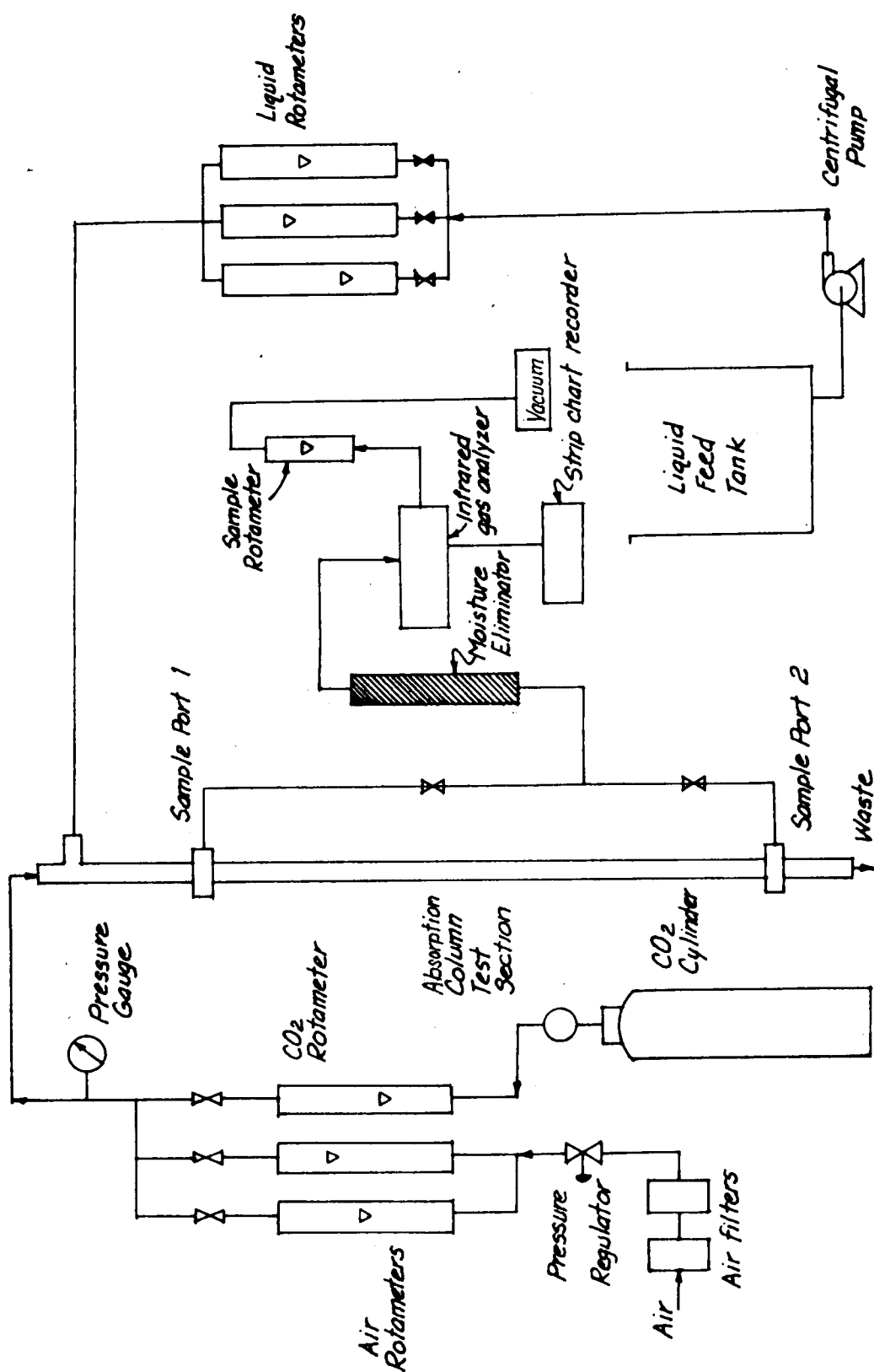


Figure 8. Experimental flow diagram.

2. The air and carbon dioxide flow rates were adjusted to the desired levels so that the analyzer read 2.5% on a full scale deflection. The pressure and temperature of the gas were recorded.

3. The liquid feed was pumped to the top of the column and the flow rate was adjusted to the desired level. At least one minute was necessary to reach steady state before taking samples.

4. Gas samples were drawn first from the top and then from the bottom of the test section. The results were recorded by a chart recorder connected to the gas analyzer.

5. The liquid rate was increased to the next desired level and step 4 was repeated until seven liquid rates had been done. This completed one run.

6. The above steps were repeated for at least three different sodium hydroxide concentrations, at least three runs were made for each gas flow rate.

Figure 9 shows the area of the flow regime map where data was collected.

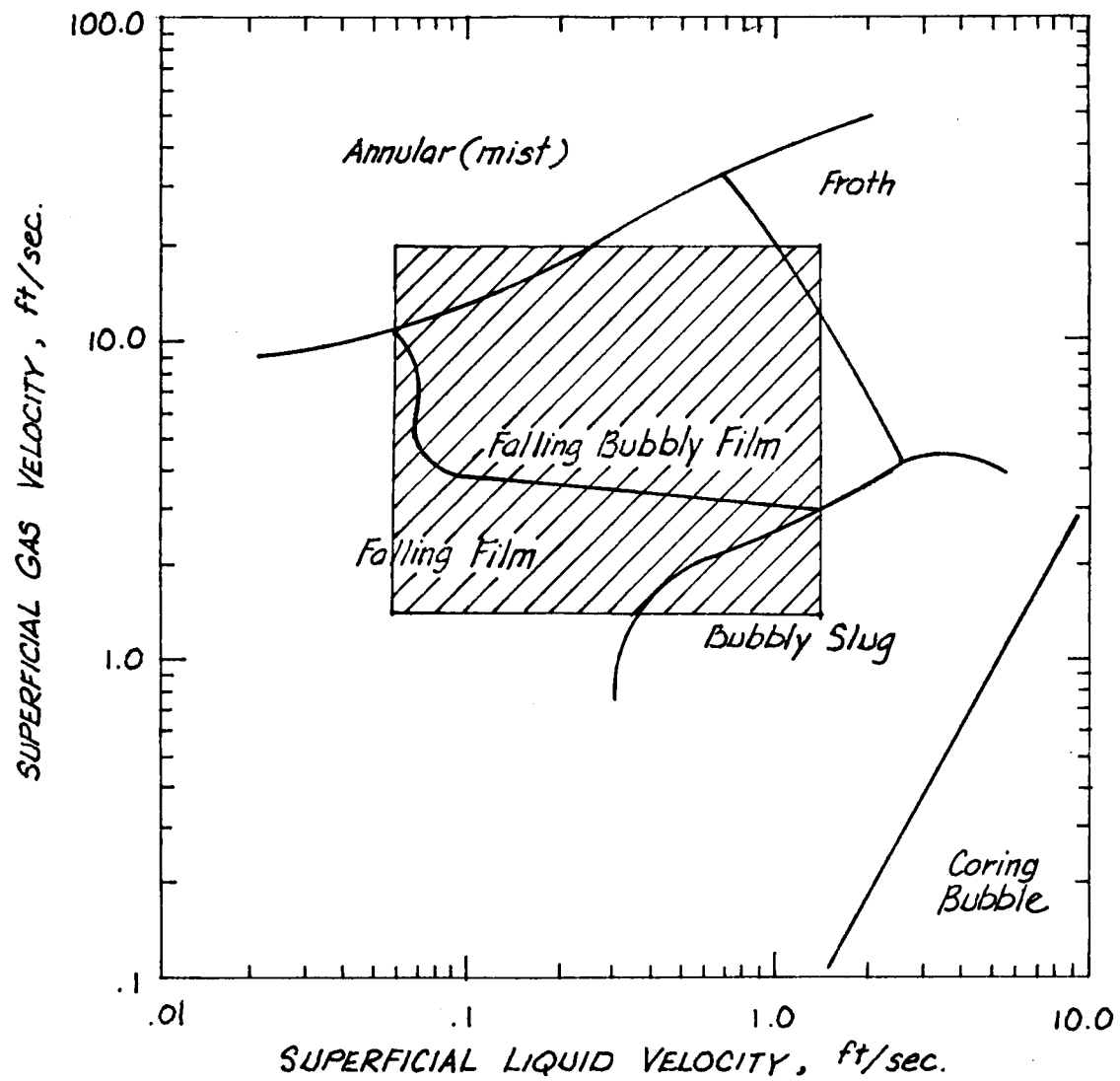


Figure 9. Region of flow regime map covered in this work.

V. ANALYSIS OF COLLECTED DATA

Chemical Absorption Data

The following quantities were measured in the laboratory for absorption data analysis: (1) gas and liquid flow rates through the column, (2) inlet gas temperature and pressure, (3) liquid feed temperature, (4) sodium hydroxide concentrations in the liquid feed, and (5) carbon dioxide mole fractions in the gas at sample ports 1 and 2. The absorption data is presented in Appendix G.

Since most of the resistance to mass transfer is in the liquid film and the rate equation is based on this, a mass balance was performed to calculate the concentration of carbonate in the liquid. The mass balance for the calculation of concentration at sample port 1 is as follows:

$$(C_{\text{CO}_3,1})(V_L^0)(A_t) = (Y_{\text{CO}_2,\text{in}} - Y_{\text{CO}_2,1})(P_G)(V_G^0)(A_t) \quad (26)$$

$$\frac{\text{mole}}{\text{sec}} = \frac{\text{mole}}{\text{sec}}$$

where $(Y_{\text{CO}_2,\text{in}} - Y_{\text{CO}_2,1})$ represents the difference in the mole fraction of the inlet gas stream to the mole fraction of the gas stream at sample port 1. Equation (26) may be written as

$$C_{\text{CO}_3,1} = \frac{(Y_{\text{CO}_2,\text{in}} - Y_{\text{CO}_2,1})(P_G)(V_G^0)}{V_L^0} \quad (27)$$

A similar procedure is followed for calculation of $C_{\text{CO}_3,2}$ at sample port 2.

Carbonate concentrations showed an exponential decrease with increasing superficial liquid velocity for both sample ports 1 and 2. See Figure 10. It was felt that greater accuracy could be obtained by curve fitting the data. When plotted on log-log plots, the data gave straight lines as shown in Figure 11. All data was fit by linear regression. Correlation coefficients were 0.99 or better in most cases.

The hydroxide ion concentration in the liquid decreased with distance down the column. An arithmetic mean concentration in the test section was calculated by the following:

$$\bar{C}_{OH^-} = C_{OH^-} - (C'_{CO_3,1} + C'_{CO_3,2}) \quad (28)$$

The second order rate constant was calculated from the following equation. See Appendix C for its development.

$$k_2 = 4.315 \times 10^{16} \exp[0.13 \bar{C}_{OH^-} - \frac{1.2 \times 10^4}{T + 460}] \quad (29)$$

By measuring the change in liquid carbonate content across the column test section, the rate of absorption per unit volume of liquid is given as follows:

$$Ra = \frac{(C'_{CO_3,2} - C'_{CO_3,1}) V_L^0}{L} \quad (30)$$

Danckwerts plot was constructed by plotting $(Ra)^2$ versus $k_2 \bar{C}_{OH^-}$. The result was a straight line of slope, $(aC_{CO_2}^*)^2 D_{CO_2}$ and intercept,

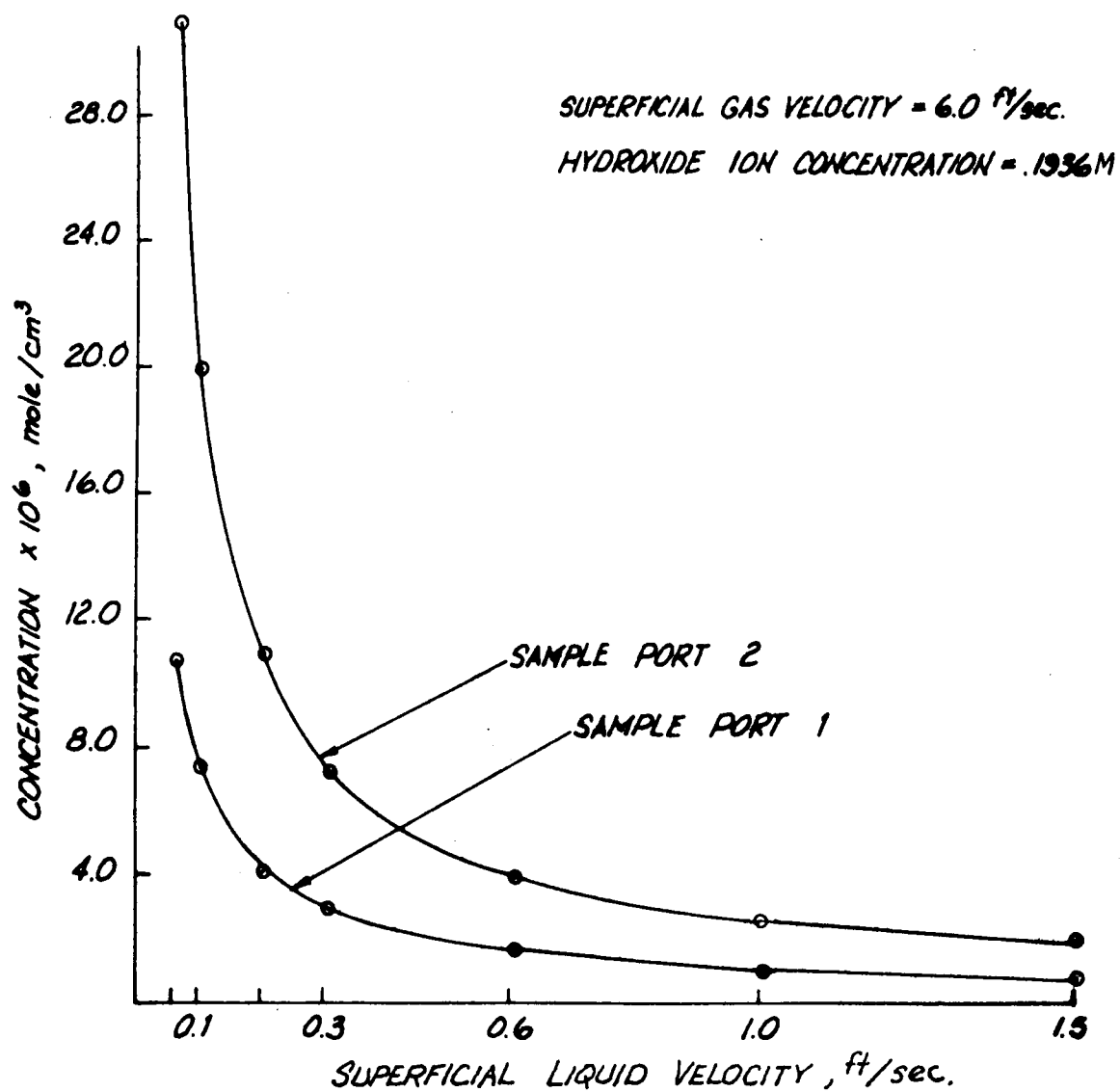


Figure 10. Effect of liquid velocity on the concentration of carbonate in the liquid.

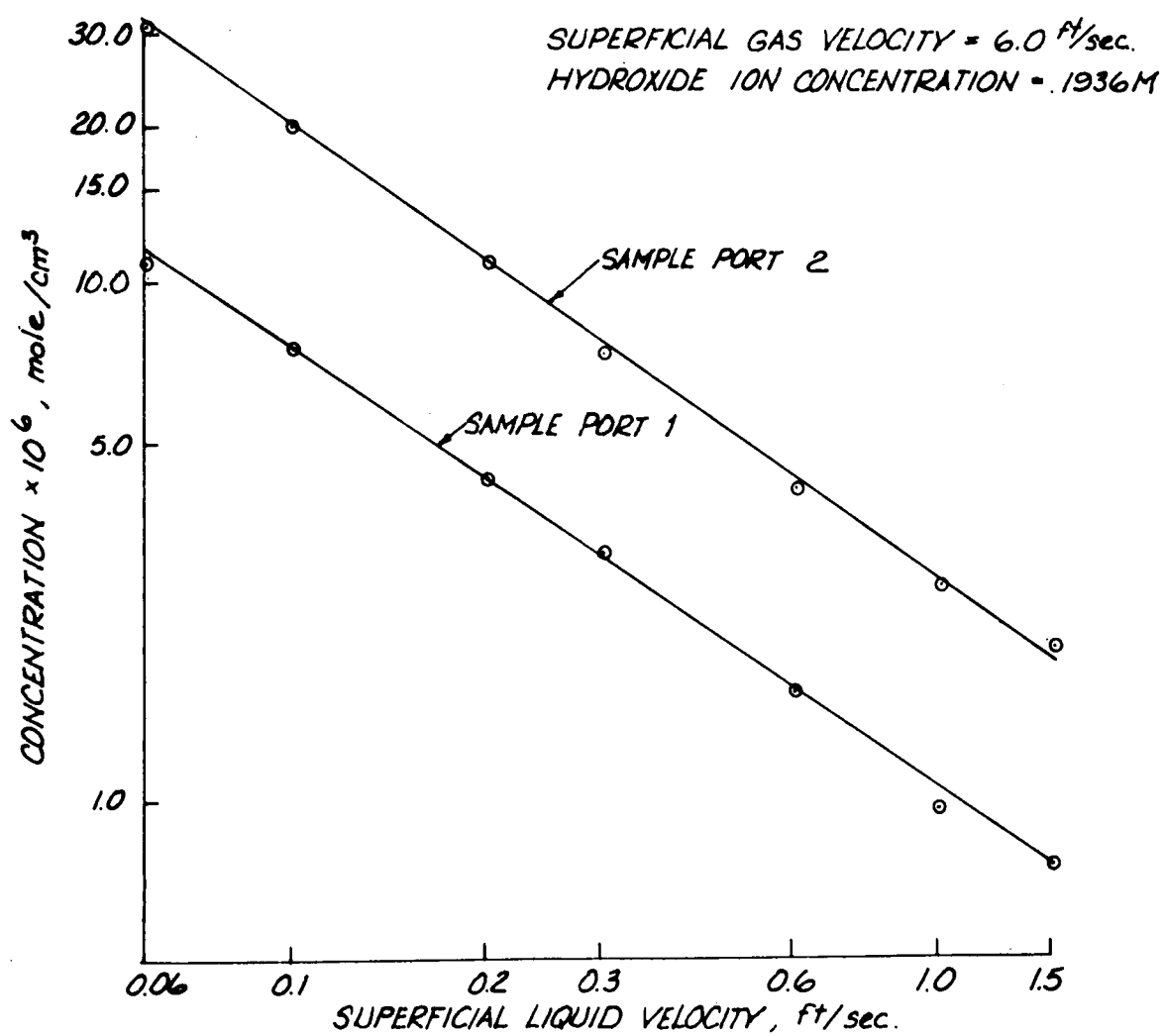


Figure 11. Liquid velocity versus concentration of carbonate in the liquid on a log-log plot.

$(k_L C_{CO_2}^* a)^2$. Plots representing all gas and liquid velocities investigated appear in Figures 12 through 18.

The equilibrium concentration of carbon dioxide was calculated from the following equation:

$$C_{CO_2}^* = \frac{\bar{Y}_{CO_2} P_t 10^{-3}}{H} (55.556 + \bar{C}_{OH^-}) \quad (31)$$

where Henry's law constant, H was calculated by the following equation developed in Appendix C:

$$\log_{10} H = \log_{10} [24.78 T - 266.9] + \bar{C}_{OH^-} [.261 - .028 \ln T] \quad (32)$$

Since $C_{CO_2}^*$ varied with hydroxide ion concentration, a mean value, $\bar{C}_{CO_2}^*$ was used in calculation of the results.

Using the calculated values of $C_{CO_2}^*$, along with the slope and intercept of the lines of the Danckwerts plot, interfacial areas and liquid phase chemical mass transfer coefficients were calculated from the following equations:

$$a = \frac{1}{\bar{C}_{CO_2}^*} \left[\frac{\text{slope}}{D_{CO_2}} \right]^{1/2} \quad (33)$$

and

$$k_L = \frac{(\text{intercept})^{1/2}}{a \bar{C}_{CO_2}^*} \quad (34)$$

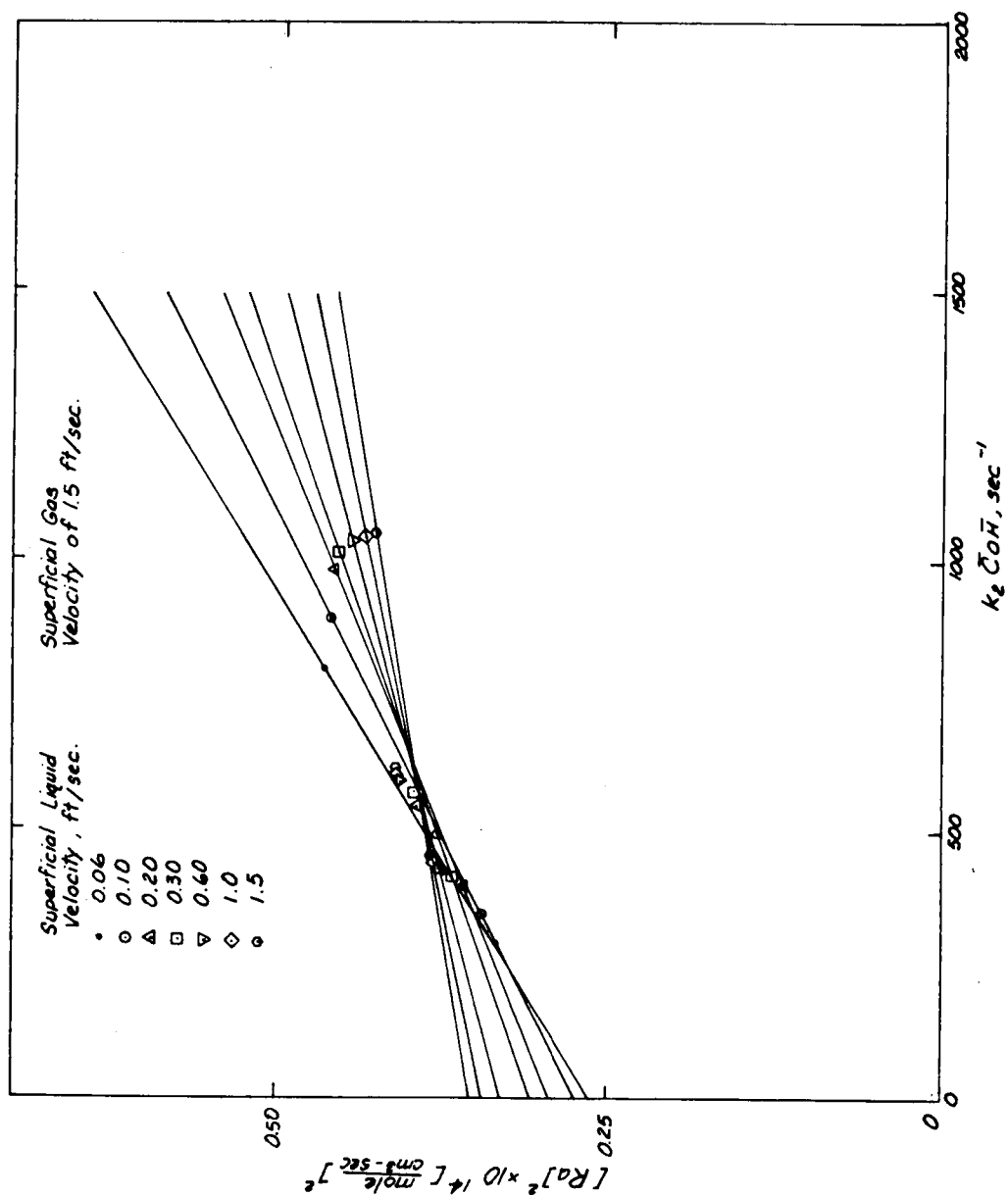


Figure 12. "Danckwerts plot" for superficial gas velocity of 1.5 ft/sec.

