A STUDY OF THE RATE OF MASS TRANSFER ACROSS A LIQUID-LIQUID INTERFACE AS A FUNCTION OF CONCENTRATION DIFFERENCE

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by

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SUMMARY

At the present time knowledge is limited about the mechanism of transfer of a solute between two immiscible phases in a liquid-liquid extraction operation. The objective of this investigation was to throw light on the mechanism by which this mass transfer occurs. The rate of transfer of acetic acid across an interface in a methyl-isobutyl ketone-acetic acid-water system was studied.

The interface was formed in a rectangular glass chamber divided into two compartments by a horizontal stainless steel plate with a 0.250 inch slot in the center. Methyl-isobutyl ketone of known acetic acid concentration was passed through the upper compartment and water with zero acetic acid concentration was passed through the lower compartment, both at equal, constant volumetric flow rates. Mass transfer occurred between the two phases across the interface formed in the plate slot. The resulting phase concentrations were obtained by titration of the acetic acid against standard sodium hydroxide.

A plot of the experimental data showed that the rate of mass transfer as a function of the acetic acid concentration difference was a linear function up to approximately 0.080 lb. mole per ft.cu., indicating that in this region diffusion was by molecular movement. The remaining portion of the curve

showed an exponential increase, indicating that here the diffusion was stimulated by mechanical mixing of the phases at the interface.

No data were available from the literature to verify the conclusions drawn, but the experimental data taken showed good precision.

Several recommendations were indicated for improvement of the equipment set-up if more work is attempted in this field.

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INTRODUCTION

In liquid-liquid extraction operations, correlation of data is frequently achieved by the use of the capacity coefficient. This coefficient is the product of the diffusion rate and the area of diffusion. In equipment, such as a liquid-liquid spray tower, the transfer area term, ie., the sum of the areas of all the drops, is almost impossible to obtain. Also, there is some question as to the method by which mass is transferred between the phases. All of these problems make a separate analysis of the two terms in the capacity coefficient very difficult for most mass transfer operations. However, if the transfer area is held constant at some known value, the rate of diffusion can be studied independently. The rate of diffusion across the interface should depend on the method of diffusion. If it is true that at low concentrations, the mechanism for mass transfer is that of pure molecular diffusion; and if at higher concentration, the mass transfer is due to some other mechanism, these differences should appear in the data for the two regions. The present work is a study of the mechanisms of mass transfer under very special conditions.

No previous work was found on the rate of mass transfer across a liquid-liquid interface as a function of the phase concentration difference under the conditions used in this work.

Smith and Wineburger[4], however, in studying the interfacial tensions in a benzene-acetic acid-water system, and also, Farmer[3], in studying interfacial tension in a methyl isobutyl ketone-acetic acid-water system, found evidence of the type of mass transfer between the phases that is studied here. Smith and Wineburger studied interfacial tension by analysis of the two-dimensional interface, and observed minute rippling of the interface due to diffusion of the acetic acid between the phases. Both investigations present photographs which demonstrate the convection currents in the respective phases set up by concentration gradients within the phases.

It is believed that the diffusion of solute between two liquid phases of different concentrations is by molecular movement when the concentration differences are relatively small, but that as the concentration difference increases beyond some critical point, the amount of transfer is excessively large for this phenomenon. The scope of this work, then, is to study the rate of mass transfer as a function of the concentration difference between the phases, and determine if the above hypothesis is reasonable.

THEORY

The mass transfer cell, which constitutes the experimental set-up of interest, consists of chamber separated into two compartments by a stainless steel plate. The plate contains a slot at which the two immiscible liquid phases, one flowing in the top compartment and the other in the bottom compartment, form an interface. The two phases flow co-currently through the cell. A concentration difference exists between the two phases causing mass to be transferred across the interface. The stainless steel plates are assumed to allow no mass transfer.

Since the transfer of mass occurs only across the interface, a model of the transfer cell can be deduced having the lateral and vertical axis of the experimental cell as shown in Figure 1. Phase one represents the high concentration stream, and phase two represents the low concentration stream. Each of the streams has its own set of coordinates. Diffusion in each of the phases is governed by its own differential equation. Since the flow of both streams is considered to be laminar, thin films will exist at the interface. If the resistance of the interface is considered to be negligible, the relative concentrations of the films will be governed by the equation of the equilibrium concentration isotherm between the two phases. Thus, in order to obtain a mathematical solution for the system, three equations must be solved simultaneously.