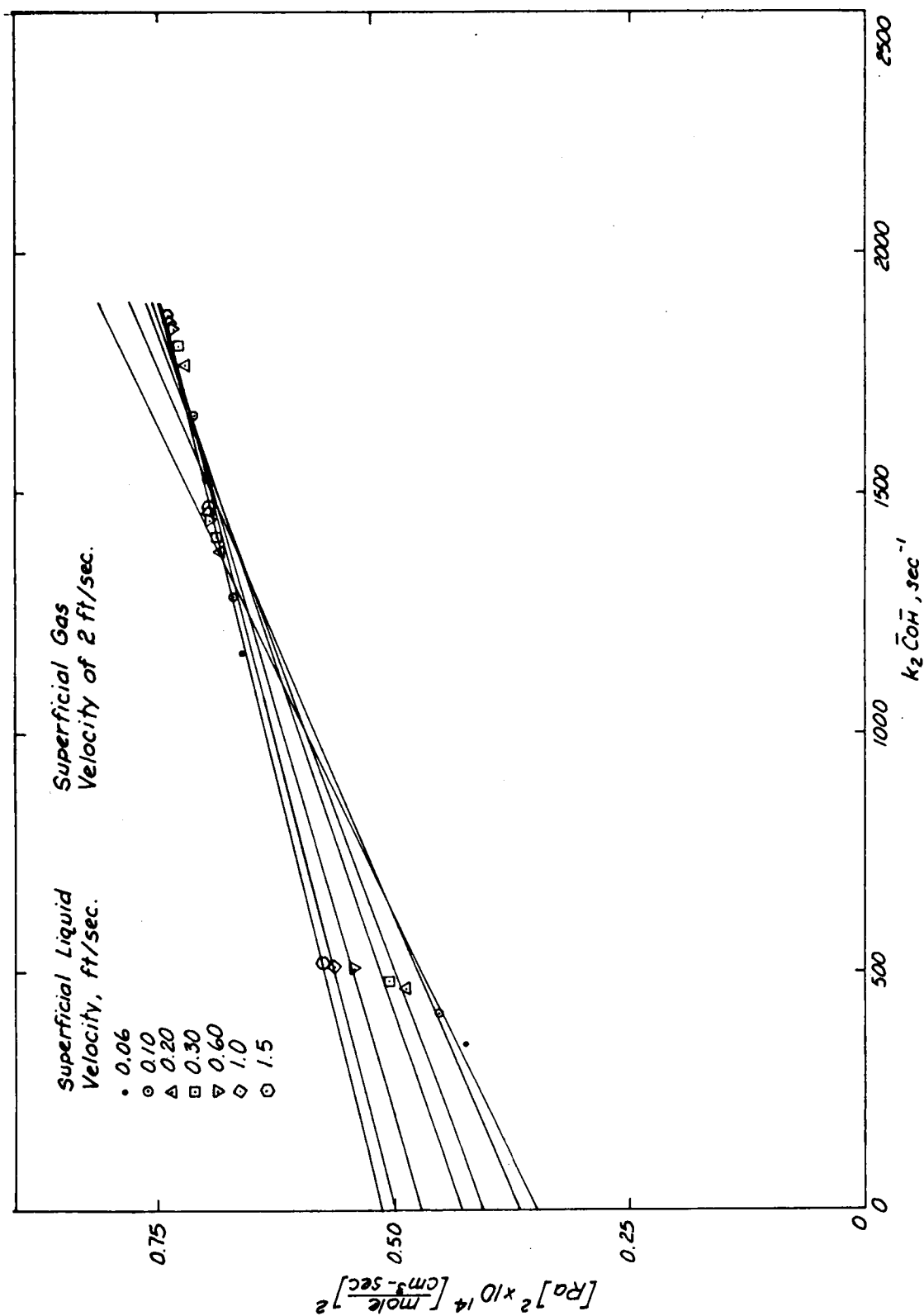


Figure 13. "Danckwerts plot" for superficial gas velocity of 2.0 ft/sec.

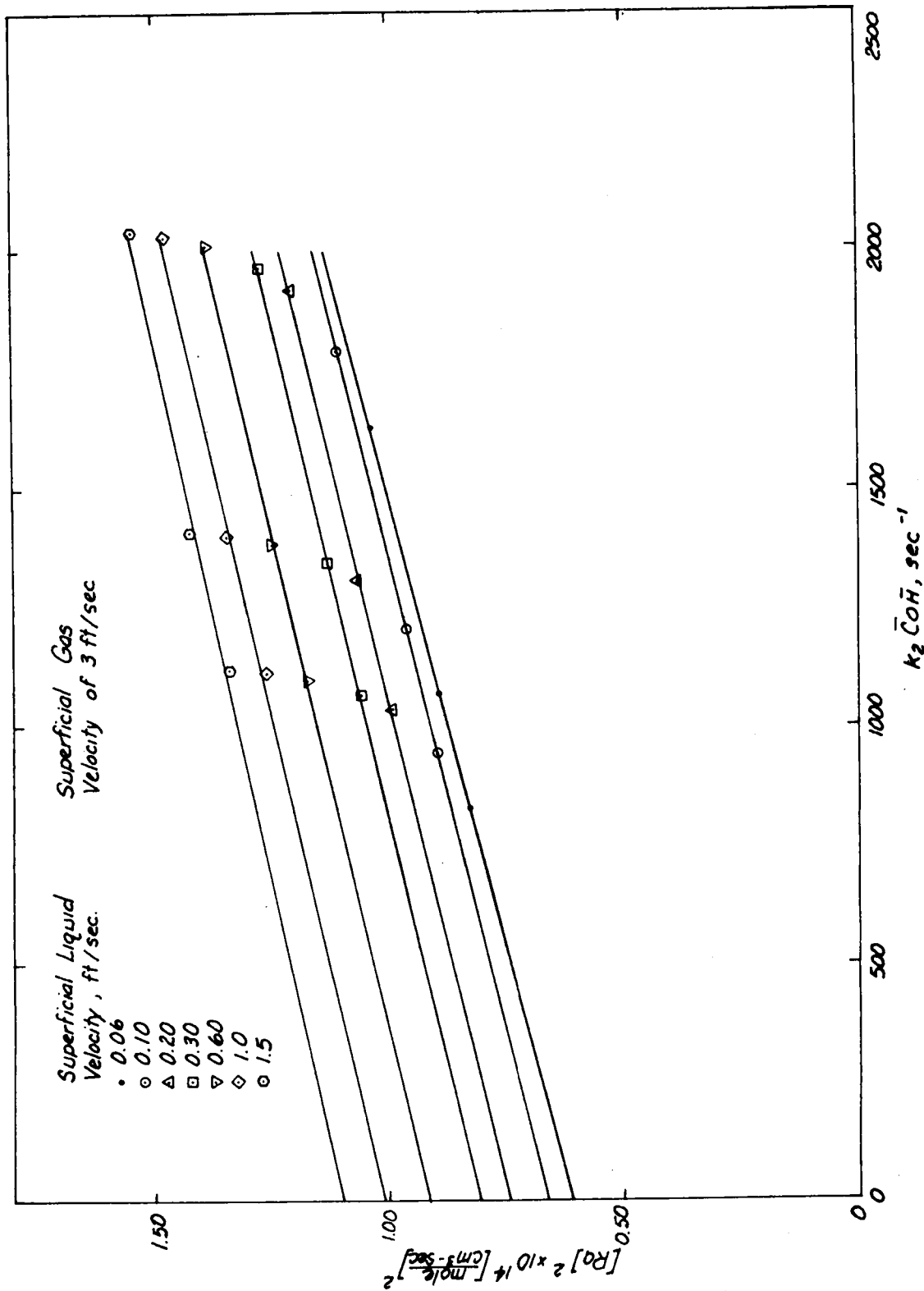


Figure 14. "Danckwerts plot" for superficial gas velocity of 3.0 ft/sec.

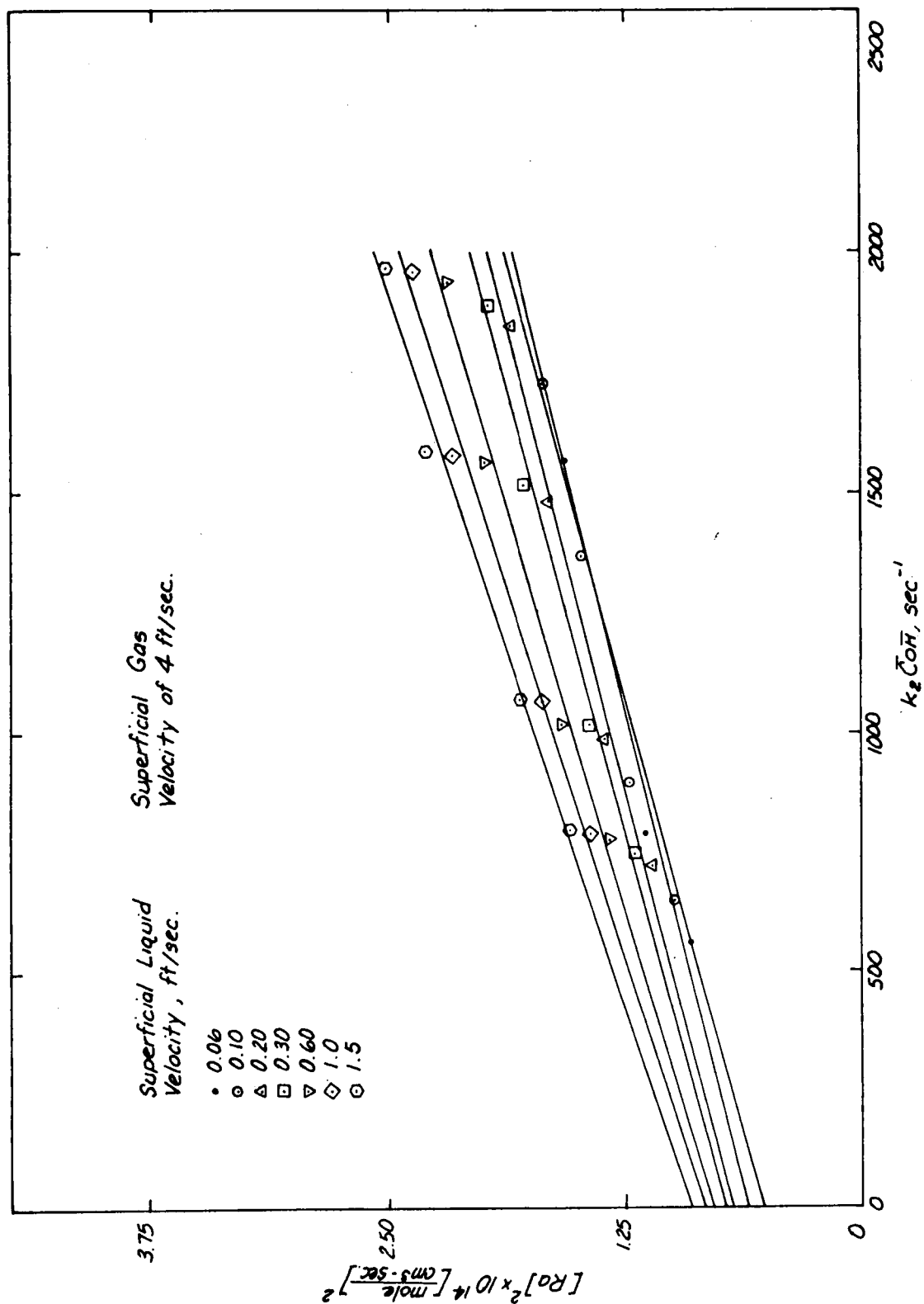


Figure 15. "Danckwerts plot" for superficial gas velocity of 4.0 ft/sec.

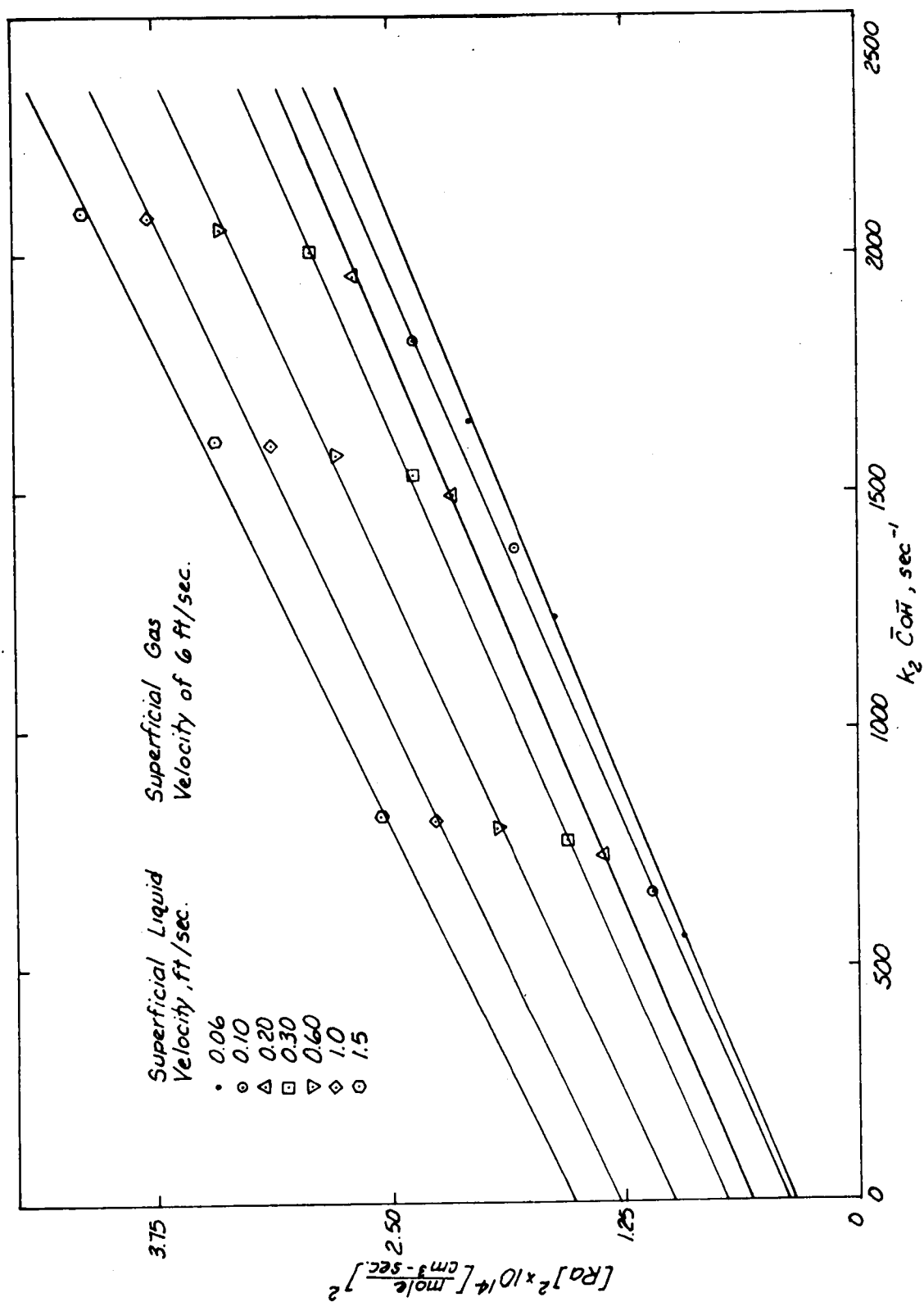


Figure 16. "Danckwerts plot" for superficial gas velocity of 6.0 ft/sec.

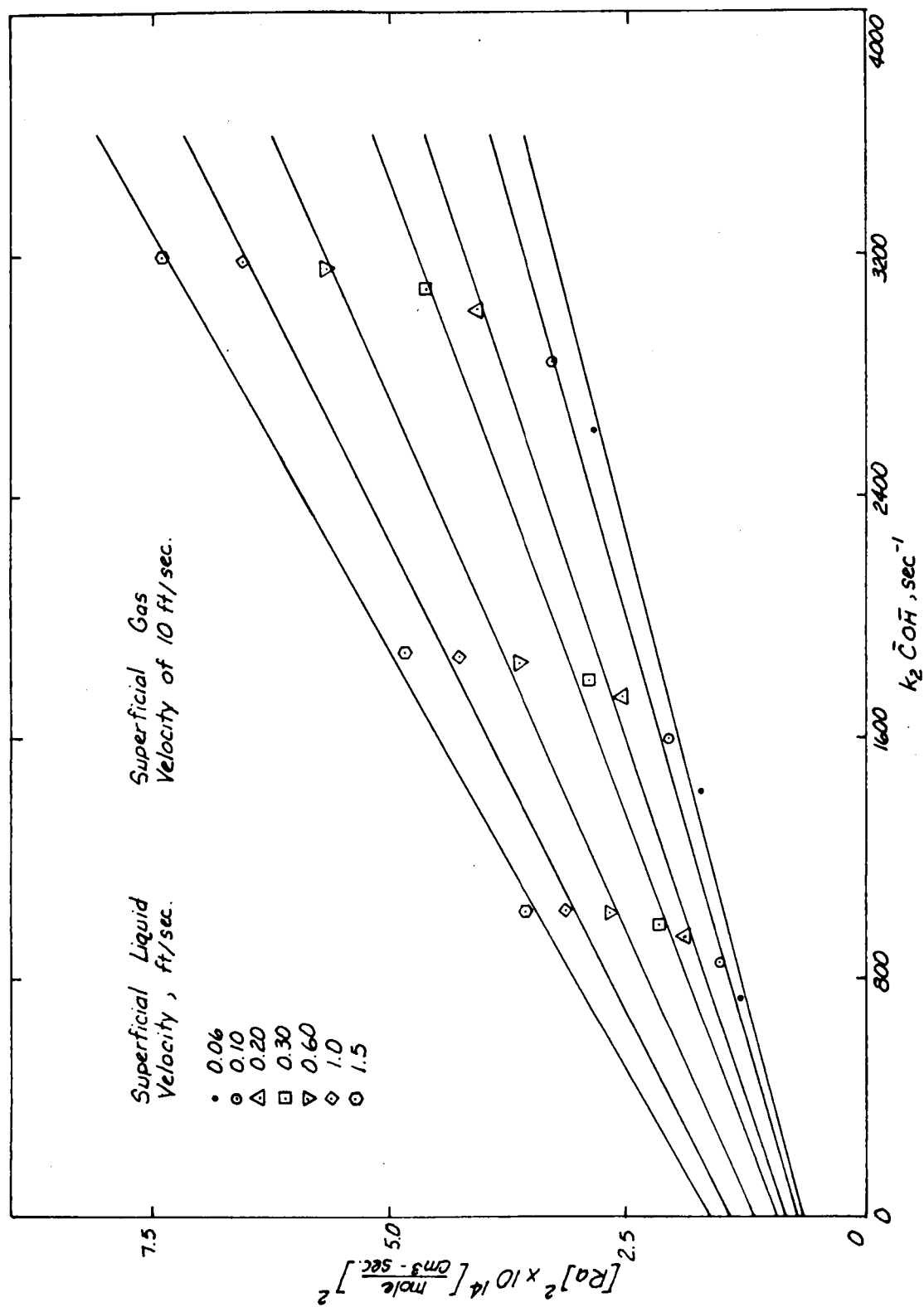


Figure 17. "Danckwerts plot" for superficial gas velocity of 10.0 ft/sec.

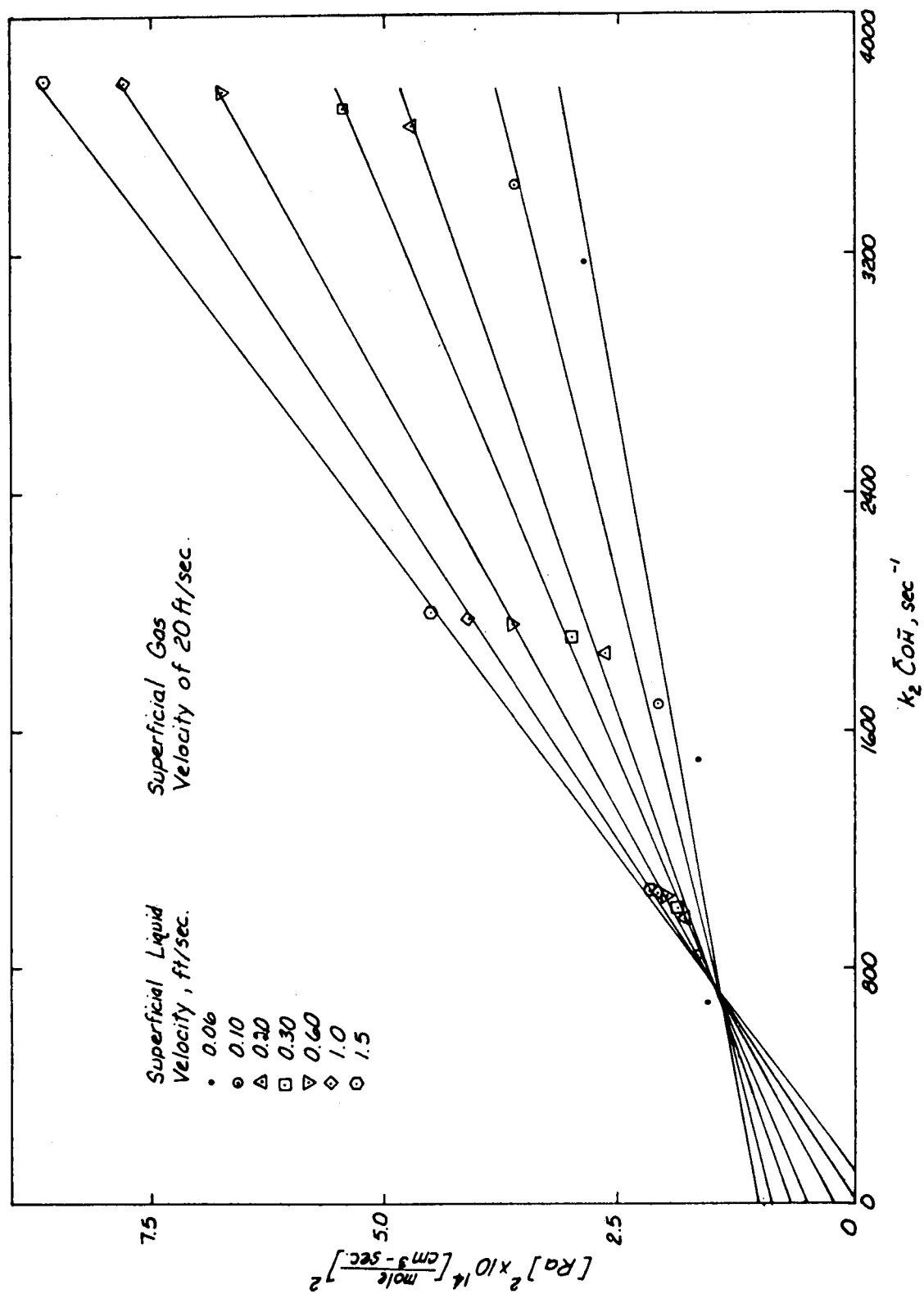


Figure 18. "Danckwerts plot" for superficial gas velocity of 20.0 ft/sec.

$$\text{where } D_{\text{CO}_2} = (0.6075 + 0.0171 T) \times 10^{-5} \quad (35)$$

The development of Equation (35) is in Appendix C.

Physical Absorption Data

The volumetric physical mass transfer coefficient k_L^o was calculated from Equation (25).

$$k_L^o a = \frac{Ra}{C_{\text{CO}_2}^*}$$

Ra was calculated from the difference in the carbon dioxide content in water across the test section similarly to Equation (30)

$$Ra = \frac{(C_{\text{CO}_2,2}' - C_{\text{CO}_2,1}') V_L^o}{L} \quad (36)$$

and $C_{\text{CO}_2}^*$ was calculated from Equation (31). C_{CO_2}' was calculated in the same way as C_{CO_3}' .

VI. DISCUSSION OF RESULTS

Results of Interfacial Areas and Liquid Phase Chemical Mass Transfer Coefficients

Interfacial areas a and liquid phase chemical mass transfer coefficients k_L were measured over a superficial liquid velocity range of 0.06 to 1.5 ft/sec and a superficial gas velocity range of 1.5 to 20 ft/sec. Values of a range from 0.63 cm^{-1} in bubbly-slug to 1.73 cm^{-1} in froth flow. The range for k_L is .084 cm/sec in falling bubbly-film to .318 cm/sec in bubbly-slug.

The effect of superficial liquid velocity on interfacial area is presented in Figure 19. For superficial gas velocities of 1.5 and 2.0 ft/sec the range of a is 0.63 cm^{-1} to 0.87 cm^{-1} . A decrease in interfacial area is observed with increase in liquid velocity, representing the transition from falling film to bubbly-slug. For gas velocities of 4.0, 6.0, 10.0 and 20.0 ft/sec, interfacial areas increase with liquid velocity ranging from 0.86 to 1.73 cm^{-1} . The greatest increase in a is observed for the transition from annular flow to froth flow at a gas velocity of 20.0 ft/sec. Interfacial areas for the other gas velocities generally show a slight increase with liquid velocity and represent falling bubbly-film.

The effect of gas velocity on interfacial area is illustrated in Figure 20. Interfacial area for liquid velocities of 0.06, 0.10, 0.20 and 0.3 ft/sec is roughly constant up to a gas velocity of 3.0 ft/sec; 0.74 to 0.87 cm^{-1} . The area represented is falling film. For liquid

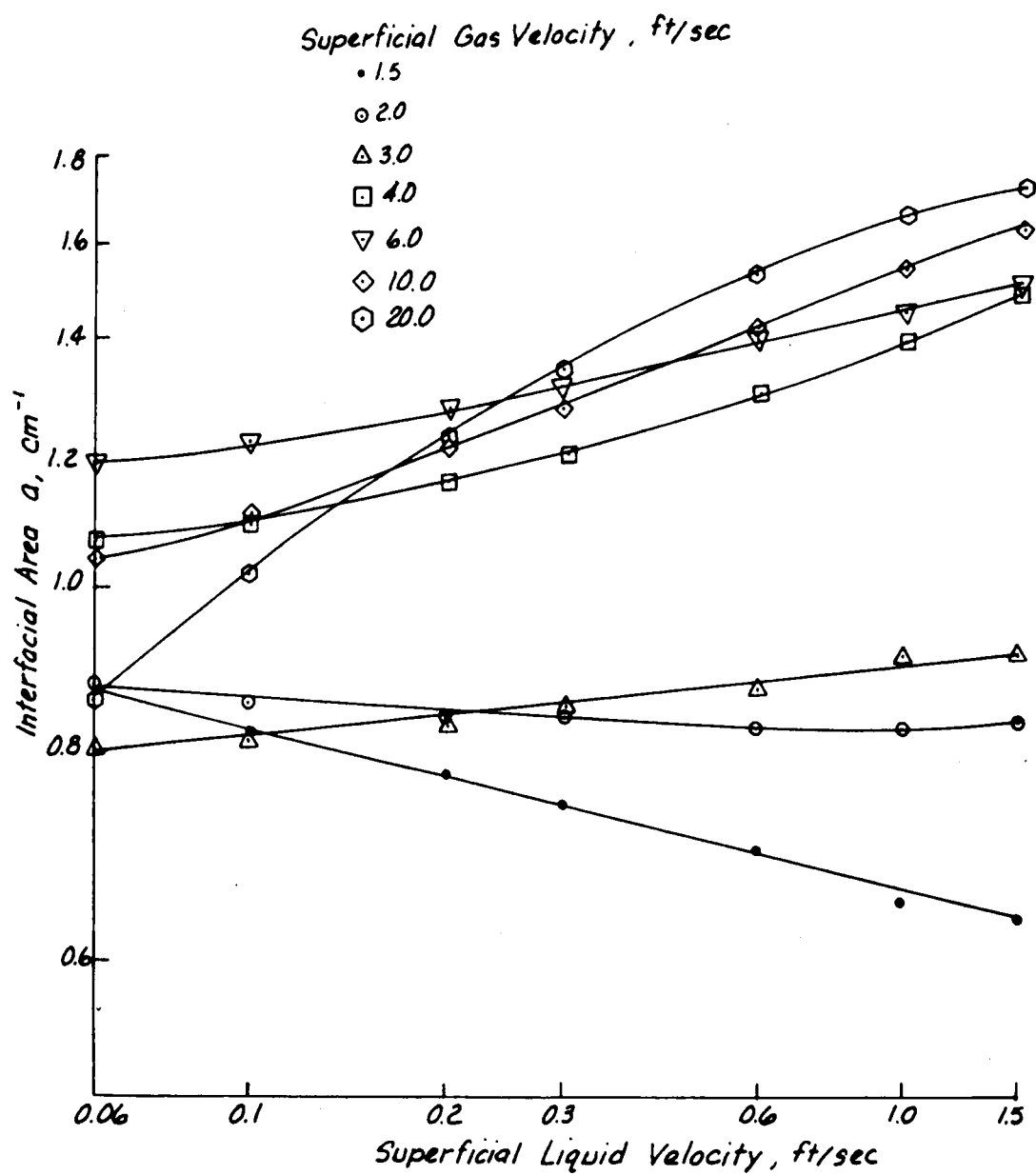


Figure 19. Effect of liquid velocity on interfacial area.

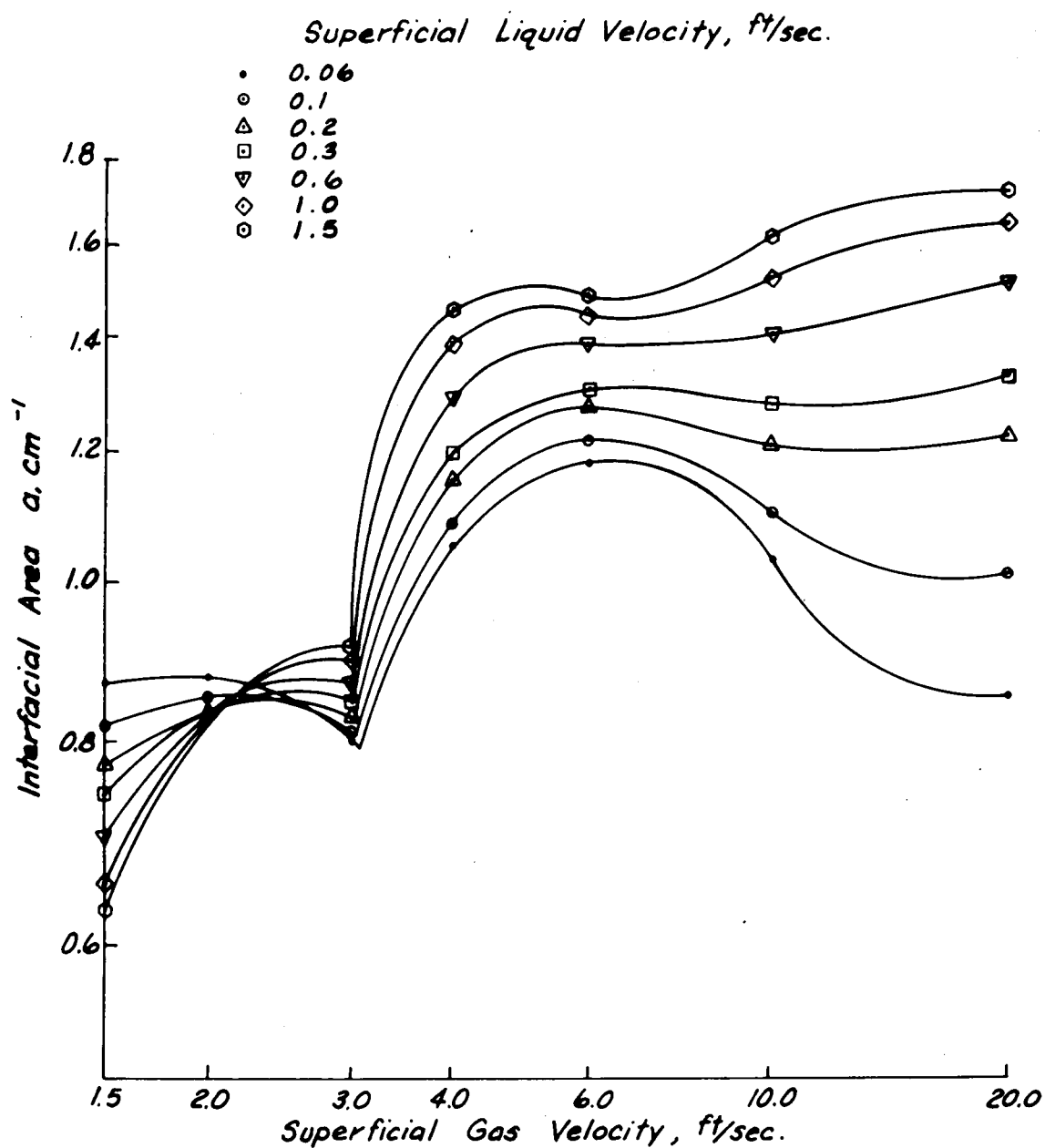


Figure 20. Effect of gas velocity on interfacial area.

velocities of 0.6, 1.0 and 1.5 ft/sec, interfacial area shows an increase up to a gas velocity of 3.0 ft/sec: 0.63 to 0.91 cm^{-1} , representing bubbly-slug. An increase in gas velocity from 3.0 to 4.0 ft/sec results in a dramatic increase in a for all liquid velocities. This represents the transition to falling bubbly-film and is the expected result due to the large number of small, dispersed gas bubbles in the liquid film in this flow regime. For liquid velocities of 0.06 and 0.10 ft/sec, interfacial area decreases with increase in gas velocity from 6.0 to 20.0 ft/sec, representing the falling bubbly-film to annular flow transition. The value of 0.86 cm^{-1} for annular flow at a gas velocity of 20.0 ft/sec and liquid velocity of 0.06 ft/sec compares closely to a obtained in falling film. This is not surprising. At the onset of annular flow, the gas core probably has little mist. As gas velocity is increased above 20.0 ft/sec, the shearing action of the gas on the liquid film is expected to increase producing more mist in the core and resultant higher interfacial area. Interfacial area increases up to 1.73 cm^{-1} with increase in gas velocity to 20.0 ft/sec for a liquid velocity of 1.5 ft/sec. The transition from falling bubbly-film to froth flow is represented.

The liquid phase chemical mass transfer coefficient k_L in most cases shows an increase with superficial liquid velocity. The expected straight lines are obtained when the results are put on a log-log plot, as shown in Figure 21. The exception is for a gas velocity of 20.0 ft/sec where k_L decreases with liquid velocity, approaching 0.05 at a liquid velocity of approximately 0.6 ft/sec. This result raises a

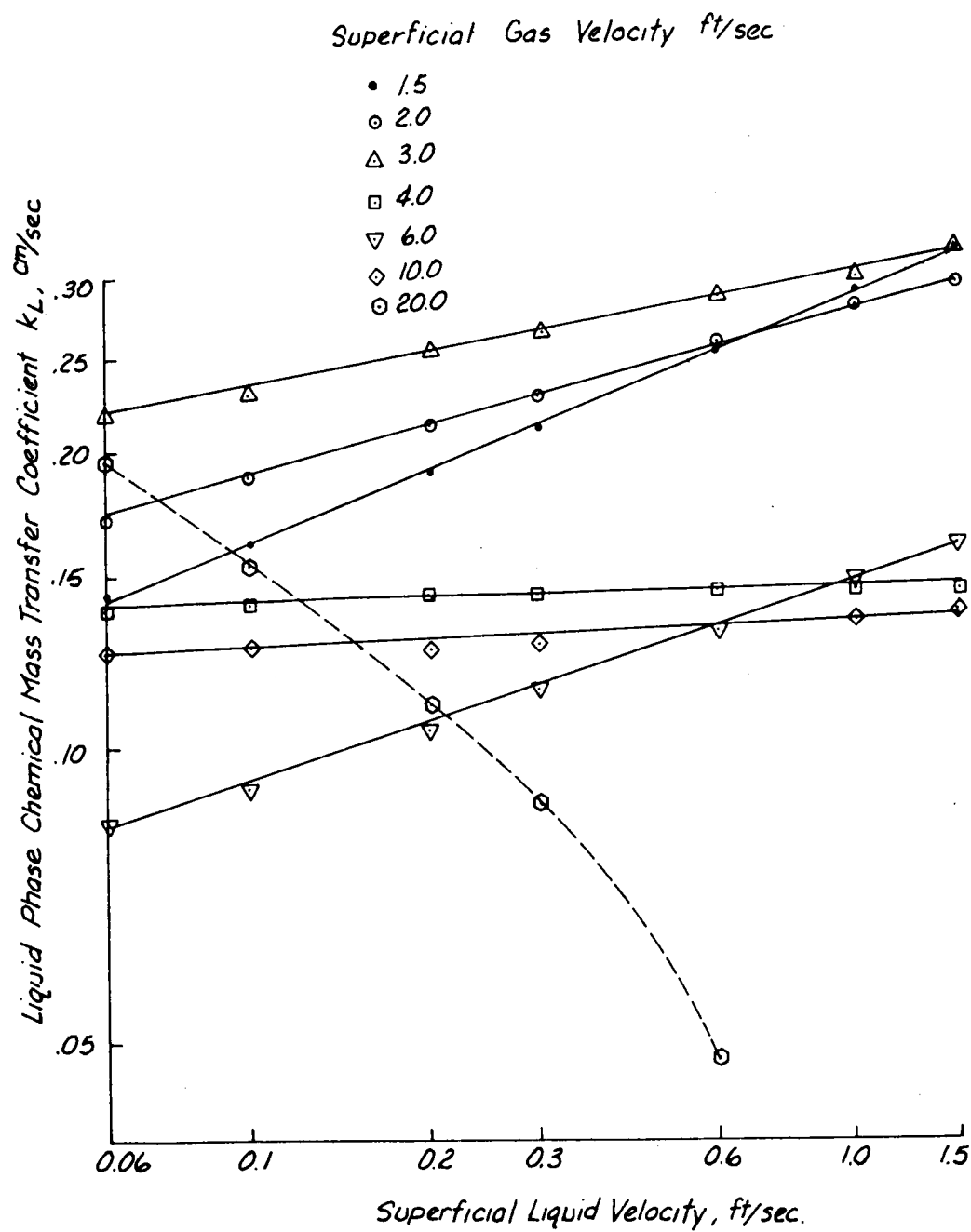


Figure 21. Effect of liquid velocity on the liquid phase chemical mass transfer coefficient.

question about the adequacy of using the intercept of the Danckwerts Plot to obtain k_L . This observation was investigated experimentally and is discussed in the next section.

The effect of superficial gas velocity on k_L is shown in Figure 22. For gas velocities from 1.5 to 3.0 ft/sec, k_L ranges from .142 to .318 cm/sec, representing falling film and bubbly-slug. An increase in gas velocity from 3.0 to 4.0 ft/sec results in k_L falling to about .140 cm/sec. This represents the transition to falling bubbly-film. For gas velocities of 4.0 to 10.0 ft/sec and liquid velocities of 0.06 to 1.5 ft/sec, k_L ranges from .084 to .159 cm/sec, generally representing falling bubbly-film.

A log-log plot of the volumetric chemical mass transfer coefficient $k_L a$ versus superficial liquid velocity is shown in Figure 23. With increase in liquid velocity, $k_L a$ increases. The expected straight lines are obtained except for a gas velocity of 20.0 ft/sec.

Illustrated in Figure 24 is the effect of superficial gas velocity on $k_L a$. Gas velocity has less effect on $k_L a$ as compared to its effect on k_L .

Results of Volumetric Physical Mass Transfer Coefficients

Due to speculation that it might not be feasible to use the intercept of the Danckwerts Plot for obtaining the chemical mass transfer coefficient k_L , experiments were conducted to measure the volumetric physical mass transfer coefficient $k_L^0 a$. The physical mass transfer coefficient k_L^0 was obtained by dividing $k_L^0 a$ by the interfacial area a .

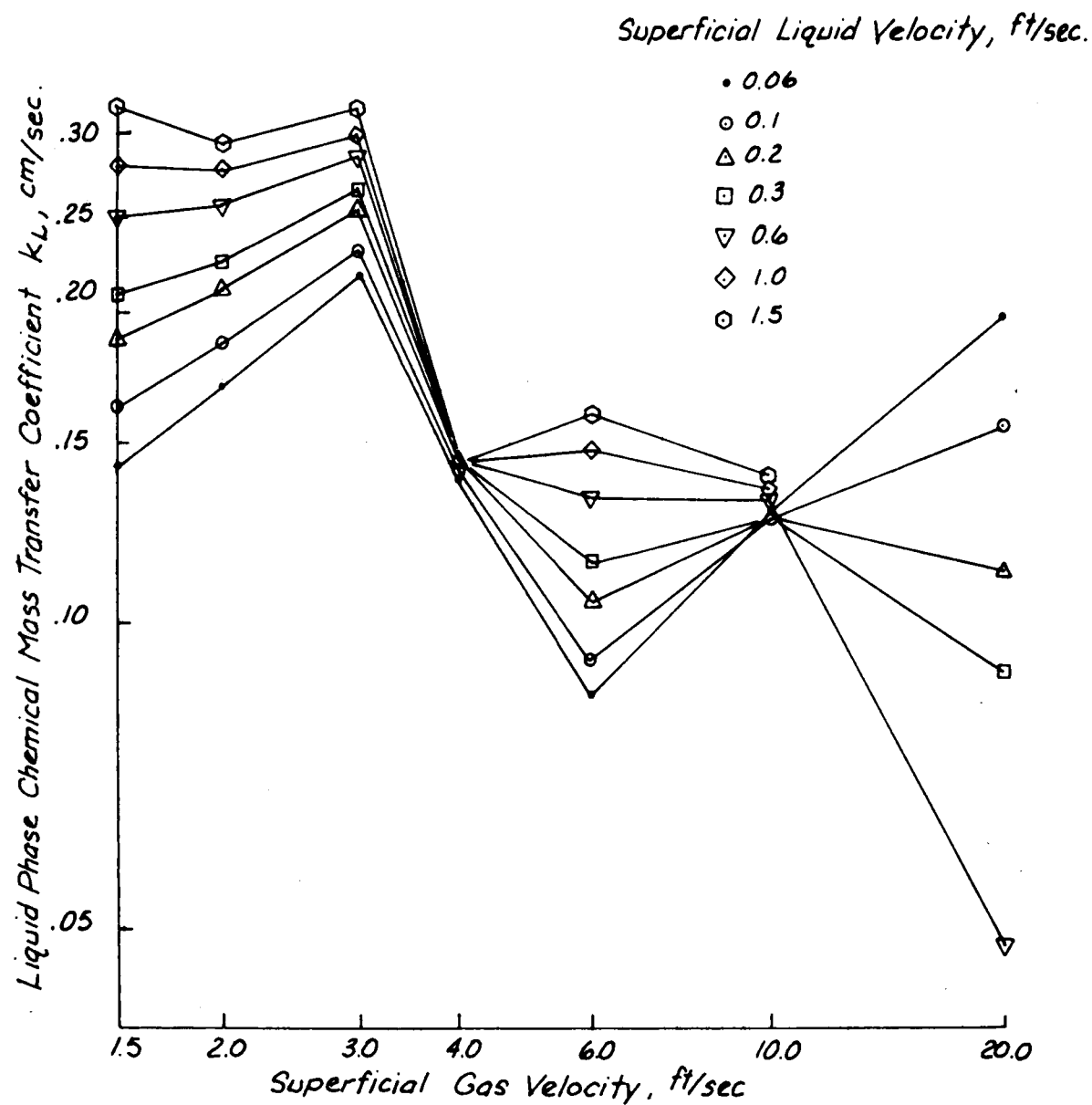


Figure 22. Effect of gas velocity on the liquid phase chemical mass transfer coefficient.

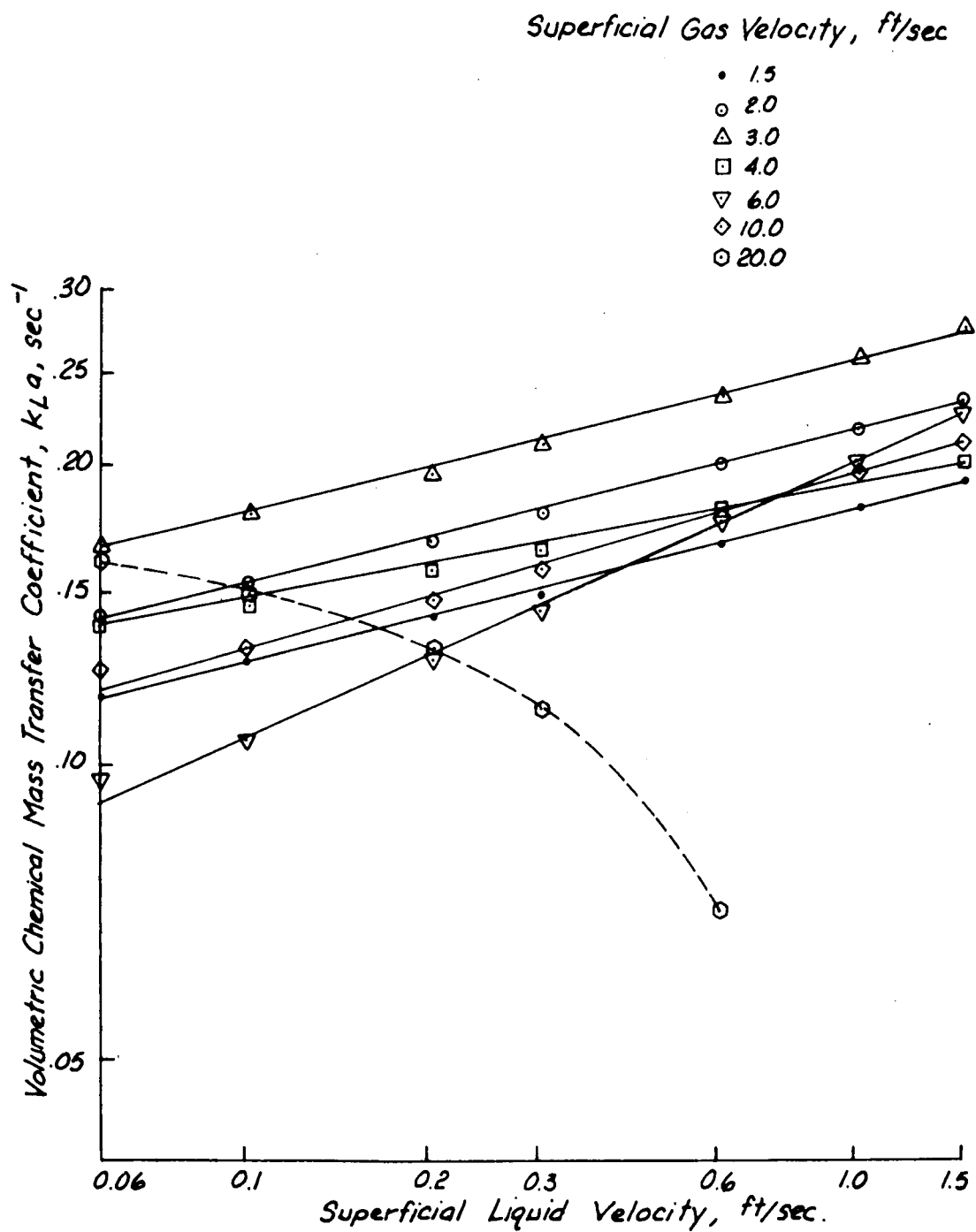


Figure 23. Effect of liquid velocity on the volumetric chemical mass transfer coefficient.