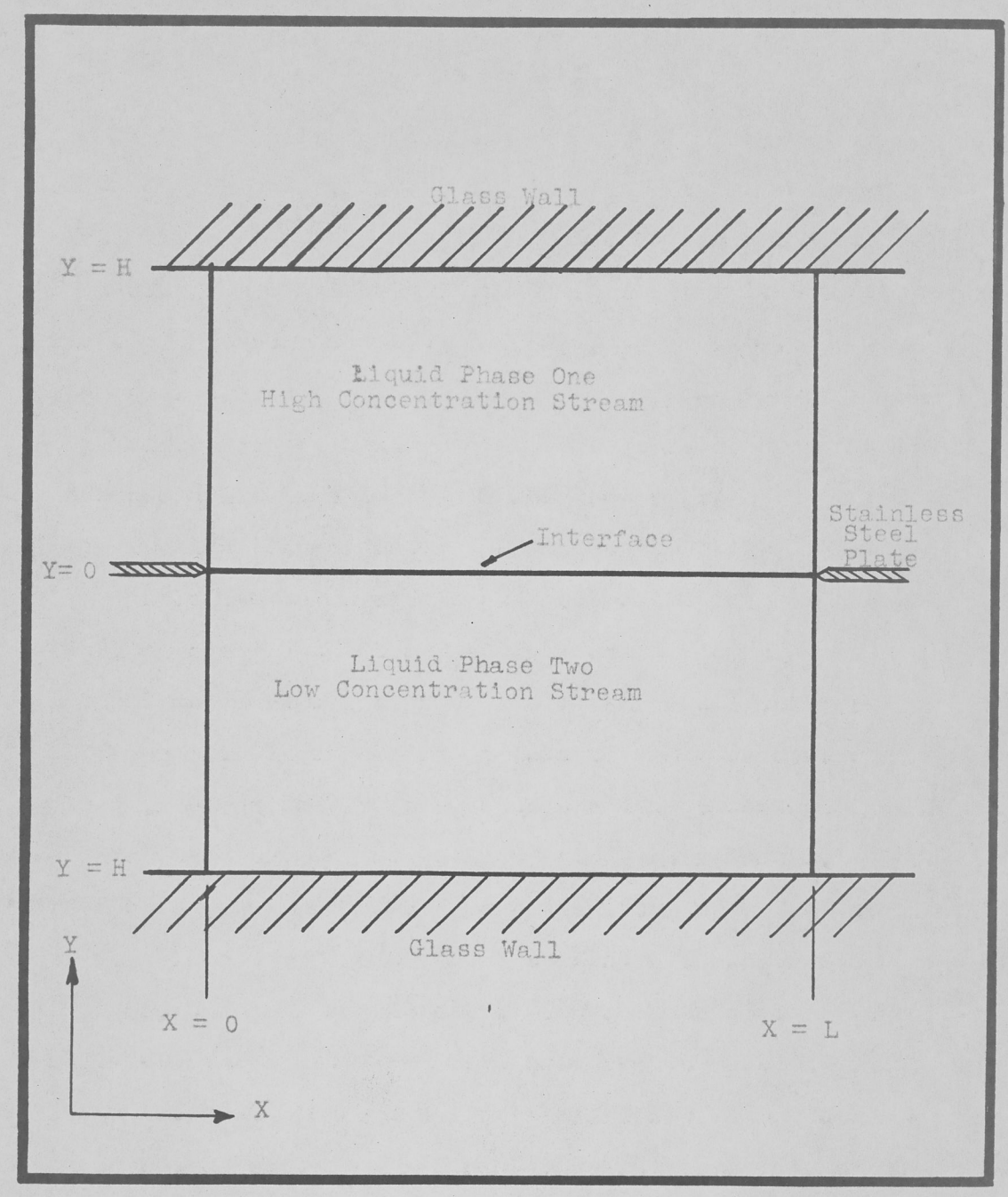

Figure 1.

Diagram of Experimental Transfer Cell

The following assumptions will be made about the system.

a. The laws developed for diffusion in gases will hold approximately for diffusion in liquids.

b. Steady state exists at all points in the system; thus, Fick's first law will apply at all points as a result of assumption a.

c. The flow of both phases is constant and never exceeds the critical value of laminar flow through the chamber.

d. The system is isothermal.

e. Mass transfer occurs by diffusion only.

f. Only vertical diffusion exists.

g. The change in concentration of the two streams is amall compared to their initial concentrations, thus, the diffusion coefficients can be assumed to be independent of the concentration change.

h. No diffusion occurs through the stainless steel plates.

An alternate way of conceiving the diffusion cases would be to consider an element of fluid in one of phases, rather than a fixed point in the system. Since, the system is in steady state, the concentration at a fixed point in the system is not a function of time, and Fick's first law will apply. However, if an element in a flowing phase is considered, the concentration of that element is a function of the time of contact of the two fluids at the interface. This concept can easily be seen by considering that as the element approaches the vertical plane which passes through the edge of the interface, the concentration of the element is the initial concentration of the phase; but as the element moves on after the phase

has been in contact for time, t, its concentration has changed by some value ΔC. Thus Fick's second law will apply.

The equations governing the phases are

THE EQUILIBRIUM ISOTHERM EQUATION (1)

$$\frac{\partial C_1}{\partial t} = D_1 \frac{\partial^2 C_1}{\partial^2 Y} \tag{2}$$

and

$$\frac{\partial C_2}{\partial t} = D_2 \frac{\partial^2 C_2}{\partial^2 Y} \tag{3}$$

where

C_1 = Concentration of the diffusion component in the liquid phase of highest concentration.

C_2 = Concentration of the diffusion component in the liquid phase of lowest concentration.

t = Time of contact.

D = Diffusion coefficient of the diffusing component in the respective phases.

X = Length of the interface.

Y = Height of the liquid phases.

An exact mathematical solution for the system at hand involves the solution of equations 1, 2, and 3 simultaneously with the appropriate boundary conditions. Since the range of concentration is small, one possibility for approximating the equilibrium isotherm would be to use the tangent to the curve at the region of interest. The equation of such a line would

be of the form

$$C_{2i} = aC_{1i} + b \qquad (4)$$

where

a = The slope of the tangent line.

b = The intercept of the tangent line at the vertical axis.

Subscript i refers to the interface concentration of the respective phases.

This concept is shown in Figure 2. The linear properties of such an equation seems to offer the greatest possibilities for an analytical solution of the system. Here, however, another difficulty arises. It will be noted that the concentrations, C_{1_i} and C_{2_i} are not constant, but are a function of the rate of diffusion in the phases. They are, therefore, a function of the time of contact between the phases. Because of this, the solution of equations 1, 2, and 3 becomes very involved and difficult. A solution is possible by the use of Laplace transforms; however, it will not be attempted in this work. A Solution to a similar system is given by Carlson,(2) but is not entirely applicable here. Carlson analyzed a system where water vapor diffused across a porpus boundary between air streams of different vapor concentrations. In his analysis, he assumes that the concentration in a vertical plane does not change as a function of the height above the boundary. This assumption is not valid in liquid phases.