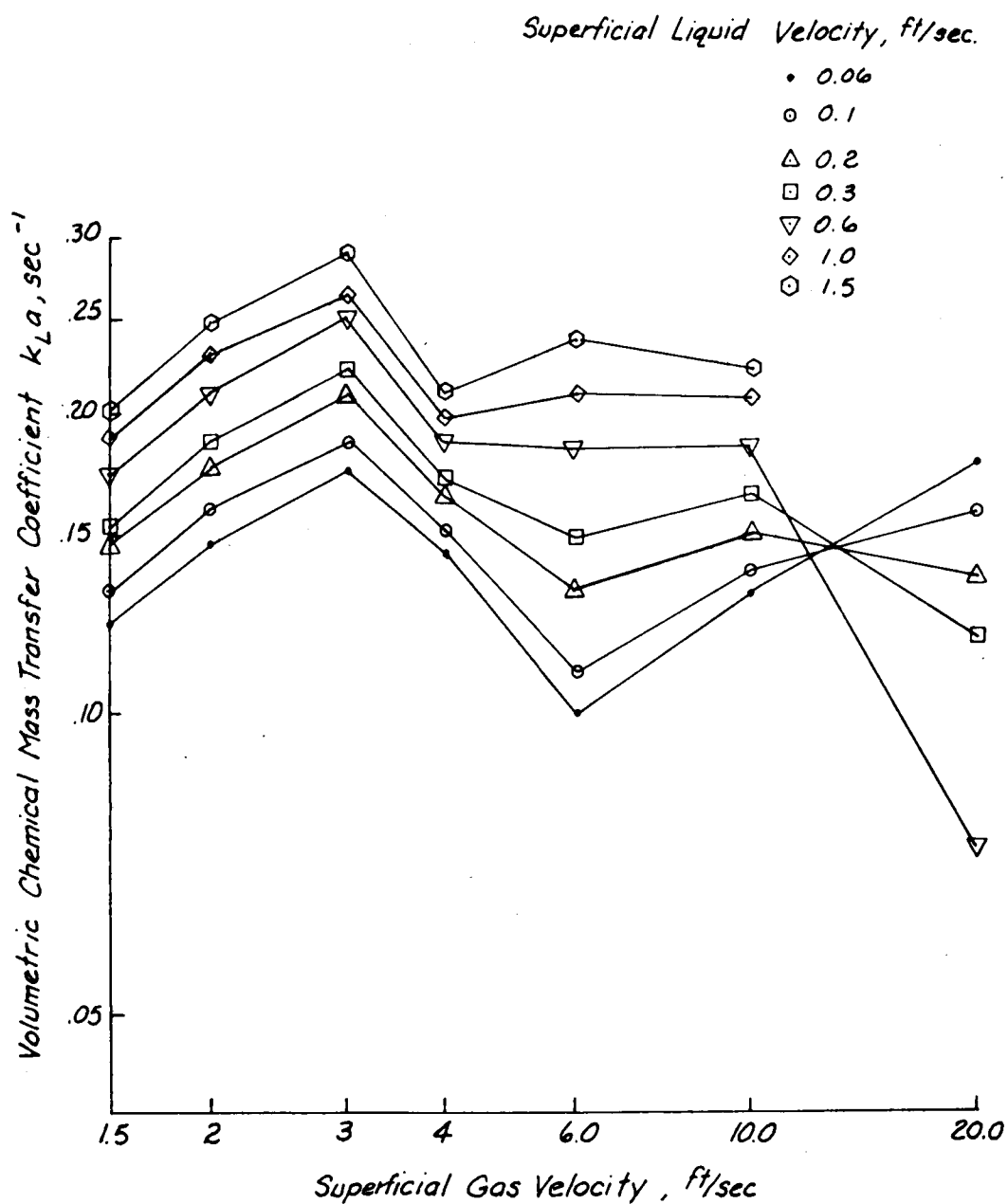


Figure 24. Effect of gas velocity on the volumetric chemical mass transfer coefficient.

Measurements were made over a superficial liquid velocity range of 0.06 to 1.5 ft/sec and a superficial gas velocity range of 1.5 to 10.0 ft/sec. Measured values of $k_L^0 a$ range from .002 to .042 sec^{-1} as compared to .100 to .290 sec^{-1} for $k_L a$. There is indeed quite a difference in k_L and k_L^0 . Caution should be used in the use of k_L .

The effect of superficial liquid velocity on $k_L^0 a$ is shown in Figure 25. Increase in liquid velocity results in an increase in $k_L^0 a$ while the effect of gas velocity, shown in Figure 26, is small. Similar results are obtained for the effect of superficial liquid and gas velocity on k_L^0 in Figures 27 and 28, respectively.

Results of Pressure Measurements

Column pressure shows an increase with both gas and liquid velocity as shown in Figure 29. Pressures ranged from 1.5mm of mercury below atmospheric pressure at the lowest gas-liquid flow rate to 30mm above for the highest gas-liquid flow rate. Pressures measured at sample port 1 at the top of the column were always higher than at sample port 2 at the bottom of the column, indicating a pressure gradient in the column. The pressure measurement data is in Appendix F.

Comparison of Interfacial Areas and Mass Transfer Coefficients with the Literature

Only one other work has been done on mass transfer in cocurrent downflow. Vavruska (38) measured mass transfer coefficients and interfacial areas using the same experimental equipment and procedure as this work. He performed a liquid analysis to obtain the results. Interfacial

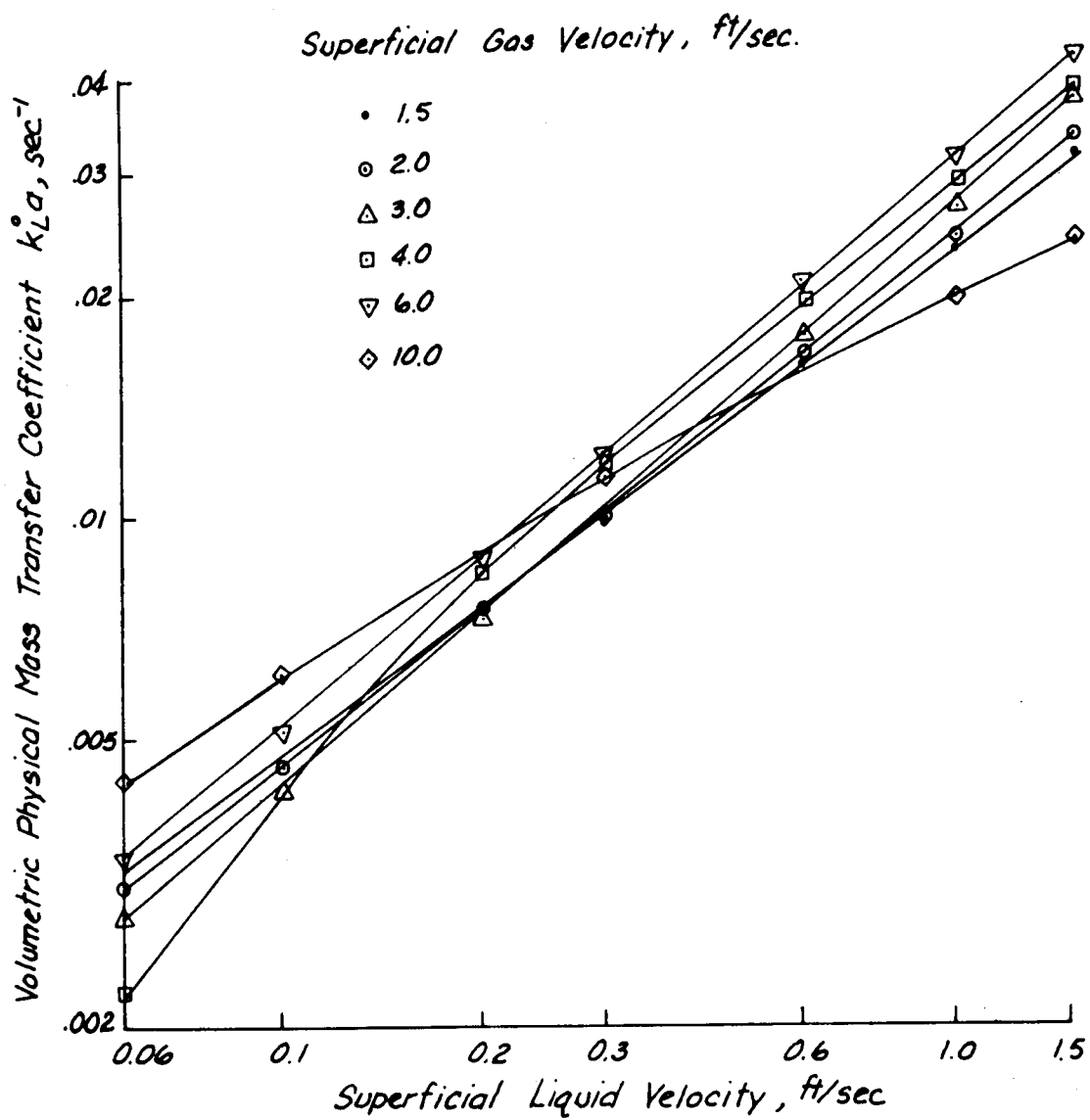


Figure 25. Effect of liquid velocity on the volumetric physical mass transfer coefficient.

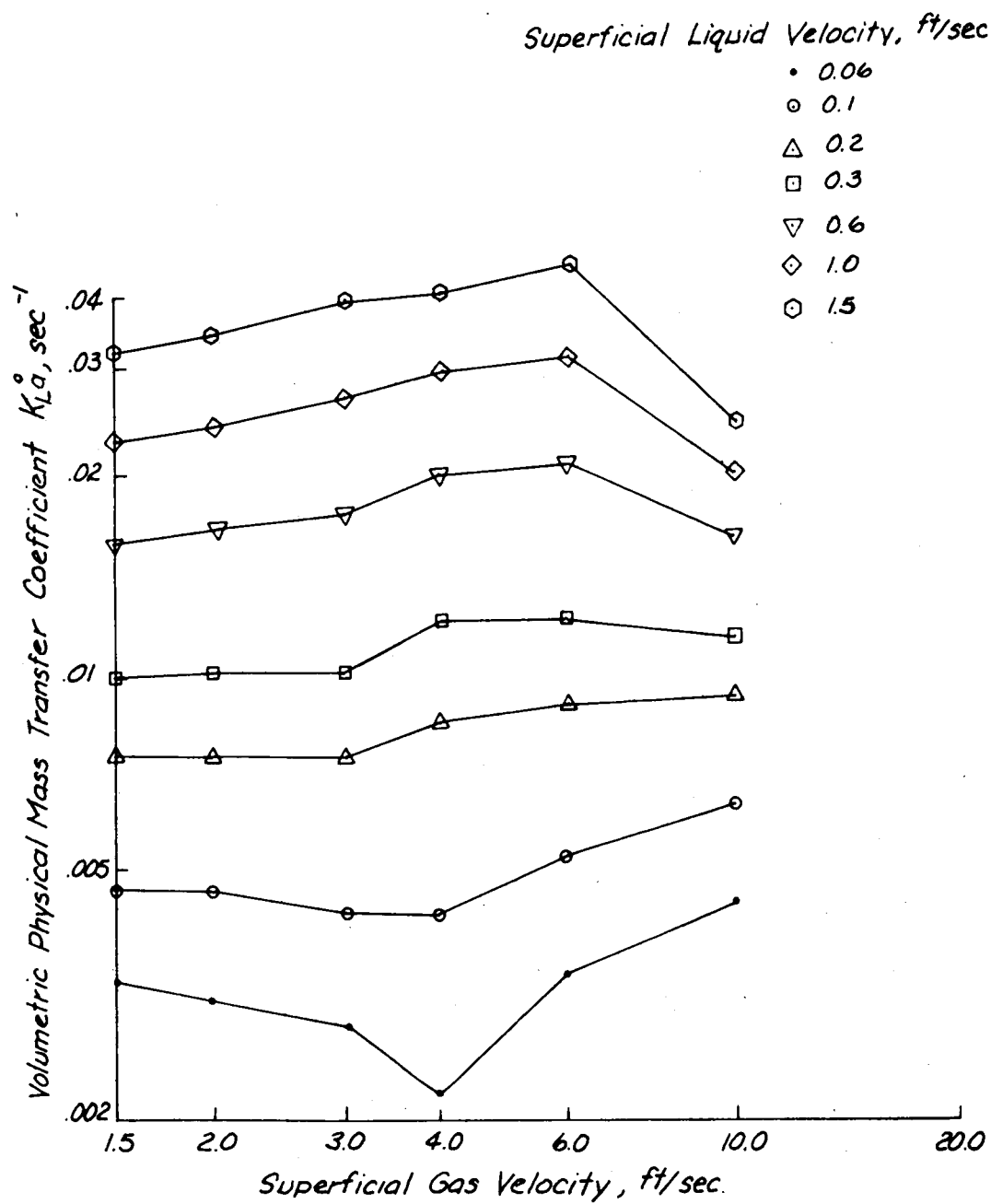


Figure 26. Effect of gas velocity on the volumetric physical mass transfer coefficient.

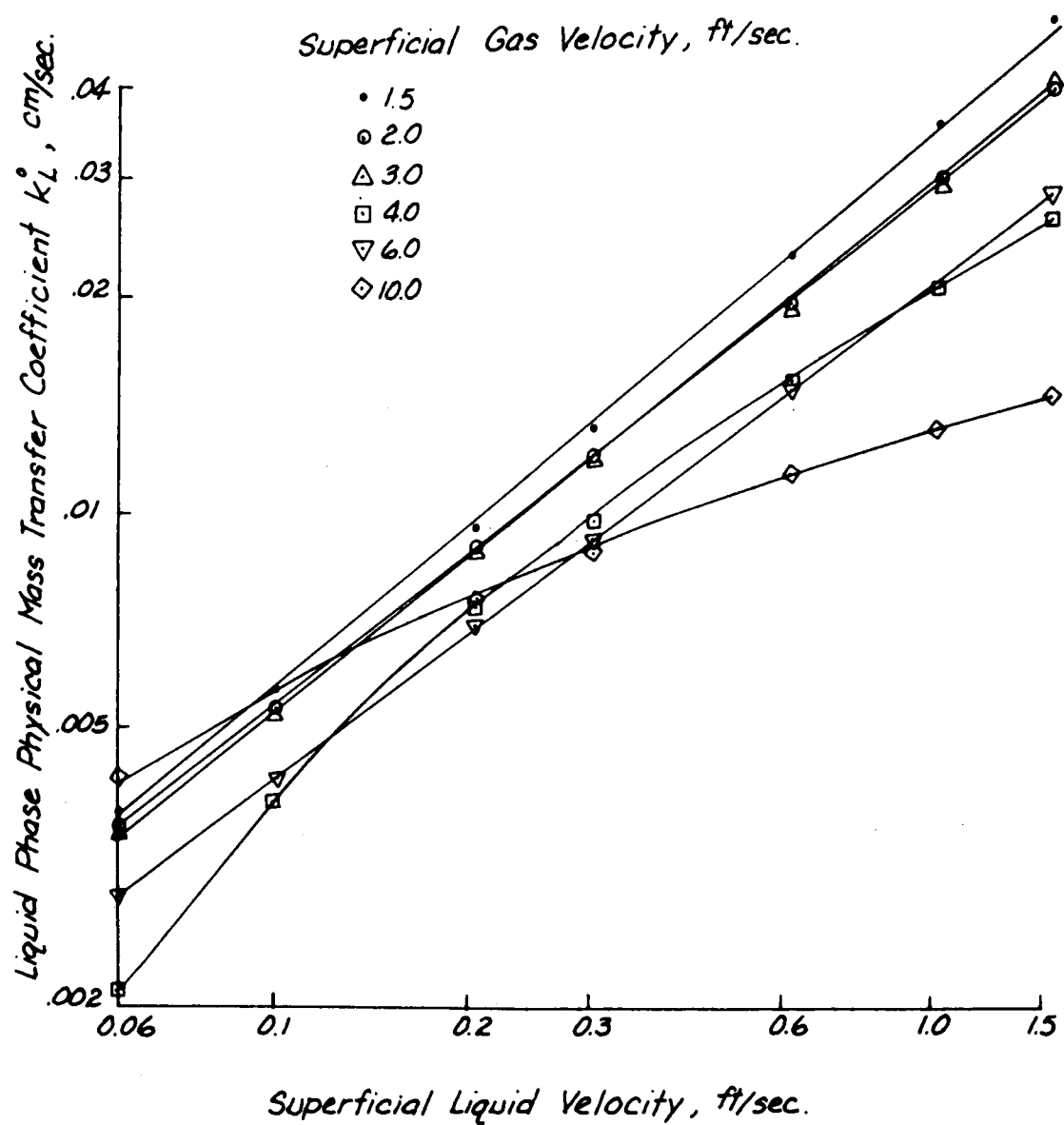


Figure 27. Effect of liquid velocity on the liquid phase physical mass transfer coefficient.

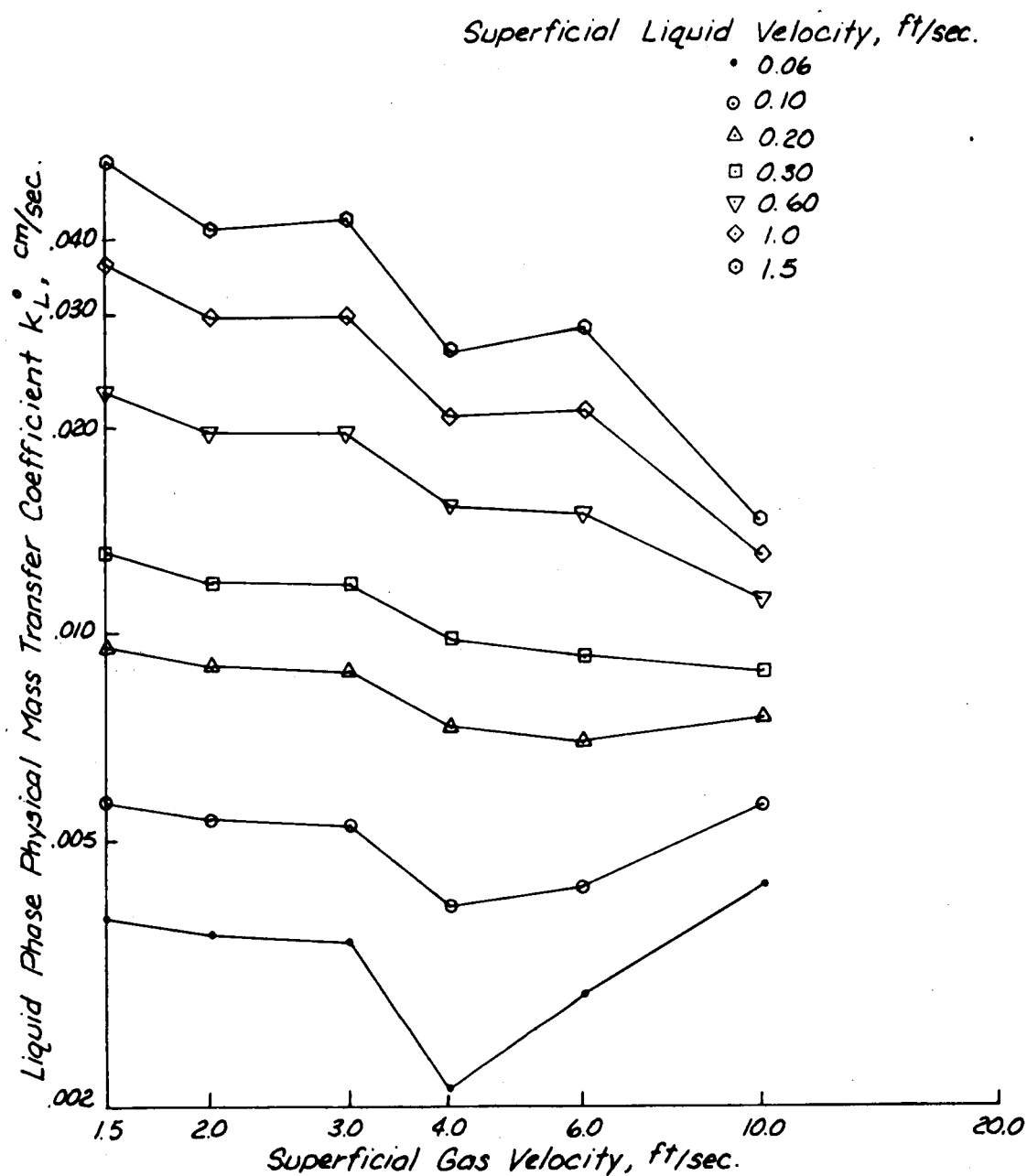


Figure 28. Effect of gas velocity on the liquid phase physical mass transfer coefficient.

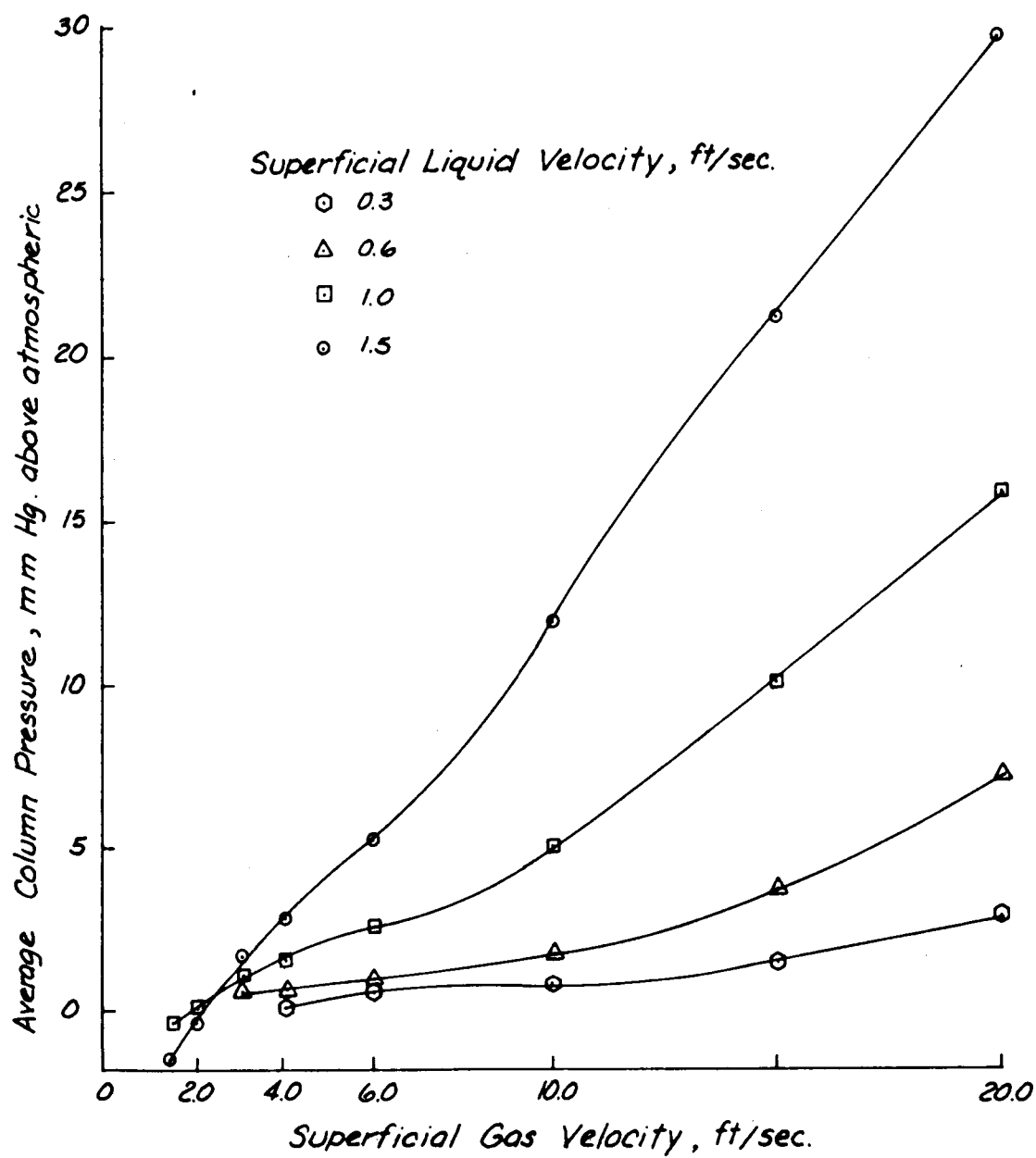


Figure 29. Effect of gas velocity on column pressure.

areas obtained by gas analysis are compared to those obtained by liquid analysis using the chemical method in Figure 30. For gas velocities of 0.3, 0.6, 1.0 and 1.5 ft/sec, a ranges from 1.28 to 1.73 cm^{-1} for gas analysis as compared to 1.05 to 2.47 cm^{-1} for liquid analysis.

Figure 31 illustrates the comparison of the mass transfer coefficient k_L obtained by gas analysis to that obtained by liquid analysis. For both means of analysis, k_L for a gas velocity of 20.0 ft/sec shows a different kind of behavior from the others. For gas velocities of 6.0 and 10.0 ft/sec, k_L ranges from .059 to .255 cm/sec for liquid analysis as compared to .114 to .159 cm/sec for gas analysis. These values are much higher than the values of k_L^0 also obtained in this study; .009 to .028 cm/sec.

All other mass transfer results in the literature are concerned with either cocurrent upflow or horizontal cocurrent flow. Note that the terminology, k_L and $k_L a$, for values from the following papers may represent either physical or chemical absorption. Any comparisons with results from these works would be of a general nature.

Scott and Hayduk (30) measured $k_L a$ for horizontal tubes of 1.228 to 2.504 cm in diameter. For liquid velocities of 0.5 to 3.6 ft/sec and gas velocities of 0.1 to 20.0 ft/sec, $k_L a$ ranged from .001 to .05 sec^{-1} . Using a 1.2 cm diameter tube, Shah and Sharma (31) measured $k_L a$ from .005 to .04 sec^{-1} . Liquid velocities were from 0.48 to 1.79 ft/sec and gas velocities from 0.16 to 1.44 ft/sec. The volumetric physical coefficients $k_L^0 a$ in this study, .002 to .042 sec^{-1} , compare well to the above literature values. The volumetric chemical coefficients $k_L a$ in

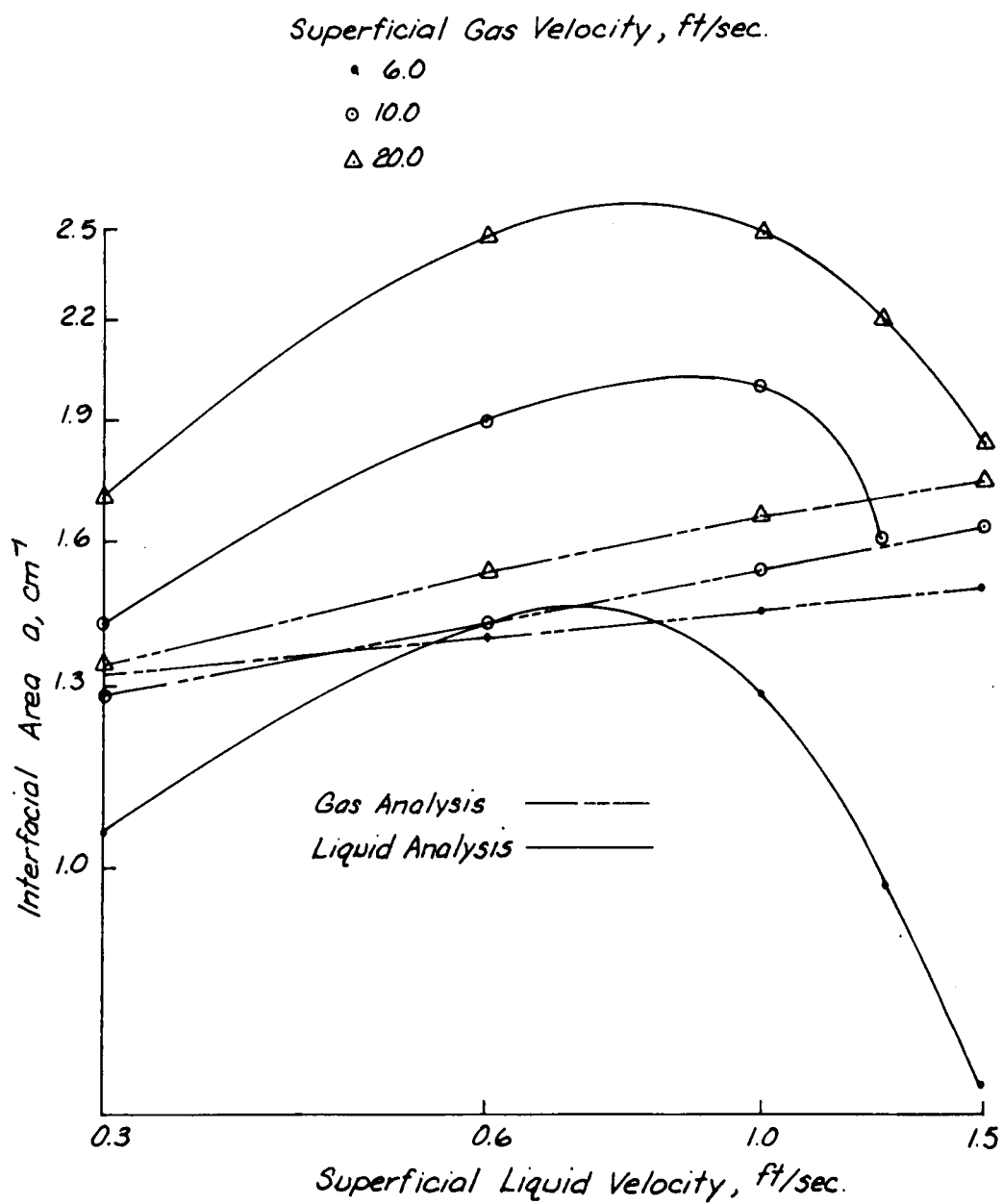


Figure 30. Comparison of interfacial areas for gas and liquid analysis.

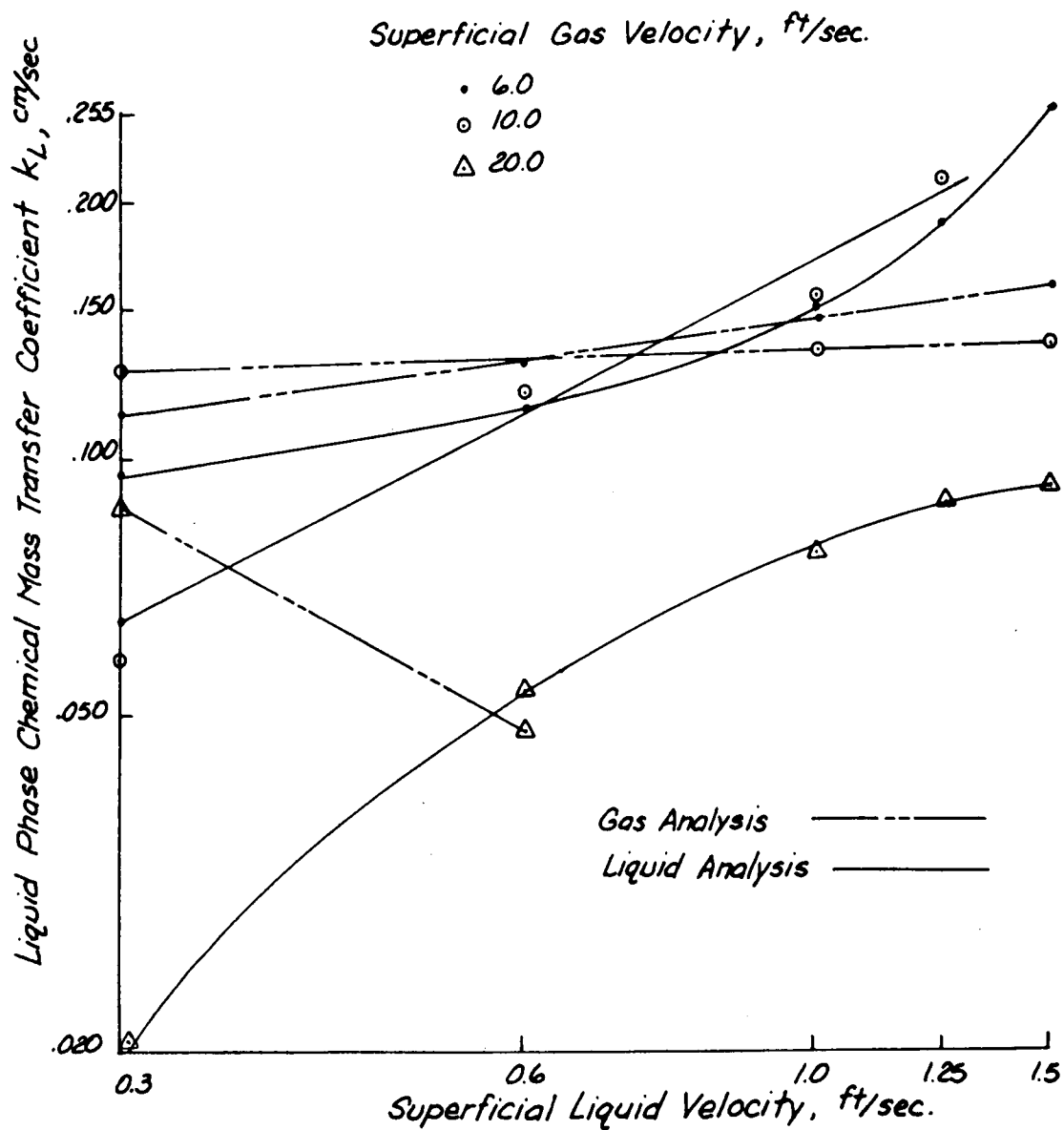


Figure 31. Comparison of liquid phase chemical mass transfer coefficients for gas and liquid analysis.

this study however, are much larger; .100 to .290 sec^{-1} . Gregory and Scott (13) measured k_L ranging from .020 to .100 cm/sec for a 3/4-inch horizontal tube as compared to .015 to .085 cm/sec for a 5/16-inch horizontal tube by Lamont and Scott (22). Sharma and Danckwerts (32) gave a comprehensive summary of mass transfer coefficients k_L . The values, representing a variety of gas-liquid contacting devices, never exceed 0.04 cm/sec. In this work, k_L^0 ranged from .002 to .049 cm/sec while k_L ranged from .084 to .318 cm/sec.

Interfacial areas were measured by Shilimkan and Stepanek (34) in a 20mm vertical tube. Gas velocity ranged from 1.0 to 23.0 ft/sec and liquid velocity from .1 to 1.2 ft/sec. Interfacial area varied from .75 to 3.0 cm^{-1} and was observed to reach a maximum when plotted against gas velocity, generally representing the transition from slug to annular flow. Kasturi and Stepanek (20) obtained interfacial area for vertical upflow in a 6mm tube; 1.2 to 10 cm^{-1} . They concentrated most of their measurements in the annular-mist regime. In a recent work, Watson (40) measured a in vertical upflow in a one-inch tube. Liquid velocities ranged from .11 to 1.56 ft/sec and gas velocities from 3.3 to 26.2 ft/sec. Interfacial areas varied from 1.0 to 7.0 cm^{-1} . The values of interfacial area in this work fall into the range of values above; 0.86 to 1.73.

Accuracy of Results

An estimate of the maximum error in using the Danckwerts plot to calculate interfacial areas and mass transfer coefficients is given here. The gas sampling technique produced error of 1 to 5% over the

range of concentrations measured. The sampling error was calculated by measuring the concentration of carbonate in the liquid at a sample port two times using the same tank of feed liquid. Concentrations were measured for three liquid velocities at a constant gas velocity. The three concentrations were fit to a linear regression on a log-log plot of concentration of carbonate versus liquid velocity. The procedure was repeated using the same experimental conditions and the error was calculated from the difference in concentration of the two runs. This was done for gas velocities over the entire range studied in this work. Liquid, air and carbon dioxide flow rates could be measured with an accuracy of 2%. The error associated with use of the Danckwerts plot to obtain k_L and a probably does not exceed 10%. The maximum error in measuring k_L and a should not exceed 20%.

The error in measuring $k_L^O a$ ranged from 10 to 40%. It was calculated by simply measuring $k_L^O a$ two times. This was done over the range of liquid and gas velocities investigated.

VII. CONCLUSIONS

1. Interfacial areas decrease with liquid velocity in the transition from falling film to bubbly-slug. In the transition from annular flow to froth flow interfacial area increases with liquid velocity. There is also a slight increase in a with liquid velocity in the falling bubbly-film regime.

2. A dramatic increase in interfacial area is observed with increase in gas velocity in the transition from falling film, bubbly-slug to falling bubbly-film. Interfacial area increases with gas velocity in the transition from falling bubbly-film to froth flow but decreases in the transition from falling bubbly-film to annular flow.

3. The liquid phase chemical mass transfer coefficient k_L increases with liquid velocity. With increase in gas velocity in the transition from falling film, bubbly-slug to falling bubbly-film, k_L experiences a sizable decrease. There is uncertainty about the accuracy or reliability of k_L .

4. The volumetric physical mass transfer coefficient $k_L^0 a$ increases with liquid velocity but generally experiences no change with increase in gas velocity.

5. Interfacial areas obtained in this study fall into the broad range of values obtained in other works. The values of a for cocurrent vertical upflow are up to five times larger.

6. The physical mass transfer coefficient k_L^0 measured in this study compares closely with mass transfer coefficients reported in the

literature. The chemical mass transfer coefficient k_L however exceeds these values by a factor of 10 to 50. Caution should be exercised in use of the liquid phase chemical mass transfer coefficient k_L measured in this work. It is felt that the straight line of the Danckwerts Plot probably curves downward as the y-intercept is approached, accounting for the high values of k_L measured.

7. The mass transfer results follow the flow regime boundaries of the flow regime map by Oshinowo and Charles very closely.

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APPENDICES

APPENDIX A

CRITERION FOR FAST PSEUDO FIRST ORDER REACTION

The calculations in this section demonstrate that the Danckwerts criterion for a fast pseudo first order reaction are satisfied for all chosen conditions in this study.

Danckwerts (8) criterion for a fast, pseudo first order reaction is given by the following:

$$1 < \frac{\sqrt{D_{\text{CO}_2} k_2 C_{\text{OH}^-}}}{k_L} < \sqrt{\frac{D_{\text{CO}_2}}{D_{\text{OH}^-}}} + \frac{C_{\text{OH}^-}}{2C_{\text{CO}_2}^*} \sqrt{\frac{D_{\text{OH}^-}}{D_{\text{CO}_2}}} \quad (\text{A1})$$

The lowest value of the term on the left occurs when k_L is largest and the concentration of sodium hydroxide is lowest. The largest values of k_L are at high liquid velocities. The average chemical mass transfer coefficient k_L for a liquid velocity of 1.5 ft/sec is .228 cm/sec. Letting $D_{\text{CO}_2} = 2.0 \times 10^{-5} \text{ cm}^2/\text{sec}$, $k_2 = 8.5 \times 10^6 \text{ cm}^3/\text{sec-mole}$ and $C_{\text{OH}^-} = 5.0 \times 10^{-5} \text{ mole/cm}^3$, the mean minimum value of the term on the left of Equation (A1) is

$$\left[\frac{\sqrt{D_{\text{CO}_2} k_2 C_{\text{OH}^-}}}{k_L} \right]_{\text{min}} = 0.4$$

The average value of the chemical mass transfer coefficient k_L for a liquid velocity of 0.06 ft/sec is .146 cm/sec. Letting $D_{\text{CO}_2} = 2.0 \times 10^{-5}$, $k_2 = 10.0 \times 10^6 \text{ cm}^3/\text{sec-mole}$ and $C_{\text{OH}^-} = 25 \times 10^{-5} \text{ mole/cm}^3$, the mean maximum value of the left term becomes

$$\left[\frac{\sqrt{D_{\text{CO}_2} k_2 C_{\text{OH}^-}}}{k_L} \right]_{\text{max}} = 1.5$$

If the average physical mass transfer coefficient k_L^0 is used instead of

k_L , for a liquid velocity of 1.5 ft/sec, $k_L^o = .033$ cm/sec, the minimum value becomes

$$\left[\frac{\sqrt{D_{CO_2} k_2 C_{OH^-}}}{k_L^o} \right]_{\min} = 2.8$$

For a liquid velocity of .06 ft/sec, $k_L^o = .004$ cm/sec, the maximum becomes

$$\left[\frac{\sqrt{D_{CO_2} k_2 C_{OH^-}}}{k_L^o} \right]_{\max} = 55.9$$

The minimum value of the term on the right of Equation (A1) occurs when $C_{CO_2}^* = 3.5 \times 10^{-7}$ mole/cm³, $C_{OH^-} = 5.0 \times 10^{-5}$ mole/cm³ and $D_{OH^-}/D_{CO_2} = 1.67$ (from Joosten and Danckwerts (18)), thus

$$\left[\sqrt{\frac{D_{CO_2}}{D_{OH^-}}} + \frac{C_{OH^-}}{2C_{CO_2}^*} \sqrt{\frac{D_{OH^-}}{D_{CO_2}}} \right]_{\min} = 93.1$$

The maximum value occurs when $C_{CO_2}^* = 5.9 \times 10^{-7}$ mole/cm³ and $C_{OH^-} = 25 \times 10^{-5}$ mole/cm³, thus

$$\left[\sqrt{\frac{D_{CO_2}}{D_{OH^-}}} + \frac{C_{OH^-}}{2C_{CO_2}^*} \sqrt{\frac{D_{OH^-}}{D_{CO_2}}} \right]_{\max} = 274.6$$

Using the liquid phase chemical mass transfer coefficient k_L , the criterion is not completely satisfied,

$$1 < 0.4 < < 93.1$$

and

$$1 < 1.5 < < 274.6$$

But if the liquid phase physical mass transfer coefficient k_L^0 is used, the criterion for fast, pseudo first order reaction is completely satisfied,

$$1 < 2.8 < < 93.1$$

and

$$1 < 55.9 < < 274.6$$

APPENDIX B

CRITERION FOR LIQUID-FILM CONTROLLING RESISTANCE

The following calculation shows that mass transfer is controlled by the liquid film resistance.

The following expression relates the overall mass transfer resistance to the individual resistances:

$$\frac{1}{k_L a} = \frac{1}{Ek_L a} + \frac{1}{Hk_G a} \quad (B1)$$

If the gas is only slightly soluble in the liquid then H will be large and the gas side resistance is negligible. The liquid film resistance would then control the physical absorption process

$$\frac{1}{Ek_L a} \gg \frac{1}{Hk_G a}$$

which can be written

$$k_G \gg \frac{Ek_L}{H} \quad (B2)$$

The enhancement factor is defined as

$$E = \frac{\sqrt{D_{CO_2} k_2 C_{OH^-}}}{k_L} \quad (B3)$$

so from Equations (B2) and (B3)

$$k_G \gg \frac{\sqrt{D_{CO_2} k_2 C_{OH^-}}}{H} \quad (B4)$$

From Kasturi and Stepanek (21) gas film coefficients, k_G obtained in vertical two-phase upflow ranged from 10^{-4} to 8×10^{-4} mole/cm²-sec-atm. Using the maximum value of $C_{OH^-} = 25 \times 10^{-5}$ mole/cm³, $D_{CO_2} = 2.0 \times 10^{-5}$

cm^2/sec , $k_2 = 1 \times 10^7 \text{ cm}^3/\text{sec-mole}$ and $H = 1800 \text{ atm mole fraction}/0.0555$
 $\text{mole}/\text{cm}^3 = 3.24 \times 10^4 \text{ atm cm}^3/\text{mole}$,

$$\left[\frac{\sqrt{D_{\text{CO}_2} k_2 C_{\text{OH}^-}}}{H} \right]_{\text{max}} = 6.9 \times 10^{-6} \frac{\text{mole}}{\text{cm}^2 \text{ sec atm}}$$

The condition is satisfied,

$$10^{-4} \gg 6.9 \times 10^{-6}$$

APPENDIX C

DEVELOPMENT OF EQUATIONS FOR PHYSIOCHEMICAL CONSTANTS

Relations are derived in this section which are used to compute the physiochemical constants. The following relations are derived: diffusivity of carbon dioxide in the liquid, Henry's Law constant, and the second order rate constant.

Diffusivity

The following experimentally determined values of the diffusivity of carbon dioxide in water were taken from the literature.

<u>Temperature, °F</u>	<u>$D_{CO_2} \times 10^5, \text{ cm}^2/\text{sec}$</u>	<u>Reference</u>
50	1.46	Treybal (36), page 30
68	1.77	Treybal (36), page 30
77	1.92	Sherwood et al. (33) page 26

Vavruska (38) fit the above data to a linear regression given by the following:

$$D_{CO_2} = (0.6075 + 0.0171 T) 10^{-5} \quad (C1)$$

Vavruska (38) measured viscosities of sodium hydroxide solutions using a Couette viscometer over a temperature range of 69 to 80°F and concentrations ranging from 0.05 to 0.30 N. No difference in viscosity between any of the sodium hydroxide solutions and distilled water was observed. Thus, viscosity corrections for the diffusivity were unnecessary.

Henry's Law Constant

Henry's Law constant in solution is related to the value in water by the following from Danckwerts (8), page 19

$$\log_{10} \left[\frac{H}{H^0} \right] = hI \quad (C2)$$

where I is the ionic strength defined by

$$I = \frac{1}{2} \sum Z_i^2 C_i \quad (C3)$$

Z_i is the number of positive or negative charges on an ion having molarity C_i . For Na^+ and OH^- , $Z_i = 1$, and $C_{\text{OH}^-} = C_{\text{Na}^+}$ for all sodium hydroxide concentrations since the concentration of carbonate is so small. Thus,

$$I = \frac{1}{2} [(1)^2 C_{\text{OH}^-} + (1)^2 C_{\text{OH}^-}] = C_{\text{OH}^-} \quad (C4)$$

The value of h is found from

$$h = h_+ + h_- + h_G \quad (C5)$$

From Sherwood et al. (33), Tables 8.4 and 8.5, for Na^+ $h_+ = 0.091$ l/gion and for OH^- , $h_- = 0.066$ l/gion. Vavruska (38) fit h_G to a logarithmic temperature dependence given as follows:

$$h_G(T) = .104 - .028 \ln T \quad (C6)$$

and h is expressed as

$$h = .261 - .028 \ln T \quad (C7)$$

Henry's Law constant for carbon dioxide in water as a function of temperature was taken from data given in Perry (27), page 14-4. Vavruska (38) fit the data to the following linear regression:

$$H_{\text{CO}_2}^0 = 24.78 T - 266.9 \quad (C8)$$

Substituting Equations (C4), (C7), and (C8) into (C2) gives

$$\log_{10} H = \log_{10}[24.78 T - 266.9] + \bar{C}_{OH^-} [.261 - .028 \ln T] \quad (C9)$$

Second Order Rate Constant

The second order rate constant for the reaction between CO_2 and OH^- as a function of temperature is given by Sherwood et al. (33) as

$$\log_{10} k_2^0 = 13.635 - \frac{2,895}{T} \quad (C10)$$

where T is in $^{\circ}K$.

From Astarita (2) page 145, the rate constant is related to the value at infinite dilution by

$$\log_{10} k_2 = \log_{10} k_2^0 + A I_i \quad (C11)$$

where $A = 0.13$ 1/mole and $I_i = C_{OH^-}$.

Substituting Equation (C10) into (C11) gives for the rate constant

$$k_2 = 4.315 \times 10^{16} \exp\left[.13 \bar{C}_{OH^-} - \frac{1.2 \times 10^4}{T + 460}\right] \quad (C12)$$

APPENDIX D

SAMPLE CALCULATIONS

The following are sample calculations of the mass transfer coefficient and the interfacial area for a set of operating conditions using the chemical method, and the volumetric mass transfer coefficient using the physical absorption method.