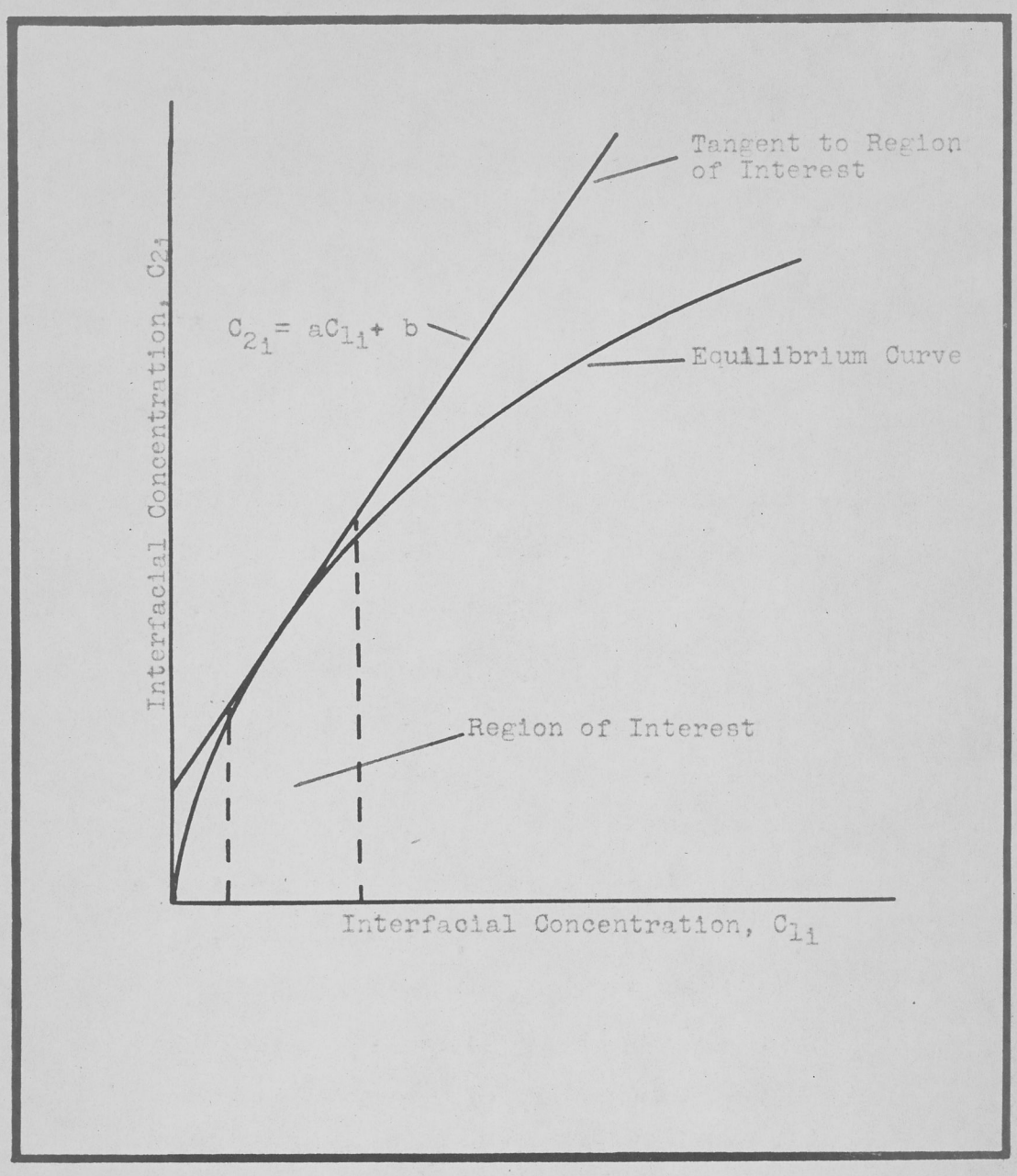

Figure 2.

Concentration Isotherm at a Particular Temparature

A solution of the system under study, where the mass transfer is by molecular diffusion, should yield an equation for the change in concentration of phase two which is a linear function of the differences in concentration between the phases. Thus, a plot of experimental data on ΔC_2 as a function of $C_1 - C_2$ should give a straight line if the mass transfer is by molecular diffusion and a non-linear line if molecular diffusion does not hold.

DESCRIPTION OF EQUIPMENT AND MATERIAL

The equipment used in this work consisted primarily of a glass chamber, liquid reservoirs, and a liquid metering system. A diagram of the equipment set-up is shown in Figure 3, while actual photographs of the equipment are shown in Figures 4 and 5. The glass chamber was originally constructed by Smith and Winebarger for a thesis, designed to study interfacial tension by a two-dimensional interface method, but it was easily adapted for use in studying mass transfer. It was necessary, however, for the chamber to be rebuilt because of aging of the cement. Most of the original dimensions and design were retained. The chamber was constructed of one-half inch glass plate. The glass was cut to the desired dimensions and then cemented into a rectangular box with C-14 Cycleweld type cement which was manufactured by the Chrysler corporation. The cement had an operating temperature not to exceed 145°F. Two compartments were formed by cementing two 22 gage stainless steel plates across the center of the chamber, in such a manner that a 0.250 inch slot was left between them, extending the full width of the chamber. The edges of the slot were machined to a knife edge to reduce the turbulence produced by the plates. A detail of the diffusion chamber is shown in the Appendices.

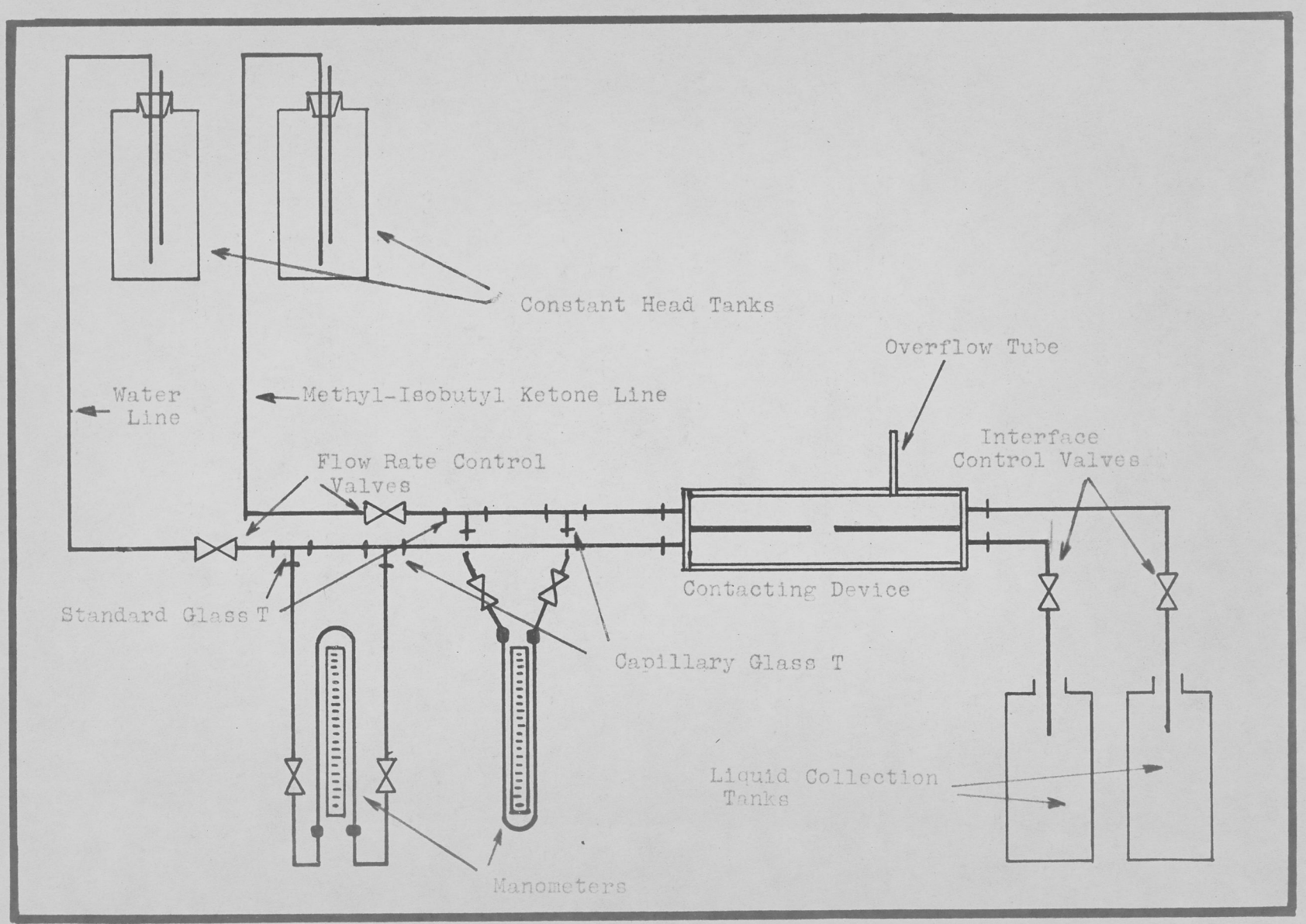

Figure 3.