The interfacial area and chemical mass transfer coefficient are calculated for a gas velocity of 6.0 ft/sec and a liquid velocity of 0.3 ft/sec.

Construction of the "Danckwerts Plot"

The concentration of carbonate in the liquid at sample port 1 is given by Equation (27) as follows:

$$C_{CO_3,1} = \frac{(Y_{CO_2,in} - Y_{CO_2,1})(\rho_G)(V_G^0)}{V_L^0}$$

The concentration at sample port 2 is calculated similarly. Rather than use the actual concentrations measured, carbonate concentrations calculated by linear regression are utilized. From Table XIV, in the Appendix, for $C_{OH^-} = .0840$ mole/liter, the concentrations at sample port 1 and 2 are $C'_{CO_3,1} = 1.916 \times 10^{-6}$ and $C'_{CO_3,2} = 5.298 \times 10^{-6}$ mole/cm³, respectively. The rate of absorption per unit volume of liquid is calculated from Equation (3),

$$\begin{aligned} Ra &= \frac{(C'_{CO_3,2} - C'_{CO_3,1}) V_L^0}{L} \\ &= \frac{[(5.298 - 1.916)10^{-6}][0.30]}{8.125} \\ &= 1.249 \times 10^{-7} \frac{\text{mole}}{\text{cm}^3 \text{sec}} \end{aligned}$$

and

$$Ra^2 = 1.560 \times 10^{-14} \left[\frac{\text{mole}}{\text{cm}^3 \text{sec}} \right]^2$$

The average sodium hydroxide concentration in the test section, using Equation (28), is

$$\begin{aligned} \bar{C}_{OH^-} &= C_{OH^-} - (C'_{CO_{3,1}} + C'_{CO_{3,2}}) \\ &= 8.40 \times 10^{-5} - (1.916 + 5.298) \times 10^{-6} \\ &= 7.679 \times 10^{-5} \text{ mole/cm}^3 \end{aligned}$$

The second order rate constant with $T = 80.5^\circ\text{F}$, is obtained using Equation (29)

$$\begin{aligned} k_2 &= 4.315 \times 10^{16} \exp\left[0.13 \bar{C}_{OH^-} - \frac{1.2 \times 10^4}{T + 460}\right] \\ &= 4.315 \times 10^{16} \exp\left[0.13(7.679 \times 10^{-2}) - \frac{1.2 \times 10^4}{80.5 + 460}\right] \\ &= 9.937 \times 10^6 \text{ cm}^3/\text{sec-mole} \end{aligned}$$

and

$$\begin{aligned} k_2 \bar{C}_{OH^-} &= (9.937 \times 10^6)(7.679 \times 10^{-5}) \\ &= 763.1 \text{ sec}^{-1} \end{aligned}$$

The above procedure is repeated for two other concentrations of sodium hydroxide to give three data points for the Danckwerts Plot. A

calculator program correlated the three points with a r factor of .9994.

The following results are obtained from the plot:

$$\text{slope} = 10.998 \times 10^{-18} \left[\frac{\text{mole}}{\text{cm}^3} \right]^2 \frac{1}{\text{sec}}$$

$$\text{intercept} = 7.102 \times 10^{-15} \left[\frac{\text{mole}}{\text{cm}^3 \text{ sec}} \right]^2$$

Equilibrium Solubility of Carbon Dioxide

Henry's Law constant is calculated as follows from Equation (32)

$$\begin{aligned} \log_{10} H &= \log_{10}(24.78 T - 266.9) + \bar{C}_{\text{OH}^-} (.261 - .028 \ln T) \\ &= \log_{10}(24.78(80.5) - 266.9) + (7.679 \times 10^{-2}) \\ &\quad (.261 - .028 \ln(80.5)) \end{aligned}$$

$$H = 1770.6 \text{ atm/mole fraction}$$

and the equilibrium solubility of CO_2 from Equation (31) is

$$\begin{aligned} C_{\text{CO}_2}^* &= \frac{\bar{Y}_{\text{CO}_2} P_t 10^{-3}}{H} (55.556 + \bar{C}_{\text{OH}^-}) \\ &= \frac{(.01992)(.9851)(10^{-3})}{1770.6} (55.556 + 7.679 \times 10^{-2}) \\ &= 6.166 \times 10^{-7} \text{ mole/cm}^3 \end{aligned}$$

The average value for the three sodium hydroxide concentrations is

$$\bar{C}_{\text{CO}_2}^* = 5.659 \times 10^{-7} \text{ mole/cm}^3$$

Diffusivity of Carbon Dioxide in the Liquid

From Equation (35)

$$\begin{aligned}
 D_{\text{CO}_2} &= (0.6075 + .0171 T) 10^{-5} \\
 &= (0.6075 + .0171(80.5)) 10^{-5} \\
 &= 1.984 \times 10^{-5} \text{ cm}^2/\text{sec}
 \end{aligned}$$

The average for the three hydroxide feed concentrations is $2.001 \times 10^{-5} \text{ cm}^2/\text{sec}$.

Interfacial Area and Mass Transfer Coefficient

From Equation (33)

$$\begin{aligned}
 a &= \frac{1}{\bar{C}_{\text{CO}_2}^*} \left[\frac{\text{slope}}{D_{\text{CO}_2}} \right]^{1/2} \\
 &= \frac{1}{5.659 \times 10^{-7}} \left[\frac{10.998 \times 10^{-18}}{2.001 \times 10^{-5}} \right]^{1/2} \\
 &= 1.31 \text{ cm}^{-1}
 \end{aligned}$$

and from Equation (34)

$$\begin{aligned}
 k_L &= \frac{(\text{Intercept})^{1/2}}{a \bar{C}_{\text{CO}_2}^*} \\
 &= \frac{(7.102 \times 10^{-15})^{1/2}}{(1.31)(5.659 \times 10^{-7})}
 \end{aligned}$$

$$= .114 \text{ cm/sec}$$

The volumetric chemical mass transfer coefficient $k_L a$ is

$$k_L a = (.114)(1.31)$$

$$= .149 \text{ sec}^{-1}$$

The volumetric physical mass transfer coefficient $k_L^0 a$ is calculated at a gas velocity of 4 ft/sec and a liquid velocity of 0.3 ft/sec.

Rate of Absorption of Carbon Dioxide into Water

Using the same procedure for finding the concentration of carbonate in the liquid, the concentration of carbon dioxide is $C_{CO_2,1}' = 4.457 \times 10^{-7} \text{ mole/cm}^3$ and $C_{CO_2,2}' = 7.107 \times 10^{-7} \text{ mole/cm}^3$ for sample ports 1 and 2, respectively.

The rate is then calculated from Equation (36)

$$\begin{aligned} Ra &= \frac{(C_{CO_2,2}' - C_{CO_2,1}') V_L^0}{L} \\ &= \frac{(7.107 - 4.457)10^{-7} (0.3)}{8.125} \\ &= 9.785 \times 10^{-9} \left(\frac{\text{mole}}{\text{cm}^3 \text{ sec}} \right) \end{aligned}$$

The Equilibrium Solubility of Carbon Dioxide into Water

From Equation (31)

$$\begin{aligned}
 C_{\text{CO}_2}^* &= \frac{\bar{Y}_{\text{CO}_2} P_t 10^{-3}}{H} \quad (55.556) \\
 &= \frac{(.02345)(.9908)(10^{-3})}{1554.4} \quad (55.556) \\
 &= 8.304 \times 10^{-7} \frac{\text{mole}}{\text{cm}^3}
 \end{aligned}$$

Where Henry's Law constant is obtained from Equation (32) with
 $T = 73.5^\circ\text{F}$

$$\begin{aligned}
 H &= 24.78T - 266.9 \\
 &= 1554.4 \text{ atm/mole fraction}
 \end{aligned}$$

Volumetric Physical Mass Transfer Coefficient

From Equation (25)

$$\begin{aligned}
 k_L^o a &= \frac{Ra}{C_{\text{CO}_2}^*} \\
 &= \frac{9.785 \times 10^{-9}}{8.304 \times 10^{-7}} \\
 &= .012 \text{ sec}^{-1}
 \end{aligned}$$

APPENDIX E

SUPPLEMENTARY FIGURES

Figures 32 through 36 are calibration curves for gas and liquid rotameters used in this work.

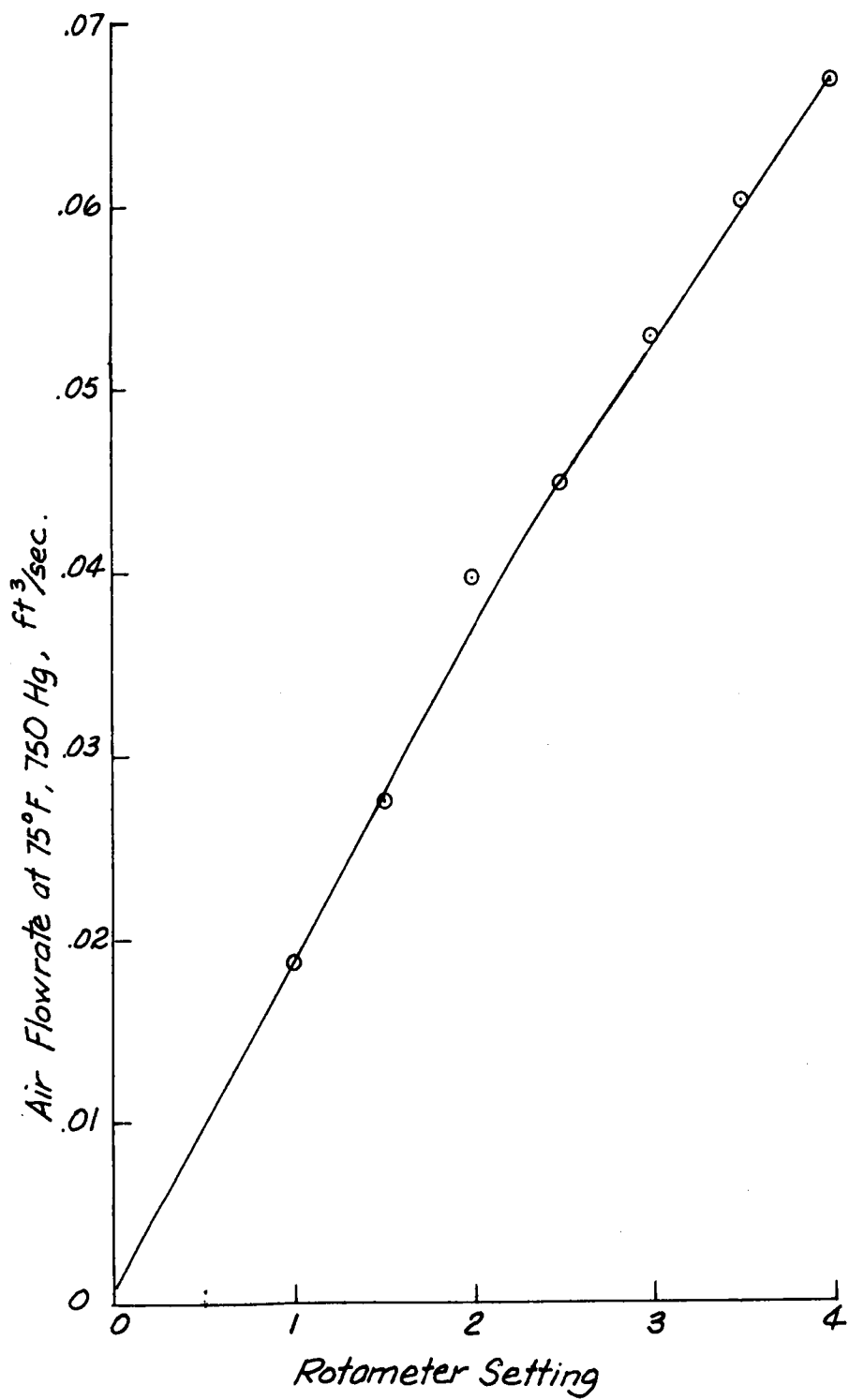


Figure 32. Calibration curve for air rotameter No. 1.

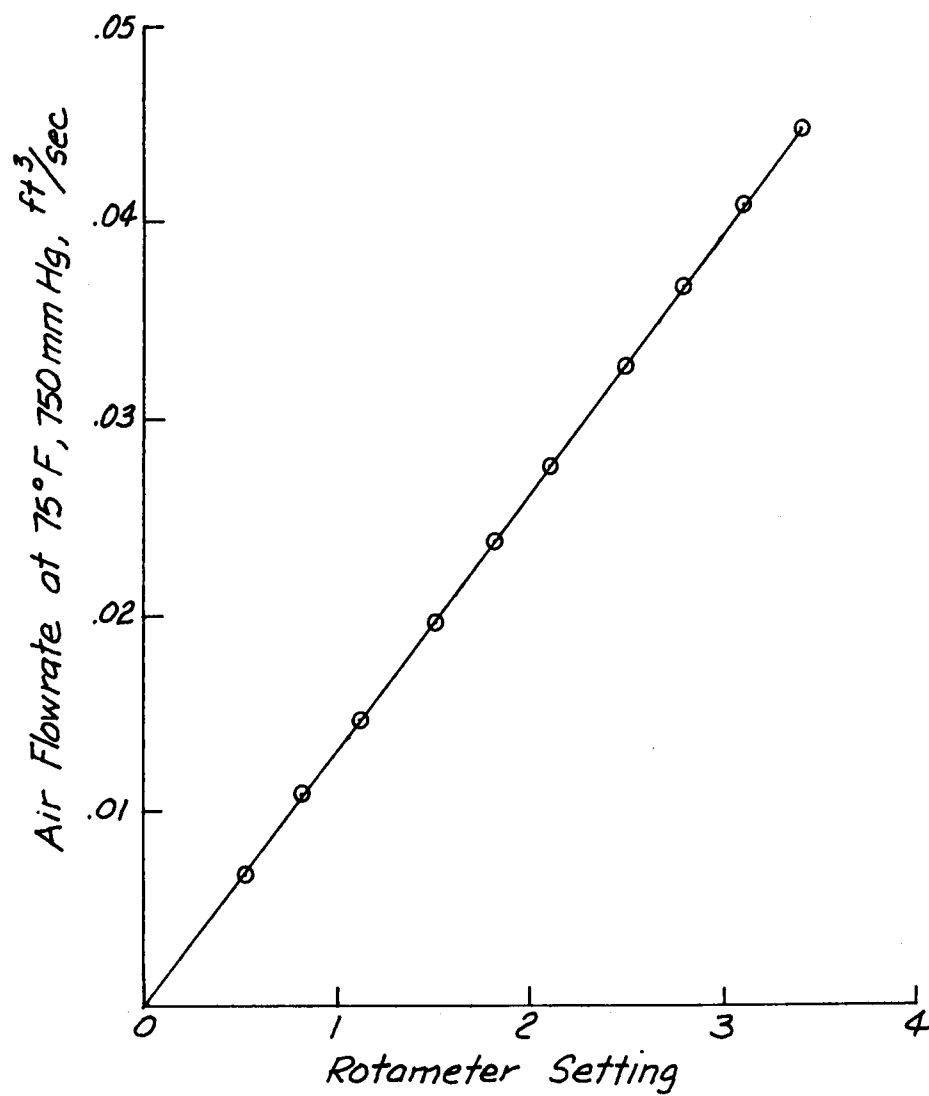


Figure 33. Calibration curve for air rotameter No. 2.

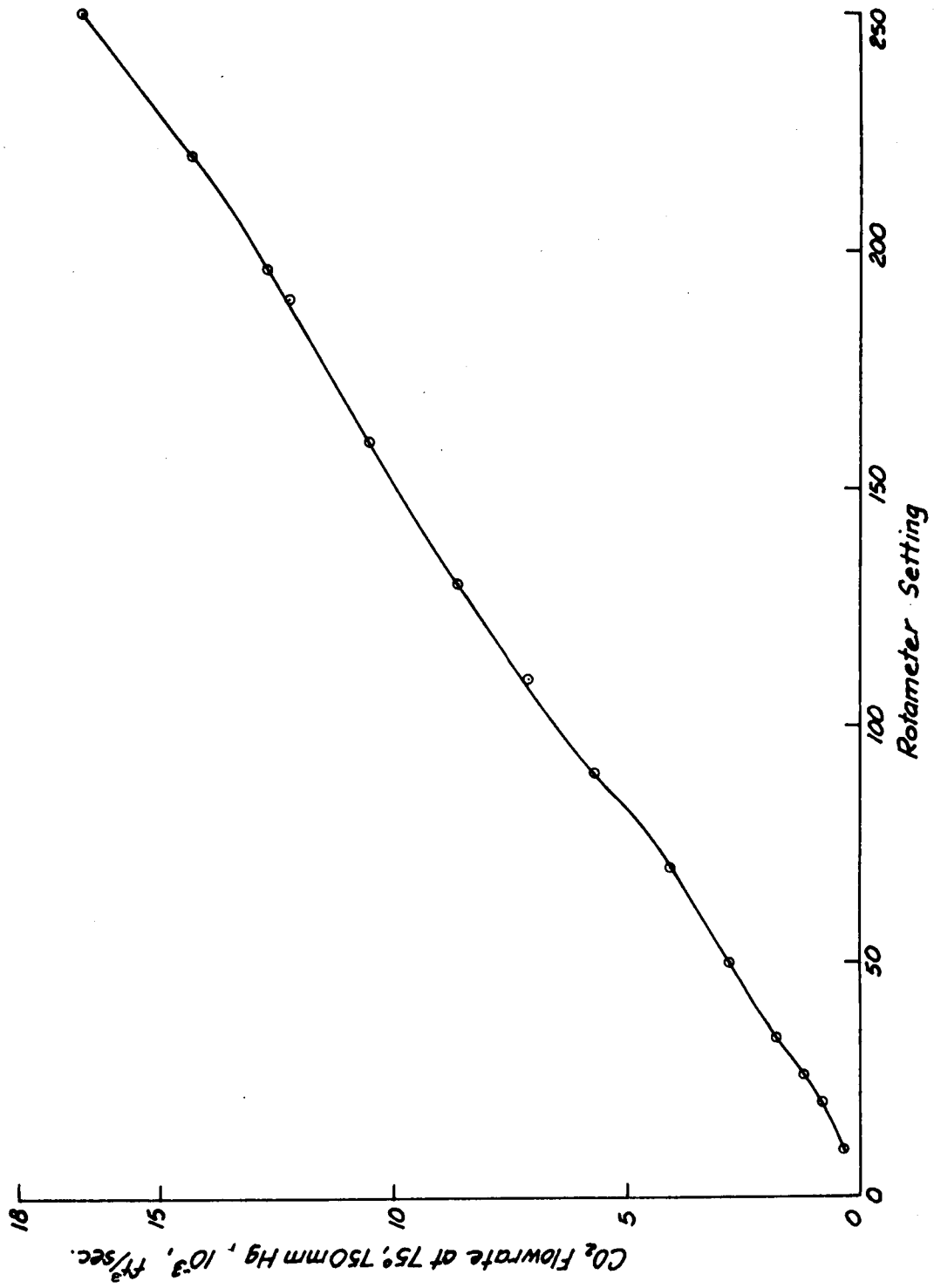


Figure 34. Calibration curve for CO₂ rotameter.

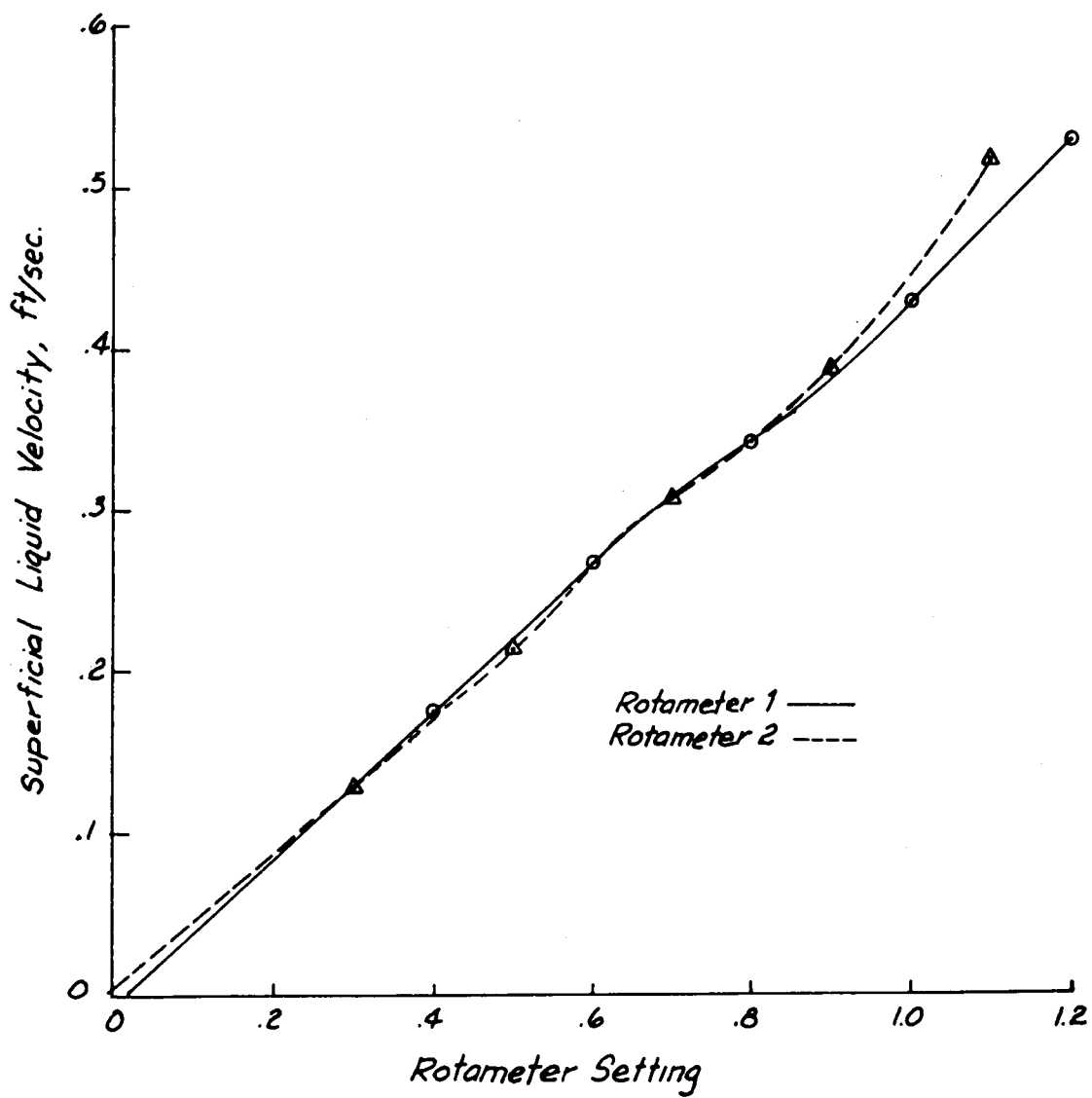


Figure 35. Calibration curve for liquid rotameter Nos. 1 and 2.