Diagram of Experimental Equipment

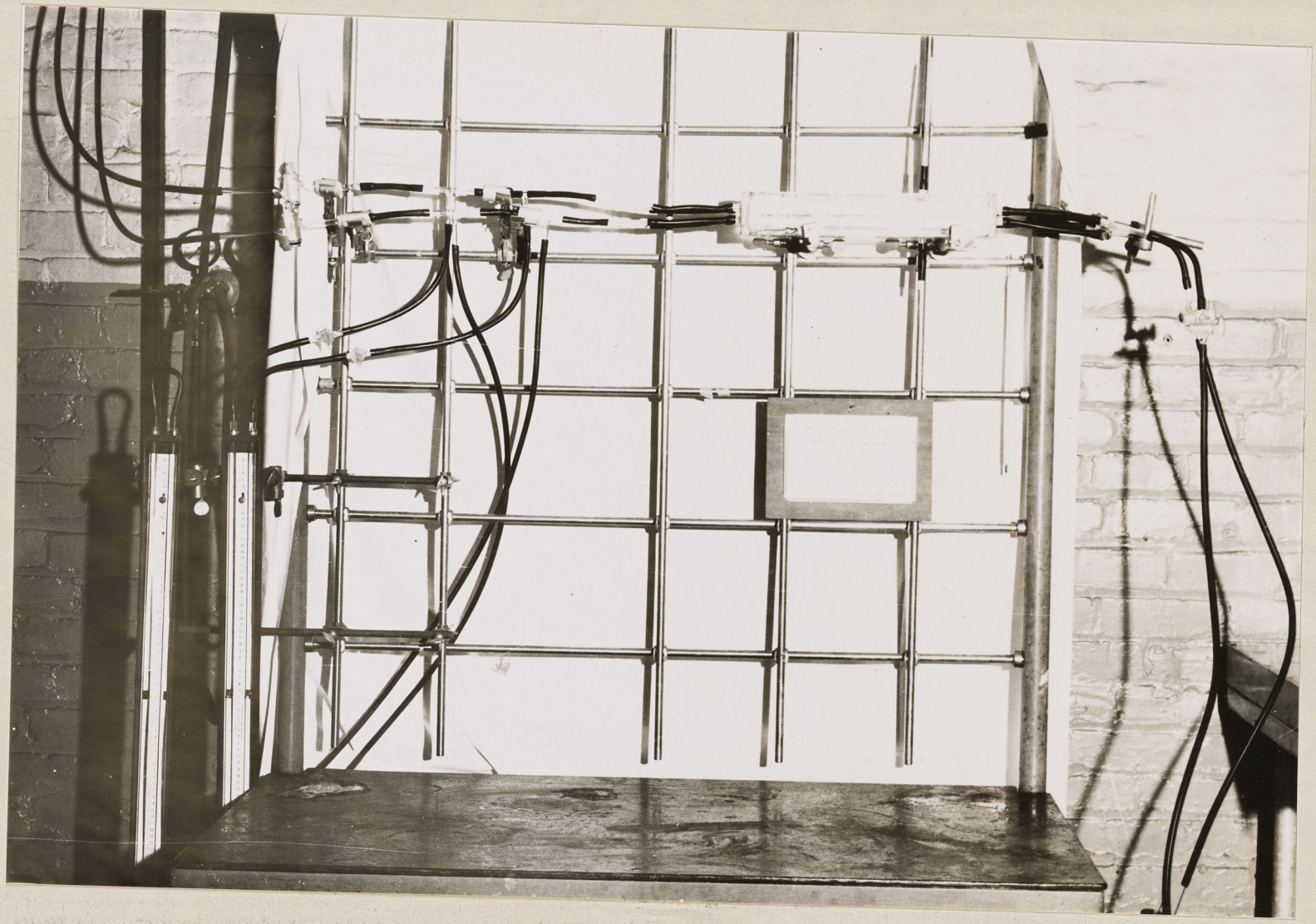

Figure 4

Photograph of The Equipment Used in Determining The Rate of Mass Transfer

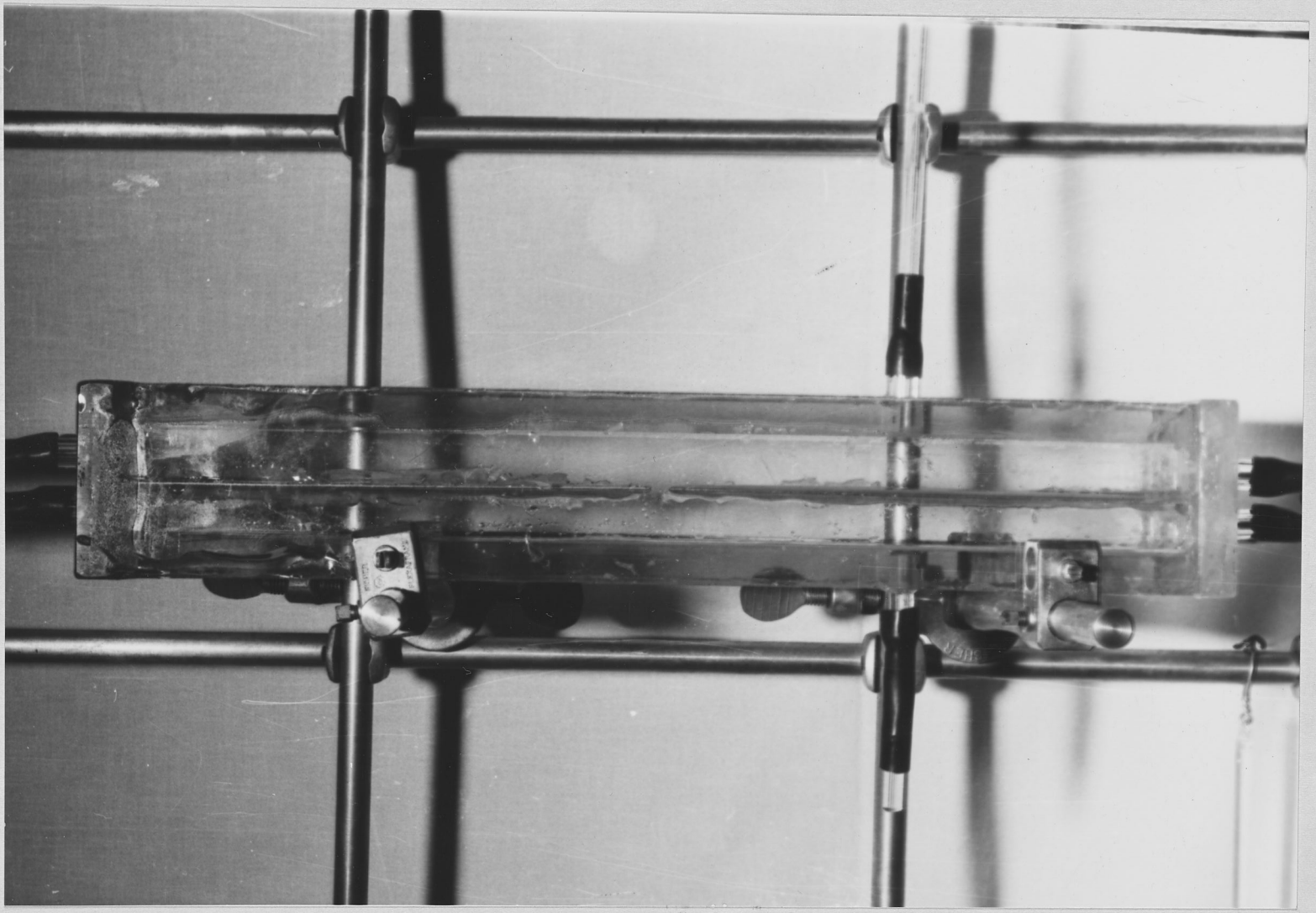

Figure 5

Photograph of The Glass Diffusion Chamber

Five-gallon jugs, thoroughly cleaned with a sulfuric acid-sodium dicromate solution, were used for the liquid reservoirs. Four jugs were used. Two were converted to constant head tanks by inserting a glass tube, open to the atmosphere, through the sealing stopper to approximately one inch above the outlet tube. These two jugs were used as the head tanks and the other two as the collecting tanks. This arrangement is shown in Figure 3. Polyethylene tubing was used for all connecting lines. In preliminary test the polyethylene was found to be inert to the Methyl-Isobutyl Ketone and Acetic acid. The flow of liquids was produced by a gravity head of approximately 4.5 feet and controlled by stopcocks placed before the chamber. Stopcocks were also placed after the chamber to be used in controlling the relative pressures within the compartments.

Manometers were used to meter the flows through the system. They were placed before the chamber; and, to prevent contamination of the system, water and Methyl-Isobutyl Ketone were used as the manometer fluids. A pressure differential was produced by taking the liquid through a non-constricted glass T and through a capillary tube glass T, which were placed in both lines before the compartments. Because the specific gravity of the Methyl-Isobutyl Ketone was less than that of water an inverted manometer had to be used for the water line. The manometers used were 80 cm. in height, graduated to one millimeter.

The photographs of the equipment and of the interface were taken with a 35-mm Exakta VX reflex camera, using a 100mm f/2.8 Meyer Trioplar lens. Kodak Panatomic X film was used. The necessary lighting was provided by a size 25 Kodak flash attachment. An enlarger was used to produce the photographs presented in this report.

The principal materials used in this work, consisted of laboratory distilled water, drum grade Methyl-Isobutyl Ketone, P. C. reagent grade glacial acetic acid, sodium hydroxide, and phenophylene. The Methyl-Isobutyl Ketone was obtained from Carbide and Carbide Chemical Company.

A sulfuric acid-sodium dicromate solution was used for cleaning the glass ware. A standard stopcock was used for timing the length of runs.

PROCEDURE

Before the actual experimental work was begun, several preliminary tests were conducted, using the experimental phases to determine the types of tubing and stopcock grease to be used. The tests consisted of placing various samples of tubing and stopcock grease in flasks containing methyl-isobutyl ketone, water and acetic acid. The samples were then allowed to stand for a week. These tests showed that polyethylene tubing was practically inert to the system and could be used in the experimental work. A successful type of stopcock grease was not found although several types were tried. A High Vacuum Silicone type was used, however, it dissolved upon standing in the ketone.

Before making runs with actual transfer, several test runs were conducted, using water, methyl-isobutyl ketone and no acetic acid. The procedure developed was as follows. Before each run, the transfer chamber was cleaned and rinsed with distilled water; then placed back into the line. Second, with all other lines to the chamber closed, the entrance water line was opened, allowing water to flow into the bottom compartment. The stopcock on the entrance water line was then adjusted until the desired flow rate, according to the manometer pressure differential, was obtained. The calibration curves for both the water manometer and the ketone manometer are given

in the Appendices. As the water level approached the separation plate, all of the air was purged from the water side by tilting the chamber so that the air bubbles were forced to the plate slot. When the water had completely filled the lower compartment, the outer water line stopcock was opened and adjusted so that the flow rate of water in was equal to the flow rate out, maintaining the water height at the slot level. The methyl-isobutyl ketone entrance line was opened next, and the desired flow rate adjusted by manipulation of the line stopcock as indicated by the ketone manometer pressure differential. The upper compartment was allowed to fill with the ketone. As the liquid level approached the compartment top, the air had to be purged from the water compartment. When the liquid began to rise in the overflow tube, the exit ketone line was opened and adjusted to maintain steady flow of the stream. The above procedure allowed the system to be set up while the liquids were flowing at the desired flow rates. The shape of the interface at the plate slot was adjusted to a horizontal plane by manipulation of the outlet water line stopcock, ie., increasing or decreasing the pressure in the lower compartment. Occasionally, it was also necessary to adjust the flow of the ketone phase in order to maintain equal pressures between the compartments.

For the actual experimental runs, the procedure outlined above was followed. Approximately five gallons of methyl-isobutyl ketone was placed in the ketone head tank and

approximately five gallons of water in the water head tank. A concentration difference was produced between the two liquids by dissolving acetic acid in the methyl-isobutyl ketone tank. The amount of acetic acid for the desired acid concentration was added to the tank; and after equilibrium had been reached, the actual concentration was determined by titration of the acid against a standard sodium hydroxide solution. It was found that approximately thirty minutes were necessary for both of the compartments to fill and for steady flow to be reached. Twenty minutes were then allowed for the system to reach steady state; a sample was taken at this time and one every ten minutes for twenty minutes. The concentration of acetic acid in the water due to the diffusion across the interface was obtained by titration of the samples against a standard sodium hydroxide solution.

Thus, the experimental procedure can be outlined in general as: first, obtaining steady flow at equal volumetric flow rates through both compartments, second, allowing time for steady state conditions to be reached, third, taking samples of the inlet methyl-isobutyl ketone stream and the outlet water stream, and fourth, titration of the various samples against standard sodium hydroxide.