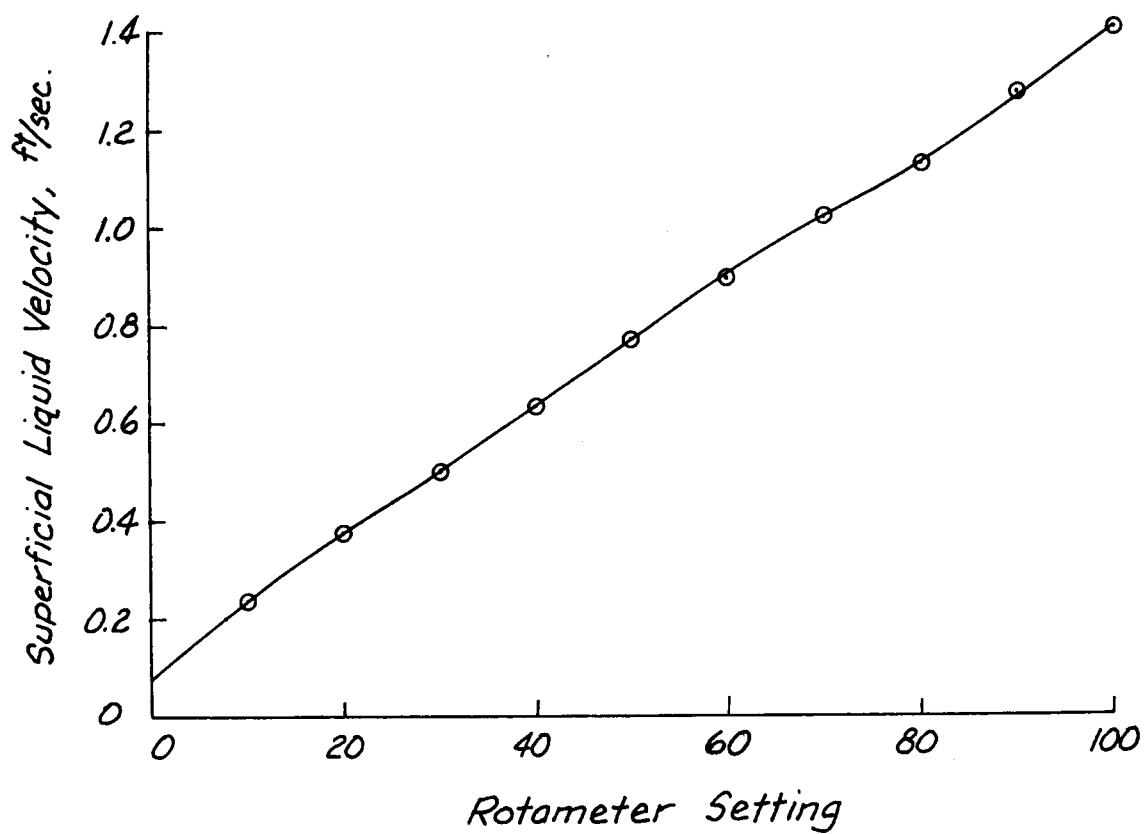


Figure 36. Calibration curve for liquid rotameter No. 3.

APPENDIX F

PRESSURE MEASUREMENT DATA

Table I presents the pressures measured in the column above atmospheric pressure at both sample ports 1 and 2 for all flow velocities covered in this work. Data was collected in inches of 1.75 specific gravity manometer fluid and was converted to mm of mercury.

Table I

 v_L^0 (ft/sec)

APPENDIX G

ABSORPTION DATA

Tables II through VIII present the chemical absorption data for all flow rates and conditions covered in this work. The tables include gas and liquid superficial velocities, sodium hydroxide feed concentrations, mole fraction of carbon dioxide in the inlet gas stream and the mole fractions of carbon dioxide in the gas at sample ports 1 and 2.

Table IX presents the physical absorption data. It includes gas and liquid velocities, inlet mole fraction of carbon dioxide and the mole fractions of carbon dioxide in the gas at both sample ports.

Table II

Chemical Absorption Data for Superficial
Gas Velocity = 1.5 ft/sec

Run	V_L^0 (ft/sec)	$C_{OH} \left(\frac{\text{mole}}{\text{liter}} \right)$	$Y_{CO_2, in}$	$Y_{CO_2, 1}$	$Y_{CO_2, 2}$
1 - 1	0.06	.0525	.02413	.01930	.01173
	0.10	.0525	.02413	.01868	.01020
	0.20	.0525	.02413	.01708	.00920
	0.30	.0525	.02413	.01650	.00848
	0.60	.0525	.02413	.01563	.00775
	1.0	.0525	.02413	.01593	.00745
	1.5	.0525	.02413	.01525	.00655
1 - 2	0.06	.0689	.02388	.01763	.00925
	0.10	.0689	.02388	.01698	.00850
	0.20	.0689	.02388	.01620	.00770
	0.30	.0689	.02388	.01508	.00703
	0.60	.0689	.02388	.01475	.00630
	1.0	.0689	.02388	.01475	.00608
	1.5	.0689	.02388	.01450	.00545
1 - 3	0.06	.0985	.02333	.01675	.00733
	0.10	.0985	.02333	.01548	.00630
	0.20	.0985	.02333	.01430	.00545
	0.30	.0985	.02333	.01388	.00538
	0.60	.0985	.02333	.01388	.00473
	1.0	.0985	.02333	.01343	.00450
	1.5	.0985	.02333	.01313	.00403

Table III

Chemical Absorption Data for Superficial
Gas Velocity = 2.0 ft/sec

Run	V_L^o (ft/sec)	C_{OH} ($\frac{\text{mole}}{\text{liter}}$)	$Y_{CO_2, in}$	$Y_{CO_2, 1}$	$Y_{CO_2, 2}$
2 - 1	0.06	.0534	.02363	.02045	.01350
	0.10	.0534	.02363	.01918	.01270
	0.20	.0534	.02363	.01870	.01150
	0.30	.0534	.02363	.01795	.01080
	0.60	.0534	.02363	.01725	.01000
	1.0	.0534	.02363	.01705	.00945
	1.5	.0534	.02363	.01700	.00875
2 - 2	0.06	.1312	.02280	.01688	.00838
	0.10	.1312	.02280	.01625	.00753
	0.20	.1312	.02280	.01495	.00688
	0.30	.1312	.02280	.01455	.00648
	0.60	.1312	.02280	.01388	.00575
	1.0	.1312	.02280	.01403	.00548
	1.5	.1312	.02280	.01405	.00483
2 - 3	0.06	.1628	.02308	.01620	.00745
	0.10	.1628	.02308	.01550	.00670
	0.20	.1628	.02308	.01450	.00600
	0.30	.1628	.02308	.01425	.00583
	0.60	.1628	.02308	.01350	.00505
	1.0	.1628	.02308	.01358	.00470
	1.5	.1628	.02308	.01330	.00405

Table IV

Chemical Absorption Data for Superficial
Gas Velocity = 3.0 ft/sec

Run	V_L^0 (ft/sec)	$C_{OH} \left(\frac{\text{mole}}{\text{liter}} \right)$	$Y_{CO_2, in}$	$Y_{CO_2, 1}$	$Y_{CO_2, 2}$
3 - 1	0.06	.1092	.02308	.01868	.01260
	0.10	.1092	.02308	.01863	.01220
	0.20	.1092	.02308	.01788	.01150
	0.30	.1092	.02308	.01780	.01118
	0.60	.1092	.02308	.01705	.01018
	1.0	.1092	.02308	.01718	.00973
	1.5	.1092	.02308	.01675	.00878
3 - 2	0.06	.1314	.02308	.01813	.01170
	0.10	.1314	.02308	.01800	.01130
	0.20	.1314	.02308	.01748	.01060
	0.30	.1314	.02308	.01755	.01045
	0.60	.1314	.02308	.01638	.00920
	1.0	.1314	.02308	.01638	.00880
	1.5	.1314	.02308	.01648	.00813
3 - 3	0.06	.1776	.02308	.01750	.01053
	0.10	.1776	.02308	.01705	.01000
	0.20	.1776	.02308	.01675	.00938
	0.30	.1776	.02308	.01675	.00908
	0.60	.1776	.02308	.01588	.00825
	1.0	.1776	.02308	.01575	.00750
	1.5	.1776	.02308	.01543	.00695

Table V

Chemical Absorption Data for Superficial
Gas Velocity = 4.0 ft/sec

Run	V_L^0 (ft/sec)	C_{OH} ($\frac{\text{mole}}{\text{liter}}$)	$Y_{CO_2, in}$	$Y_{CO_2, 1}$	$Y_{CO_2, 2}$
4 - 1	0.06	.0865	.02330	.02088	.01613
	0.10	.0865	.02330	.02068	.01530
	0.20	.0865	.02330	.02000	.01473
	0.30	.0865	.02330	.01938	.01440
	0.60	.0865	.02330	.01925	.01383
	1.0	.0865	.02330	.01940	.01320
	1.5	.0865	.02330	.01888	.01225
4 - 2	0.06	.1114	.02330	.02045	.01475
	0.10	.1114	.02330	.02005	.01443
	0.20	.1114	.02330	.01928	.01375
	0.30	.1114	.02330	.01950	.01375
	0.60	.1114	.02330	.01875	.01270
	1.0	.1114	.02330	.01875	.01218
	1.5	.1114	.02330	.01850	.01120
4 - 3	0.06	.1599	.02330	.01938	.01345
	0.10	.1599	.02330	.01918	.01258
	0.20	.1599	.02330	.01870	.01258
	0.30	.1599	.02330	.01888	.01233
	0.60	.1599	.02330	.01813	.01163
	1.0	.1599	.02330	.01800	.01043
	1.5	.1599	.02330	.01775	.00963
4 - 4	0.06	.1856	.02330	.01973	.01303
	0.10	.1856	.02330	.01878	.01220
	0.20	.1856	.02330	.01825	.01163
	0.30	.1856	.02330	.01823	.01183
	0.60	.1856	.02330	.01818	.01105
	1.0	.1856	.02330	.01825	.01025
	1.5	.1856	.02330	.01775	.00928

Table VI

Chemical Absorption Data for Superficial
Gas Velocity = 6.0 ft/sec

Run	V_L^0 (ft/sec)	$C_{OH} \left(\frac{\text{mole}}{\text{liter}} \right)$	$Y_{CO_2, in}$	$Y_{CO_2, 1}$	$Y_{CO_2, 2}$
5 - 1	0.06	.0840	.02438	.02275	.01943
	0.10	.0840	.02438	.02250	.01888
	0.20	.0840	.02438	.02213	.01813
	0.30	.0840	.02438	.02163	.01775
	0.60	.0840	.02438	.02155	.01720
	1.0	.0840	.02438	.02170	.01668
	1.5	.0840	.02438	.02125	.01553
5 - 2	0.06	.1563	.02438	.02225	.01775
	0.10	.1563	.02438	.02150	.01700
	0.20	.1563	.02438	.02120	.01625
	0.30	.1563	.02438	.02100	.01623
	0.60	.1563	.02438	.02073	.01558
	1.0	.1563	.02438	.02100	.01500
	1.5	.1563	.02438	.02050	.01380
5 - 3	0.06	.1936	.02438	.02170	.01675
	0.10	.1936	.02438	.02130	.01610
	0.20	.1936	.02438	.02095	.01538
	0.30	.1936	.02438	.02070	.01535
	0.60	.1936	.02438	.02038	.01463
	1.0	.1936	.02438	.02045	.01388
	1.5	.1936	.02438	.01975	.01250

Table VII

Chemical Absorption Data for Superficial
Gas Velocity = 10.0 ft/sec

Run	V_L^0 (ft/sec)	$C_{OH} \left(\frac{\text{mole}}{\text{liter}} \right)$	$Y_{CO_2, in}$	$Y_{CO_2, 1}$	$Y_{CO_2, 2}$
6 - 1	0.06	.1018	.02420	.02330	.02078
	0.10	.1018	.02420	.02299	.02044
	0.20	.1018	.02420	.02256	.02018
	0.30	.1018	.02420	.02272	.01986
	0.60	.1018	.02420	.02265	.01943
	1.0	.1018	.02420	.02243	.01922
	1.5	.1018	.02420	.02293	.01860
6 - 2	0.06	.1647	.02420	.02275	.01983
	0.10	.1647	.02420	.02219	.01912
	0.20	.1647	.02420	.02176	.01886
	0.30	.1647	.02420	.02198	.01911
	0.60	.1647	.02420	.02220	.01845
	1.0	.1647	.02420	.02185	.01798
	1.5	.1647	.02420	.02193	.01676
6 - 3	0.06	.2642	.02420	.02225	.01873
	0.10	.2642	.02420	.02199	.01824
	0.20	.2642	.02420	.02218	.01811
	0.30	.2642	.02420	.02168	.01811
	0.60	.2642	.02420	.02190	.01759
	1.0	.2642	.02420	.02210	.01708
	1.5	.2642	.02420	.02203	.01563

Table VIII

Chemical Absorption Data for Superficial
Gas Velocity = 20.0 ft/sec

Run	V_L^0 (ft/sec)	$C_{OH} \left(\frac{\text{mole}}{\text{liter}} \right)$	$Y_{CO_2, in}$	$Y_{CO_2, 1}$	$Y_{CO_2, 2}$
7 - 1	0.06	.0999	.02330	.02275	.02155
	0.10	.0999	.02330	.02237	.02122
	0.20	.0999	.02330	.02272	.02128
	0.30	.0999	.02330	.02250	.02108
	0.60	.0999	.02330	.02286	.02111
	1.0	.0999	.02330	--	--
	1.5	.0999	.02330	--	--
7 - 2	0.06	.1767	.02225	.02145	.02000
	0.10	.1767	.02225	.02124	.01987
	0.20	.1767	.02225	.02136	.01978
	0.30	.1767	.02225	.02133	.01963
	0.60	.1767	.02225	.02175	.01979
	1.0	.1767	.02225	--	--
	1.5	.1767	.02225	--	--
7 - 3	0.06	.2986	.02225	.02148	.01950
	0.10	.2986	.02225	.02124	.01937
	0.20	.2986	.02225	.02141	.01943
	0.30	.2986	.02225	.02145	.01918
	0.60	.2986	.02225	.02177	.01924
	1.0	.2986	.02225	--	--
	1.5	.2986	.02225	--	--

Table IX
Physical Absorption Data

V_G^O (ft/sec)	V_L^O (ft/sec)	$Y_{CO_2,in}$	$Y_{CO_2,1}$	$Y_{CO_2,2}$
1.5	0.06	.02370	--	--
	0.10	.02370	--	--
	0.20	.02370	--	--
	0.30	.02370	.02263	.02170
	0.60	.02370	.02195	.02020
	1.0	.02370	.02153	.01933
	1.5	.02370	.02095	.01830
2.0	0.06	.02458	--	--
	0.10	.02458	--	--
	0.20	.02458	.02388	.02330
	0.30	.02458	.02368	.02293
	0.60	.02458	.02325	.02188
	1.0	.02458	.02300	.02100
	1.5	.02458	.02235	.02025
3.0	0.06	.02373	--	--
	0.10	.02373	--	--
	0.20	.02373	.02340	.02300
	0.30	.02373	.02325	.02275
	0.60	.02373	--	--
	1.0	.02373	.02260	.02117
	1.5	.02373	.02245	.02070
4.0	0.06	.02450	--	--
	0.10	.02450	.02388	.02375
	0.20	.02450	--	--
	0.30	.02450	.02375	.02325
	0.60	.02450	.02351	.02235
	1.0	.02450	.02328	.02233
	1.5	.02450	.02324	.02187
6.0	0.06	.02400	.02388	.02378
	0.10	.02400	--	--
	0.20	.02400	.02373	.02355
	0.30	.02400	.02371	.02330
	0.60	.02400	.02350	.02297
	1.0	.02400	--	--
	1.5	.02400	--	--

Table IX (continued)

V_G^0 (ft/sec)	V_G^0 (ft/sec)	$Y_{CO_2,in}$	$Y_{CO_2,1}$	$Y_{CO_2,2}$
10.0	0.06	.02263	.02250	.02243
	0.10	.02263	--	--
	0.20	.02263	.02248	.02235
	0.30	.02263	--	--
	0.60	.02263	.02245	.02220
	1.0	.02263	--	--
	1.5	.02263	--	--

APPENDIX H

CALCULATED RESULTS

Tables X through XVI present the calculated carbonate concentrations in the liquid for both sample ports, obtained from the mass balance, and the concentrations of carbonate calculated by linear regression. Table XVII presents the same calculated results for the physical absorption data.

Tables XVIII through XXIV present the experimental conditions and calculated data used to construct "Danckwerts Plots."

Table XXV presents the calculated data used to calculate the interfacial area a and the liquid phase chemical mass transfer coefficient k_L , along with k_L , a and $k_L a$. Table XXVI presents the calculated data used to calculate the volumetric physical mass transfer coefficient $k_L^o a$, along with $k_L^o a$.

Table X

Calculated Chemical Absorption Data From Mass Balance and Linear Regression, Superficial Gas Velocity = 1.5 ft/sec

Run	V_L^0 (ft/sec)	$C_{CO_{3,1}} \times 10^6$ ($\frac{\text{mole}}{\text{cm}^3}$)	$C_{CO_{3,2}} \times 10^6$ ($\frac{\text{mole}}{\text{cm}^3}$)	$C_{CO_{3,1}}' \times 10^6$ ($\frac{\text{mole}}{\text{cm}^3}$)	$C_{CO_{3,2}}' \times 10^6$ ($\frac{\text{mole}}{\text{cm}^3}$)
1 - 1	0.06	4.834	12.411	5.185	12.990
	0.10	3.273	8.366	3.421	8.193
	0.20	2.117	4.483	1.946	4.384
	0.30	1.528	3.133	1.399	3.041
	0.60	.851	1.640	.796	1.627
	1.0	.492	1.002	.525	1.026
	1.5	.356	.704	.378	.712
1 - 2	0.06	6.257	14.643	6.553	14.836
	0.10	4.144	9.237	4.196	9.224
	0.20	2.306	4.859	2.292	4.840
	0.30	1.762	3.373	1.609	3.319
	0.60	.914	1.760	.879	1.742
	1.0	.548	1.069	.563	1.083
	1.5	.376	.738	.395	.743
1 - 3	0.06	7.136	16.565	7.530	16.740
	0.10	4.715	10.228	4.763	10.280
	0.20	2.712	5.616	2.559	5.304
	0.30	1.892	3.594	1.779	3.602
	0.60	.946	1.862	.956	1.859
	1.0	.595	1.131	.605	1.141
	1.5	.408	.773	.420	.775

Table XI

Calculated Chemical Absorption Data From Mass Balance and Linear Regression, Superficial Gas Velocity = 2.0 ft/sec

Run	V_L^0 (ft/sec)	$C_{CO_2,1} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$C_{CO_2,2} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$C'_{CO_2,1} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$C'_{CO_2,2} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$
2 - 1	0.06	4.211	13.414	4.884	13.702
	0.10	3.536	8.685	3.266	8.727
	0.20	1.959	4.819	1.892	4.731
	0.30	1.504	3.398	1.375	3.307
	0.60	.845	1.805	.796	1.793
	1.0	.523	1.127	.532	1.142
	1.5	.351	.788	.387	.798
2 - 2	0.06	7.817	19.042	8.469	19.485
	0.10	5.190	12.100	5.414	12.076
	0.20	3.110	6.308	2.949	6.310
	0.30	2.398	4.530	2.068	4.316
	0.60	1.178	2.252	1.126	2.255
	1.0	.695	1.372	.720	1.398
	1.5	.462	.949	.505	.956
2 - 3	0.06	9.097	20.666	9.541	20.885
	0.10	6.014	12.996	6.044	12.899
	0.20	3.404	6.776	3.253	6.708
	0.30	2.335	4.562	2.264	4.576
	0.60	1.267	2.384	1.219	2.380
	1.0	.754	1.458	.772	1.470
	1.5	.517	1.005	.537	1.003

Table XII

Calculated Chemical Absorption Data From Mass Balance and Linear Regression, Superficial Gas Velocity = 3.0 ft/sec

Run	V_L^0 (ft/sec)	$C_{CO_2,1} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$C_{CO_2,2} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$C_{CO_2,1}' \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$C_{CO_2,2}' \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$
3 - 1	0.06	8.843	21.062	8.536	20.843
	0.10	5.367	13.121	5.447	13.124
	0.20	3.136	6.983	2.960	7.006
	0.30	2.123	4.784	2.072	4.853
	0.60	1.212	2.593	1.126	2.591
	1.0	.712	1.610	.719	1.631
	1.5	.509	1.150	.503	1.130
3 - 2	0.06	9.948	22.871	9.853	22.645
	0.10	6.126	14.207	6.231	14.198
	0.20	3.377	7.525	3.346	7.536
	0.30	2.223	5.077	2.326	5.203
	0.60	1.347	2.790	1.249	2.762
	1.0	.788	1.722	.790	1.732
	1.5	.531	1.202	.549	1.195
3 - 3	0.06	11.298	25.223	11.341	25.127
	0.10	7.272	15.774	7.142	15.686
	0.20	3.817	8.261	3.814	8.276
	0.30	2.545	5.628	2.642	5.694
	0.60	1.447	2.981	1.411	3.004
	1.0	.884	1.879	.889	1.876
	1.5	.615	1.297	.616	1.290

Table XIII

Calculated Chemical Absorption Data From Mass Balance and Linear Regression, Superficial Gas Velocity = 4.0 ft/sec

Run	V_L^o (ft/sec)	$C_{CO_2,1} \times 10^6$ ($\frac{\text{mole}}{\text{cm}^3}$)	$C_{CO_2,2} \times 10^6$ ($\frac{\text{mole}}{\text{cm}^3}$)	$C'_{CO_2,1} \times 10^6$ ($\frac{\text{mole}}{\text{cm}^3}$)	$C'_{CO_2,2} \times 10^6$ ($\frac{\text{mole}}{\text{cm}^3}$)
4 - 1	0.06	6.501	19.261	6.810	19.663
	0.10	4.223	12.896	4.489	12.555
	0.20	2.660	6.907	2.550	6.831
	0.30	2.106	4.782	1.832	4.785
	0.60	1.088	2.544	1.041	2.603
	1.0	.629	1.628	.686	1.662
	1.5	.475	1.188	.493	1.164
4 - 2	0.06	7.656	22.968	8.104	22.538
	0.10	5.239	14.298	5.268	14.267
	0.20	3.240	7.697	2.937	7.672
	0.30	2.042	5.132	2.086	5.337
	0.60	1.222	2.848	1.163	2.870
	1.0	.733	1.793	.756	1.817
	1.5	.516	1.300	.537	1.264
4 - 3	0.06	10.531	26.461	10.498	26.312
	0.10	6.641	17.281	6.663	16.558
	0.20	3.708	8.640	3.596	8.833
	0.30	2.375	5.895	2.507	6.116
	0.60	1.389	3.135	1.353	3.262
	1.0	.854	2.075	.859	2.053
	1.5	.596	1.469	.599	1.422
4 - 4	0.06	9.590	27.589	10.893	27.790
	0.10	7.286	17.893	6.888	17.421
	0.20	4.070	9.406	3.698	9.244
	0.30	2.724	6.163	2.570	6.381
	0.60	1.376	3.291	1.380	3.386
	1.0	.814	2.104	.872	2.123
	1.5	.596	1.507	.606	1.465

Table XIV

Calculated Chemical Absorption Data From Mass Balance and Linear Regression, Superficial Gas Velocity = 6.0 ft/sec

Run	V_L^0 (ft/sec)	$C_{CO_2,1} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$C_{CO_2,2} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$C'_{CO_2,1} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$C'_{CO_2,2} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$
5 - 1	0.06	6.581	19.986	7.054	20.236
	0.10	4.555	13.325	4.665	13.225
	0.20	2.726	7.571	2.661	7.426
	0.30	2.223	5.360	1.916	5.298
	0.60	1.144	2.903	1.093	2.975
	1.0	.652	1.872	.723	1.945
	1.5	.509	1.439	.520	1.387
5 - 2	0.06	8.600	26.769	9.977	27.251
	0.10	6.978	17.880	6.460	17.464
	0.20	3.852	9.849	3.582	9.548
	0.30	2.732	6.588	2.537	6.707
	0.60	1.476	3.558	1.406	3.667
	1.0	.822	2.280	.911	2.350
	1.5	.631	1.721	.645	1.651
5 - 3	0.06	10.821	30.807	11.295	30.783
	0.10	7.462	20.061	7.316	19.674
	0.20	4.155	10.903	4.058	10.717
	0.30	2.975	7.300	2.874	7.512
	0.60	1.617	3.942	1.594	4.092
	1.0	.955	2.553	1.033	2.615
	1.5	.753	1.932	.731	1.833