RESULTS

The results obtained in the experimental work on mass transfer across a liquid-liquid interface in a water-methyl-isobutyl ketone system are presented in Table I. The phase concentration difference denotes the initial concentration of the ketone solution since the initial concentration of the water phase was zero. The change in concentration denotes the amount of acetic acid which transferred across the interface per cubic foot of water passed through the chamber. The volumetric flow rates of the fluids in both compartments was held approximately constant at 0.00282 cubic feet per minute;; therefore, the velocity of the fluid through each compartment was o.197 feet per minute, giving a time of contact at the interface of the two flowing fluids of 0.1057 minutes. The values of the mass transfer rate are given in colume 4 as mass transferred per unit area of transfer per unit of transfer time.

The resulting water phase concentrations as given in Table I are also plotted in Figure 6 as a function of the concentration difference between the phases. The values of mass transfer rates are plotted in Figure 7 as a function of the concentration differences between the phases.

TABLE I

TABULATION OF EXPERIMENTAL RESULTS

Run	Phase Concentration Difference lb-mole per cu.ft.	Change in Concentration of Water Phase $\times 10^2$ lb-mole per cu.ft.	Rate of Mass Transfer $\times 10^5$ lb-mole/sq.ft.-min.
1	0.04370	0.05664	7.680
2	0.05709	0.04189	5.680
3	0.05709	0.02017	2.735
4	0.06473	0.02903	3.936
5	0.08015	0.06361	8.625
6	0.09476	0.07260	9.844
7	0.00197	undetectable	
8	0.00434	0.002102	0.2850
9	0.00827	0.004778	0.6479
10	0.01525	0.006224	0.8439
11	0.02420	0.009770	1.325
12	0.04287	0.01661	2.252
13	0.07366	0.01622	2.199
14	0.07678	0.02790	3.783
15	0.08371	0.03094	4.195
16	0.09164	0.03883	5.265
17	0.09164	0.08190	11.105
18	0.10810	0.05423	7.354
19	0.11482	0.07329	9.938
20	0.12720	0.1626	22.049

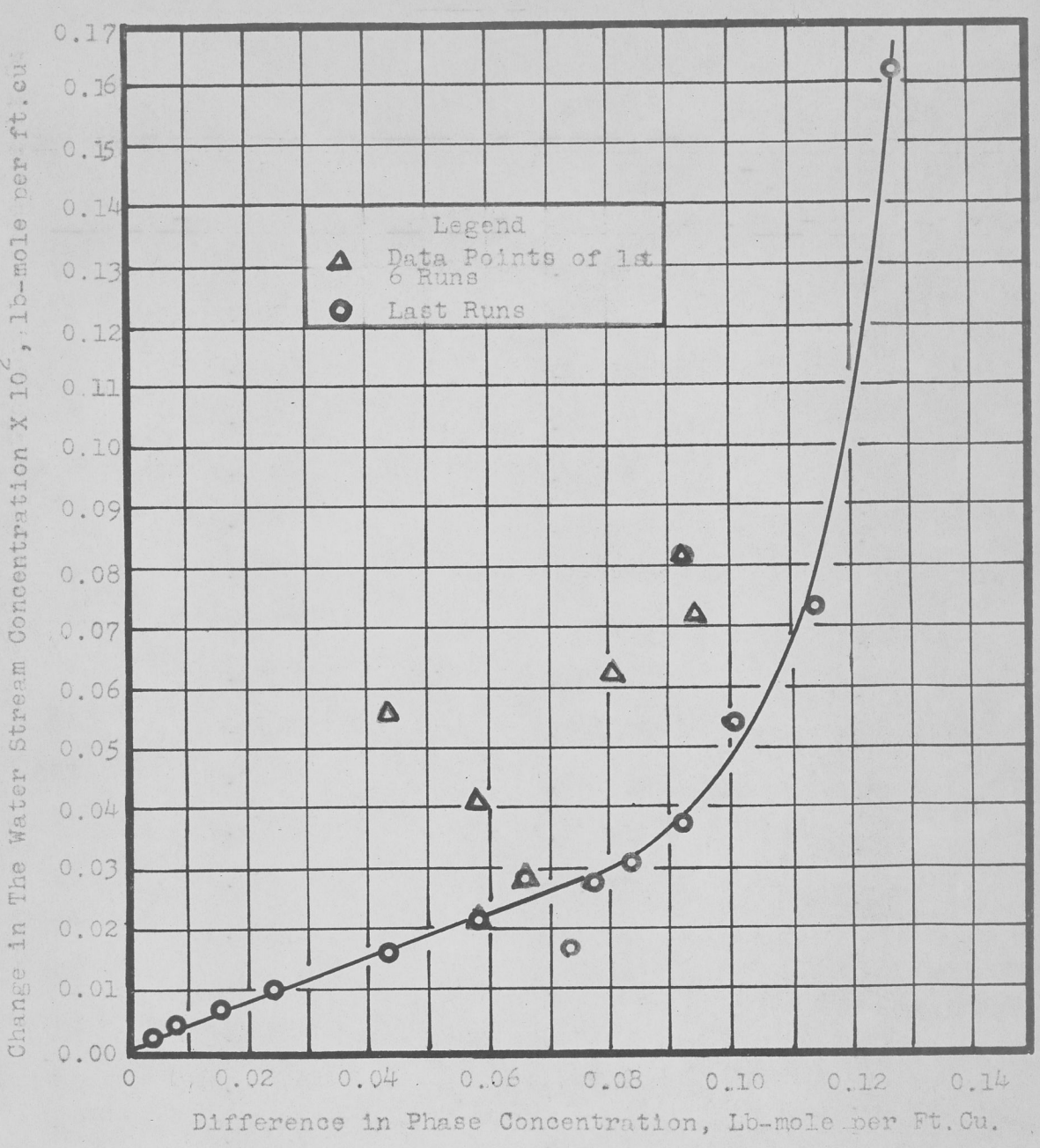

Figure 6

The Change in Concentration of The Water Stream as a Function of The Difference in Phase Concentration.

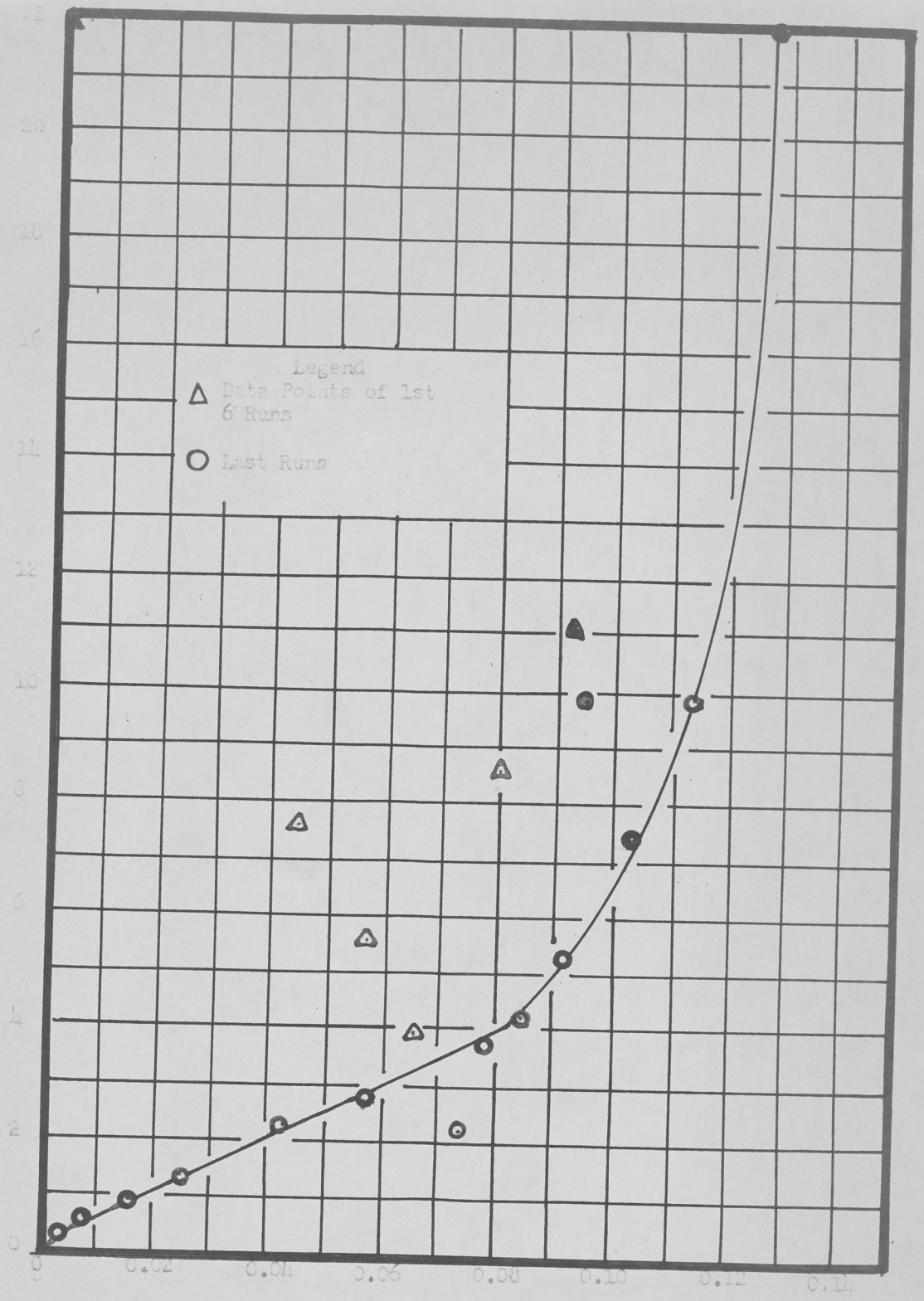

Figure 7

Reynolds Number through the Compartment as a Function of the Flow rate.

DISCUSSION OF RESULTS

The data presented in Table I and plotted in Figure 6 show the manner in which mass transfer varies with the phase concentration difference. As would be expected from a study of the concentration gradients, the amount of mass transferred was directly proportional to the bulk stream concentration difference. The mechanism of transfer, however, was indicated only by the form of the curve in Figure 6.

The portion of the curve at a difference in phase concentration of 0.08 lb.moles per ft.cu. or less was linear, indicating that at such low concentration differences the mechanism of mass transfer across the interface was by molecular diffusion. Thus, in this region as the number of molecules on one side of the interface increased, the rate at which molecules crossed to the more dilute solution increased proportionately.

The limiting concentration difference for molecular diffusion occurred where the linear characteristics break down and the amount of mass transfer increased at an apparent exponential rate. From observation of the differences that exist between the linear region and the exponential region, it is obvious that the mass transfer mechanism has changed drastically. In the photographs of the interface, showing the mass transfer, Figure 8, turbulence can be observed at the interface and in the water stream below the interface. In the experimental work this turbulence was first noticed, to any great extent, at a



Figure 8

Photograph of The Interface Showing Diffusion at A Phase Concentration Difference of 0.091 Lb-mole per Ft. Cu.

phase concentration difference of approximately 0.08 lb.moles per ft.cu. or at the point where the linear characteristics of the curve of Figure 6 changed. At higher concentration differences, the turbulence and eddy currents increased to an even greater extent. There are several phenomena which could have caused the turbulence observed. First, as the amount of acetic acid crossing the interface became in excess of the amount that could be absorbed by the bulk water stream by molecular diffusion, actual mechanical mixing occurred near the interface between the two phases. The heats of mixing released by this action created a temperature gradient in the liquid films, causing eddy currents. Smith and Wineburger[4] also reported that they observed minute rippling of the interface caused by diffusion. A second phenomenon observed was that as large amounts of acetic acid transferred, convection of the more concentrated liquid occurred. The convection currents were set up by a density difference between the liquid near the interface and the bulk stream. The "ever shifting phase boundary" reported by Smith and Wineburger was probably this same situation. It also appeared that the very mass of the acetic acid when diffusing in large amounts had the effect of causing minute disturbances on the interface surface.

There was another phenomenon which helped to produce the interfacial turbulence. In the experimental work at high concentration differences the interface appeared to twitch back and

forth, indicating that some kind of forces were at work there. Interfacial tension is a function of the liquid concentration. Considering this fact, it is easy to formulate the mechanism which caused the twitching. Diffusion across the interface was not uniform over the entire diffusion area. Thus, concentration gradients actually existed laterally along the interface. If the interface is considered to be composed of tiny cells, then each of these cells would have a concentration that was different with relation to the other cells. Therefore, each cell would also have an interfacial tension which was different from the other cells. The cells with higher interfacial tension would contract and the cells with lower concentration would stretch yielding to the higher tension cells. Since diffusion is constantly occurring, the respective concentration of the cells are constantly changing. Therefore, the cells are continually contracting and stretching, producing the twitching effect observed. This phenomenon is known as the Marangoni Effect and has been studied to some extent by Sternling and Scriven[5]. Sternling and Scriven give a mathematical analysis of a simplified model of the cells mentioned above.