Table XV

Calculated Chemical Absorption Data From Mass Balance and Linear Regression, Superficial Gas Velocity = 10.0 ft/sec

Run	V_L^0 (ft/sec)	$C_{CO_2,1} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$C_{CO_2,2} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$C'_{CO_2,1} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$C'_{CO_2,2} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$
6 - 1	0.06	6.032	22.923	7.525	22.956
	0.10	4.870	15.134	4.809	14.848
	0.20	3.301	8.092	2.619	8.221
	0.30	1.987	5.826	1.836	5.817
	0.60	1.042	3.205	1.000	3.221
	1.0	.717	2.017	.639	2.083
	1.5	.346	1.525	.448	1.474
6 - 2	0.06	9.719	29.290	11.850	29.656
	0.10	8.090	20.447	7.483	19.090
	0.20	4.912	10.749	4.010	10.501
	0.30	2.980	6.832	2.784	7.402
	0.60	1.344	3.864	1.492	4.072
	1.0	.952	2.519	.942	2.621
	1.5	.618	2.027	.654	1.848
6 - 3	0.06	11.394	36.663	13.153	35.906
	0.10	8.895	23.989	8.106	22.880
	0.20	4.066	12.259	4.203	12.413
	0.30	3.382	8.175	2.862	8.680
	0.60	1.546	4.442	1.484	4.709
	1.0	.851	2.884	.915	3.001
	1.5	.591	2.335	.623	2.098

Table XVI

Calculated Chemical Absorption Data From Mass Balance and Linear Regression, Superficial Gas Velocity = 20.0 ft/sec

Run	V_L^0 (ft/sec)	$C_{CO_2,1} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$C_{CO_2,2} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$C'_{CO_2,1} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$C'_{CO_2,2} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$
7 - 1	0.06	7.349	23.383	9.746	26.652
	0.10	7.459	16.682	5.503	15.985
	0.20	2.328	8.106	2.534	7.989
	0.30	2.143	5.947	1.610	5.324
	0.60	.593	2.950	.741	2.661
	1.0	--	--	.419	1.596
	1.5	--	--	.266	1.064
7 - 2	0.06	10.703	30.102	13.258	30.732
	0.10	8.112	19.116	7.233	18.918
	0.20	3.576	9.924	3.179	9.794
	0.30	2.468	7.029	1.965	6.664
	0.60	.675	3.319	.864	3.450
	1.0	--	--	.471	2.124
	1.5	--	--	.291	1.445
7 - 3	0.06	10.314	36.837	12.902	35.829
	0.10	8.122	23.161	6.953	22.402
	0.20	3.380	11.348	3.005	11.846
	0.30	2.149	8.246	1.840	8.160
	0.60	.648	4.066	.795	4.315
	1.0	--	--	.428	2.698
	1.5	--	--	.262	1.858

Table XVII
Calculated Physical Absorption Data From Mass
Balance and Linear Regression

V_G^0 (ft/sec)	V_L^0 (ft/sec)	$C_{CO_2,1} \times 10^7$ ($\frac{\text{mole}}{\text{cm}^3}$)	$C_{CO_2,2} \times 10^7$ ($\frac{\text{mole}}{\text{cm}^3}$)	$C_{CO_2,1}^* \times 10^7$ ($\frac{\text{mole}}{\text{cm}^3}$)	$C_{CO_2,2}^* \times 10^7$ ($\frac{\text{mole}}{\text{cm}^3}$)
1.5	0.06	--	--	4.422	7.980
	0.10	--	--	3.560	6.535
	0.20	--	--	2.653	4.984
	0.30	2.166	4.048	2.234	4.254
	0.60	1.771	3.542	1.665	3.244
	1.0	1.318	2.653	1.340	2.657
	1.5	1.113	2.186	1.129	2.268
2.0	0.06	--	--	4.950	8.377
	0.10	--	--	3.929	6.888
	0.20	2.839	5.192	2.872	5.281
	0.30	2.434	4.462	2.391	4.521
	0.60	1.798	3.650	1.747	3.466
	1.0	1.282	2.904	1.387	2.850
	1.5	1.206	2.342	1.155	2.439
3.0	0.06	--	--	3.130	6.252
	0.10	--	--	2.664	5.451
	0.20	2.031	4.493	2.140	4.525
	0.30	1.970	4.021	1.883	4.058
	0.60	--	--	1.512	3.369
	1.0	1.393	3.156	1.287	2.937
	1.5	1.053	2.492	1.132	2.634
4.0	0.06	--	--	14.083	16.568
	0.10	10.176	12.310	9.774	12.665
	0.20	--	--	5.955	8.796
	0.30	4.103	6.839	4.457	7.107
	0.60	2.711	5.887	2.715	4.936
	1.0	2.007	3.570	1.885	3.773
	1.5	1.384	2.889	1.410	3.049
6.0	0.06	4.924	9.027	4.958	8.862
	0.10	--	--	4.052	7.536
	0.20	3.324	5.540	3.081	6.049
	0.30	2.382	5.750	2.625	5.318
	0.60	2.054	4.232	1.997	4.269
	1.0	--	--	1.632	3.630
	1.5	--	--	1.390	3.192
10.0	0.06	8.907	13,704	8.830	13.428
	0.10	--	--	5.696	9.549
	0.20	3.086	5.761	3.143	6.012
	0.30	--	--	2.219	4.587
	0.60	1.236	2.953	1.224	2.888
	1.0	--	--	.790	2.054
	1.5	--	--	.558	1.567

Table XVIII

Calculated Data For "Danckwerts Plot,"
Superficial Gas Velocity = 1.5 ft/sec

V_L^0 (ft/sec)	$\bar{C}_{OH} \times 10^5$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$k_2 \times 10^{-6}$ $\left(\frac{\text{cm}^3}{\text{mole-sec}}\right)$	$Ra^2 \times 10^{14}$ $\left(\frac{\text{mole}}{\text{cm}^3\text{-sec}}\right)^2$	$k_2 \bar{C}_{OH}$ (sec ⁻¹)
0.06	3.433	8.551	0.332	293.6
	4.751	8.929	0.375	424.2
	7.423	10.781	0.462	792.6
0.10	4.089	8.558	0.345	349.9
	5.548	8.938	0.383	495.9
	8.346	10.794	0.461	900.9
0.20	4.617	8.564	0.360	395.4
	6.177	8.945	0.393	552.5
	9.064	10.804	0.457	979.3
0.30	4.806	8.566	0.367	411.7
	6.397	8.948	0.398	572.4
	9.312	10.807	0.453	1006.3
0.60	5.008	8.568	0.377	429.1
	6.628	8.951	0.406	593.3
	9.569	10.811	0.445	1034.5
1.0	5.095	8.569	0.381	436.6
	6.725	8.952	0.410	602.0
	9.675	10.813	0.436	1046.2
1.5	5.141	8.570	0.381	440.6
	6.776	8.952	0.412	606.6
	9.731	10.813	0.429	1052.2

Table XIX

Calculated Data For "Danckwerts Plot,"
Superficial Gas Velocity = 2.0 ft/sec

v_L^0 (ft/sec)	$\bar{C}_{OH} \times 10^5$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$k_2 \times 10^{-6}$ $\left(\frac{\text{cm}^3}{\text{mole-sec}}\right)$	$Ra^2 \times 10^{14}$ $\left(\frac{\text{mole}}{\text{cm}^3\text{-sec}}\right)^2$	$k_2 \bar{C}_{OH}$ (sec ⁻¹)
0.06	3.481	9.882	0.424	344.0
	10.325	11.271	0.663	1163.7
	13.237	11.546	0.702	1528.3
0.10	4.141	9.891	0.452	409.6
	11.371	11.287	0.672	1283.4
	14.386	11.563	0.712	1663.5
0.20	4.678	9.898	0.489	463.0
	12.194	11.299	0.684	1377.8
	15.284	11.577	0.723	1769.4
0.30	4.872	9.901	0.508	482.4
	12.482	11.303	0.689	1411.2
	15.596	11.581	0.729	1806.2
0.60	5.081	9.904	0.542	503.2
	12.782	11.307	0.696	1445.3
	15.920	11.586	0.734	1844.5
1.0	5.173	9.905	0.564	512.4
	12.908	11.309	0.696	1459.8
	16.056	11.588	0.738	1860.6
1.5	5.222	9.905	0.576	517.2
	12.974	11.310	0.694	1467.4
	16.126	11.589	0.740	1868.8

Table XX

Calculated Data For "Danckwerts Plot,"
Superficial Gas Velocity = 3.0 ft/sec

v_L^0 (ft/sec)	$\bar{C}_{OH} \times 10^5$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$k_2 \times 10^{-6}$ $\left(\frac{\text{cm}^3}{\text{mole-sec}}\right)$	$Ra^2 \times 10^{14}$ $\left(\frac{\text{mole}}{\text{cm}^3\text{-sec}}\right)^2$	$k_2 \bar{C}_{OH}$ (sec ⁻¹)
0.06	7.982	10.357	0.826	826.7
	9.890	10.816	0.893	1069.7
	14.113	11.559	1.036	1631.3
0.10	9.063	10.372	0.893	940.0
	11.097	10.833	0.962	1202.1
	15.477	11.580	1.107	1792.2
0.20	9.923	10.383	0.992	1030.3
	12.052	10.846	1.063	1307.2
	16.551	11.596	1.206	1919.3
0.30	10.228	10.387	1.055	1062.4
	12.387	10.851	1.128	1344.1
	16.926	11.601	1.270	1963.6
0.60	10.548	10.392	1.171	1096.1
	12.739	10.856	1.248	1382.9
	17.319	11.607	1.383	2010.2
1.0	10.685	10.393	1.259	1110.5
	12.888	10.858	1.343	1399.4
	17.484	11.610	1.476	2029.9
1.5	10.757	10.394	1.341	1118.1
	12.966	10.859	1.423	1408.0
	17.569	11.611	1.548	2039.9

Table XXI

Calculated Data For "Danckwerts Plot,"
 Superficial Gas Velocity = 4.0 ft/sec

V_L^0 (ft/sec)	$\bar{C}_{OH} \times 10^5$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$k_2 \times 10^{-6}$ $\left(\frac{\text{cm}^3}{\text{mole-sec}}\right)$	$Ra^2 \times 10^{14}$ $\left(\frac{\text{mole}}{\text{cm}^3\text{-sec}}\right)^2$	$k_2 \bar{C}_{OH}$ (sec ⁻¹)
0.06	6.003	9.321	0.901	559.5
	8.076	9.740	1.136	786.6
	12.309	9.997	1.364	1230.5
	14.692	10.663	1.558	1566.6
0.10	6.946	9.333	0.986	648.3
	9.187	9.754	1.228	896.1
	13.668	10.015	1.484	1368.9
	16.129	10.683	1.687	1723.1
0.20	7.712	9.342	1.111	720.5
	10.079	9.765	1.360	984.2
	14.747	10.029	1.662	1479.0
	17.266	10.699	1.863	1847.3
0.30	7.988	9.345	1.188	746.5
	10.398	9.769	1.440	1015.8
	15.128	10.034	1.777	1517.9
	17.665	10.705	1.980	1891.0
0.60	8.286	9.349	1.329	774.7
	10.737	9.774	1.590	1049.4
	15.529	10.039	1.988	1559.0
	18.083	10.711	2.193	1936.9
1.0	8.415	9.351	1.442	786.9
	10.883	9.775	1.706	1063.8
	15.699	10.041	2.161	1576.3
	18.261	10.713	2.372	1956.3

Table XXI (continued)

V_L^0 (ft/sec)	$\bar{C}_{\bar{O}H} \times 10^5$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$k_2 \times 10^{-6}$ $\left(\frac{\text{cm}^3}{\text{mole-sec}}\right)$	$Ra^2 \times 10^{14}$ $\left(\frac{\text{mole}}{\text{cm}^3\text{-sec}}\right)^2$	$k_2 \bar{C}_{\bar{O}H}$ (sec ⁻¹)
1.5	8.484	9.351	1.535	793.3
	10.960	9.776	1.801	1071.4
	15.788	10.042	2.307	1585.4
	18.353	10.714	2.515	1966.3

Table XXII

Calculated Data For "Danckwerts Plot,"
 Superficial Gas Velocity = 6.0 ft/sec

V_L^0 (ft/sec)	$\bar{C}_{OH} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$k_2 \times 10^{-6}$ $\left(\frac{\text{cm}^3}{\text{mole-sec}}\right)$	$Ra^2 \times 10^{14}$ $\left(\frac{\text{mole}}{\text{cm}^3\text{-sec}}\right)^2$	$k_2 \bar{C}_{OH}$ (sec ⁻¹)
0.06	5.671	9.911	0.949	562.1
	11.907	10.410	1.628	1239.5
	15.152	10.890	2.071	1650.1
0.10	6.611	9.923	1.111	656.0
	13.238	10.428	1.833	1380.5
	16.661	10.911	2.313	1817.9
0.20	7.391	9.933	1.376	734.1
	14.317	10.443	2.158	1495.1
	17.883	10.929	2.686	1954.4
0.30	7.679	9.937	1.560	763.1
	14.706	10.448	2.372	1536.5
	18.321	10.935	2.931	2003.4
0.60	7.993	9.941	1.932	794.6
	15.123	10.454	2.789	1581.0
	18.791	10.941	3.404	2056.0
1.0	8.133	9.943	2.262	808.7
	15.304	10.456	3.136	1600.2
	18.995	10.944	3.791	2078.8
1.5	8.209	9.944	2.563	816.3
	15.400	10.457	3.448	1610.4
	19.104	10.946	4.137	2091.1

Table XXIII

Calculated Data For "Danckwerts Plot,"
Superficial Gas Velocity = 10.0 ft/sec

v_L^0 (ft/sec)	$\bar{C}_{OH} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$k_2 \times 10^{-6}$ $\left(\frac{\text{cm}^3}{\text{mole-sec}}\right)$	$Ra^2 \times 10^{14}$ $\left(\frac{\text{mole}}{\text{cm}^3\text{-sec}}\right)^2$	$k_2 \bar{C}_{OH}$ (sec ⁻¹)
0.06	7.132	10.346	1.300	737.9
	12.319	11.532	1.729	1420.6
	21.514	12.153	2.822	2614.6
0.10	8.214	10.360	1.528	851.0
	13.813	11.555	2.042	1596.1
	23.321	12.181	3.305	2840.7
0.20	9.096	10.372	1.902	943.4
	15.019	11.573	2.554	1738.1
	24.758	12.204	4.084	3021.5
0.30	9.415	10.376	2.161	976.9
	15.451	11.579	2.907	1789.1
	25.266	12.212	4.614	3085.5
0.60	9.758	10.381	2.690	1013.0
	15.914	11.586	3.629	1843.8
	25.801	12.221	5.674	3153.1
1.0	9.908	10.383	3.158	1028.7
	16.114	11.589	4.268	1867.5
	26.028	12.224	6.589	3181.7
1.5	9.988	10.384	3.587	1037.2
	16.220	11.591	4.858	1880.1
	26.148	12.226	7.415	3196.9

Table XXIV

Calculated Data For "Danckwerts Plot,"
 Superficial Gas Velocity = 20.0 ft/sec

V_L^0 (ft/sec)	$C_{\bar{O}H} \times 10^6$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$k_2 \times 10^{-6}$ $\left(\frac{\text{cm}^3}{\text{mole-sec}}\right)$	$Ra^2 \times 10^{14}$ $\left(\frac{\text{mole}}{\text{cm}^3\text{-sec}}\right)^2$	$k_2 \bar{C}_{\bar{O}H}$ (sec ⁻¹)
0.06	6.350	10.766	1.560	683.6
	13.271	11.314	1.667	1501.5
	24.987	12.710	2.866	3175.8
0.10	7.841	10.787	1.664	845.8
	15.055	11.341	2.068	1707.4
	26.925	12.742	3.614	3430.8
0.20	8.938	10.802	1.804	965.5
	16.373	11.360	2.650	1860.0
	28.375	12.766	4.735	3622.4
0.30	9.297	10.807	1.880	1004.7
	16.807	11.367	3.010	1910.5
	28.860	12.774	5.448	3686.6
0.60	9.650	10.812	2.011	1043.4
	17.239	11.373	3.648	1960.6
	29.349	12.783	6.755	3751.7
1.0	9.789	10.814	2.100	1058.6
	17.411	11.376	4.137	1980.7
	29.547	12.786	7.806	3777.9
1.5	9.897	10.816	2.170	1070.5
	17.496	11.377	4.537	1990.5
	29.648	12.788	8.679	3791.4

Table XXV

Calculated Chemical Absorption Data and Results

V_G^0 (ft/sec)	V_L^0 (ft/sec)	Intercept $\times 10^{15}$ $\left(\frac{\text{mole}}{\text{cm}^3\text{-sec}}\right)^2$	Slope $\times 10^{18}$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)^2\left(\frac{1}{\text{sec}}\right)$	$\bar{C}_{\text{CO}_2}^* \times 10^7$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$\bar{D}_{\text{CO}_2} \times 10^5$ (cm ² -sec)	k_L $\left(\frac{\text{cm}}{\text{sec}}\right)$	a $\left(\frac{1}{\text{cm}}\right)$	$k_L a$ (sec ⁻¹)
1.5	0.06	2.612	2.552	4.151	1.961	.142	.869	.123
	0.10	2.760	2.067	3.976	1.961	.162	.817	.132
	0.20	2.988	1.627	3.731	1.961	.190	.772	.147
	0.30	3.125	1.409	3.611	1.961	.209	.742	.155
	0.60	3.357	1.074	3.356	1.961	.248	.697	.173
	1.0	3.509	0.836	3.156	1.961	.287	.654	.188
	1.5	3.583	0.701	2.987	1.961	.317	.633	.201
2.0	0.06	3.491	2.443	3.981	2.021	.170	.873	.148
	0.10	3.714	2.151	3.831	2.021	.187	.852	.159
	0.20	4.092	1.852	3.633	2.021	.211	.833	.176
	0.30	4.300	1.719	3.505	2.021	.225	.832	.187
	0.60	4.717	1.468	3.273	2.021	.255	.823	.210
	1.0	4.987	1.309	3.091	2.021	.278	.823	.229
	1.5	5.135	1.219	2.939	2.021	.292	.836	.244
3.0	0.06	6.127	2.599	4.473	2.021	.218	.802	.175
	0.10	6.592	2.502	4.341	2.021	.231	.811	.187
	0.20	7.471	2.395	4.162	2.021	.251	.827	.208
	0.30	8.057	2.370	4.056	2.021	.262	.844	.221
	0.60	9.244	2.292	3.873	2.021	.285	.870	.248
	1.0	10.080	2.320	3.732	2.021	.296	.908	.269
	1.5	11.022	2.202	3.619	2.021	.318	.912	.290
4.0	0.06	5.925	6.249	5.306	1.982	.137	1.058	.145
	0.10	6.158	6.302	5.179	1.982	.139	1.089	.151
	0.20	6.763	6.541	5.006	1.982	.143	1.148	.164
	0.30	7.111	6.847	4.903	1.982	.143	1.199	.171
	0.60	7.839	7.452	4.728	1.982	.144	1.297	.187
	1.0	8.357	8.059	4.596	1.982	.143	1.387	.198
	1.5	8.819	8.549	4.484	1.982	.143	1.465	.209
6.0	0.06	3.661	10.284	6.040	2.001	.084	1.187	.100
	0.10	4.281	10.307	5.917	2.001	.091	1.213	.110
	0.20	5.827	10.689	5.752	2.001	.104	1.271	.132
	0.30	7.102	10.998	5.659	2.001	.114	1.310	.149
	0.60	9.960	11.592	5.481	2.001	.131	1.389	.182
	1.0	12.771	11.938	5.354	2.001	.146	1.443	.211
	1.5	15.414	12.227	5.260	2.001	.159	1.486	.236
10.0	0.06	6.413	8.228	6.173	2.001	.126	1.030	.130
	0.10	6.955	9.056	6.096	2.001	.125	1.094	.137
	0.20	8.249	10.635	5.996	2.001	.126	1.206	.152
	0.30	9.306	11.775	5.940	2.001	.127	1.281	.163
	0.60	11.743	14.094	5.849	2.001	.130	1.423	.185
	1.0	14.122	16.088	5.803	2.001	.134	1.532	.205
	1.5	16.440	17.873	5.804	2.001	.137	1.615	.221
20.0	0.06	10.437	5.525	6.075	2.044	.196	.856	.168
	0.10	9.033	7.747	6.049	2.044	.154	1.018	.157
	0.20	6.680	11.143	6.033	2.044	.111	1.224	.136
	0.30	5.054	13.363	6.034	2.044	.088	1.340	.118
	0.60	1.987	17.493	6.062	2.044	.048	1.526	.073
	1.0	-0.696	20.905	6.131	2.044	--	1.650	--
	1.5	-3.064	23.795	6.255	2.044	--	1.725	--

Table XXVI

Calculated Physical Absorption Data and Results

V_G^0 (ft/sec)	V_L^0 (ft/sec)	$Ra \times 10^9$ $\left(\frac{\text{mole}}{\text{cm}^3 \cdot \text{sec}}\right)$	$C_{CO_2}^* \times 10^7$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$k_L^0 a$ (sec^{-1})
1.5	0.06	2.628	7.999	.0033
	0.10	3.662	7.922	.0046
	0.20	5.738	7.777	.0074
	0.30	7.458	7.657	.0097
	0.60	11.660	7.370	.0158
	1.0	16.210	7.070	.0229
	1.5	21.030	6.758	.0311
2.0	0.06	2.531	8.216	.0031
	0.10	3.642	8.158	.0045
	0.20	5.930	8.042	.0074
	0.30	7.865	7.950	.0099
	0.60	12.690	7.728	.0164
	1.0	18.010	7.495	.0240
	1.5	23.700	7.251	.0327
3.0	0.06	2.306	8.231	.0028
	0.10	3.430	8.156	.0042
	0.20	5.871	8.081	.0073
	0.30	8.031	8.019	.0100
	0.60	13.710	7.864	.0174
	1.0	20.310	7.687	.0264
	1.5	27.730	7.490	.0370
4.0	0.06	1.835	8.478	.0022
	0.10	3.558	8.433	.0042
	0.20	6.993	8.357	.0084
	0.30	9.785	8.304	.0118
	0.60	16.400	8.189	.0200
	1.0	23.240	8.085	.0287
	1.5	30.260	7.987	.0379
6.0	0.06	2.883	8.372	.0034
	0.10	4.288	8.349	.0051
	0.20	7.306	8.302	.0088
	0.30	9.943	8.269	.0120
	0.60	16.780	8.174	.0205
	1.0	24.590	8.085	.0304
	1.5	33.270	8.000	.0416

Table XXVI (continued)

V_G^0 (ft/sec)	V_L^0 (ft/sec)	$Ra \times 10^9$ $\left(\frac{\text{mole}}{\text{cm}^3 \cdot \text{sec}}\right)$	$C_{CO_2}^* \times 10^7$ $\left(\frac{\text{mole}}{\text{cm}^3}\right)$	$k_L^0 a$ (sec ⁻¹)
10.0	0.06	3.396	7.830	.0043
	0.10	4.742	7.828	.0061
	0.20	7.062	7.818	.0090
	0.30	8.743	7.811	.0112
	0.60	12.290	7.802	.0158
	1.0	15.560	7.820	.0199
	1.5	18.630	7.878	.0236

VITA

Gary Wayne Holden was born in Florence, Alabama, on June 6, 1952, the son of Mr. Cecil and Mrs. Edith Nell Holden. He attended Elgin Elementary School in Elgin, Alabama until 1964. He graduated from Lauderdale County High School in Rogersville, Alabama in June 1970. The following fall he entered The University of Alabama at Tuscaloosa and in May 1974 he received a Bachelor of Science degree with a major in Chemistry. From September 1974 to June 1976, he attended the Graduate School of The University of Tennessee at Knoxville in Biochemistry where he held a teaching assistantship. In January 1977 he revised his program of study to Chemical Engineering. He received the Master of Science in Chemical Engineering in August 1980.