One of the most important factors to be controlled during the experimental work was the interfacial geometry. This fact is evident since the rate of mass transfer is directly proportional to the transfer area. Because the continuity of the runs depended on this area being constant, it is believed that

variations in it were the greatest source of error in the experimental work. An increase in the pressure of one phase above that of the other phase could cause a bulge in the interface of as much as 0.16 inches. The area of the bulged interface could then have an area 20 per cent larger than the level interface area. Figure 9 is a photograph of the interface, showing such a bulge. The relative concentrations of the phases are the same as those in Figure 8. The increase in mass transfer can easily be seen by comparing the diffusion lines appearing in the two figures. With the types of valves used in the experimental work, it was very difficult to maintain equal pressures between the two phases over a period of time. Although great emphasis was placed on this operation during the entire experiment, the first six runs were performed before the exact importance of technique was discovered. These runs are indicated in Figure 6 as the data points outlined in triangles. Since all of these points appear to be high, it was assumed that the error was due to the interface geometry, and they were, therefore disregarded in drawing the experimental curve. Further, it was found that differences existed in the sample concentrations obtained for a particular run. In view of the above discussion, when such differences did appear, the lowest value was taken. Since plenty of time was allowed for steady state to be reached, the observed sample differences could not have been due to non-steady state conditions. The time for steady state to be reached was checked by placing an indicator, methyl red,



Figure 9

Photograph Showing The Mass Transfer With The Interface Bulging at a Phase Concentration Difference of 0.091 Lb-mole per Ft.Cu.

in the entrance water and observing the color change in the stream until steady state appeared to have been reached. The twenty minutes allowed in the experimental work seemed to be ample.

Since no information of the nature presented in this report was found in literature, it is hard to estimate the accuracy of the results. The precision, not considering the points discussed above, appears to be good. Thus, since the interfacial area for the later runs was maintained reasonably constant, the results presented are considered to contain little error.

CONCLUSIONS AND RECOMMENDATIONS

It can be concluded from the results obtained in this work that there is a definite difference in the mechanism of mass transfer between liquid phases of low concentration difference and of mass transfer between liquid phases of high concentration difference. The mechanism at low phase concentration differences appeared to be by molecular movement across the interface, while at higher concentration differences transfer rates appeared to increase due to some form of mechanical mixing at the interface. Since the experimental work in this report was performed under somewhat ideal conditions, in which the area for diffusion was known and held constant, the results offer little direct application to liquid-liquid extraction operations of the type already discussed. It does, however, offer much insight into the mechanism of mass transfer. This information will, perhaps, after further study in the field, lead to methods of predicting accurately the rate of mass transfer that will be encountered in commercial type equipment.

It is recommended that if further study is performed certain changes be made in the equipment set-up. First, it was doubtful that laminar flow actually existed in the bulk streams at the interface. Although the rate of flow through the compartments did not exceed the critical value for laminar flow, turbulence was created by the force of the

liquid entering the compartments. The length of the apparatus should therefore be increased so that this force could be absorbed. Second, the entire diffusion chamber should be constructed of stainless steel because the cement used in the glass chamber, although supposedly inert, did eventually react with the methyl-isobutyl ketone. The action at the interface could still be observed by installing a sight glass in the chamber wall. Much better control of the interfacial geometry could be obtained by replacing the stopcocks with needle valves made of stainless steel.

It is believed that the results obtained in this work are sufficiently promising to warrant further investigation in which more of the variables controlling the rate of mass transfer, such as flow rates, fluid viscosities, fluid densities, and interfacial tensions could be studied. These studies if continued could lead to considerable progress in understanding the mechanism of mass transfer between immiscible liquid phases

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APPENDICES

APPENDIX I

SAMPLE CALCULATIONS

The following calculations were made from the experimental data obtained. In the cases where calculations were made for each run, the work will be presented for only for the thirteenth run.

A. Standardization of Sodium Hydroxide.

Method: By Comparison of the volume necessary to neutralize 25 ml. samples of an acetic acid solution between the unknown and a known sodium hydroxide.

Term:

1. Normality of known solution = 0.5502
2. Volume of known solution used = 35.22 ml.
3. Volume of unknown solution used = 27.29 ml.

$$\text{Unknown concentration} = \frac{(\text{Term 1})(\text{Term 2})}{(\text{Term 3})} = 0.7101 \text{ N.}$$

B. Calculation of Reynold's Number For a Flow Rate of 80 cc. per min.

Method: $$N_{Re} = 4 R_H Q / u \qquad (1)$$

where

R_H = area perpendicular to the flow divided by the periphrey of flow.

Q = mass flow rate

u = absolute viscosity

Terms:

1. Width of flow channel = 2.875 in.
2. Height of flow channel = 0.719 in.
3. Cross-sectional area = (Term 1)(Term 2) = 2.066 sq,in.
4. Periphrey of flow = 2 X (Term 1 + Term 2) = 7.188 in.
5. Absolute viscosity of water* = 0.00836 gm/cm-sec.
6. One minute = 60 sec.
7. One inch = 2.54 cm.
8. Volumetric Flow rate = 80 cc.per min.

$$\text{Reynold's Number} = \frac{4 \text{ X } (\text{Term } 3)(\text{Term } 8)}{(\text{Term } 4)(\text{Term } 5)(\text{Term } 3)(\text{Term } 6)(\text{Term } 7)}$$

$$= 34.9$$

C. Calculation of the change in the water phase concentration due to diffusion.

Method: Titration of water sample against standard sodium hydroxide.

Terms:

1. Normality of standard sodium hydroxide = 0.003550 N
2. Volume of standard required to neutralize the sample = 19.83 ml
3. Correction due to indicator = 1.53 ml
4. Corrected volume = (Term 2 - Term 3) = 18.30 ml.
5. One cubic foot = 28.316 l
6. One pound mole = 453.6 gm-mole
7. Volume of sample = 25 ml.

* Calculations will be made for water compartment only.

Change in the water phase is equal to the final water phase concentration minus the initial water phase concentration which was zero.

$$= \frac{(\text{Term 1})(\text{Term 4})(\text{Term 5})}{(\text{Term 7})(\text{Term 6})} = 0.0001661 \frac{\text{lb-mole}}{\text{cu.ft.}}$$

D. Calculation of the time of contact between the phases.

Method: Time of contact = contact length ÷ velocity

Terms:

1. Flow rate = 0.00282 ft^3 per min.
2. cross-sectionas area of channel = 0.01434 ft^2
3. Velocity = (Term 1)/(Term 2) = 0.197 ft.per min.
4. Contact length = 0.208 ft.

Time of contact = (Term 4)/(Term 3) = 0.1057 min.

E. Calculation of the rate of mass transfer

Method: Concentration X volumetric flow rate ÷ contact length

Terms:

1. Concentration of water phase due to diffusion = $0.0001661 \frac{\text{lb-mole}}{\text{cu.ft.}}$
2. Volumetric flow rate = 0.00282 ft^3 per min.
3. Contact length = 0.208 ft.

Rate of mass transfer, R =(Term 1)(Term 2)(Term 3)

$$= 2.253 \times 10^{-5} \frac{\text{lb-mole}}{ft^3\text{-min.}}$$

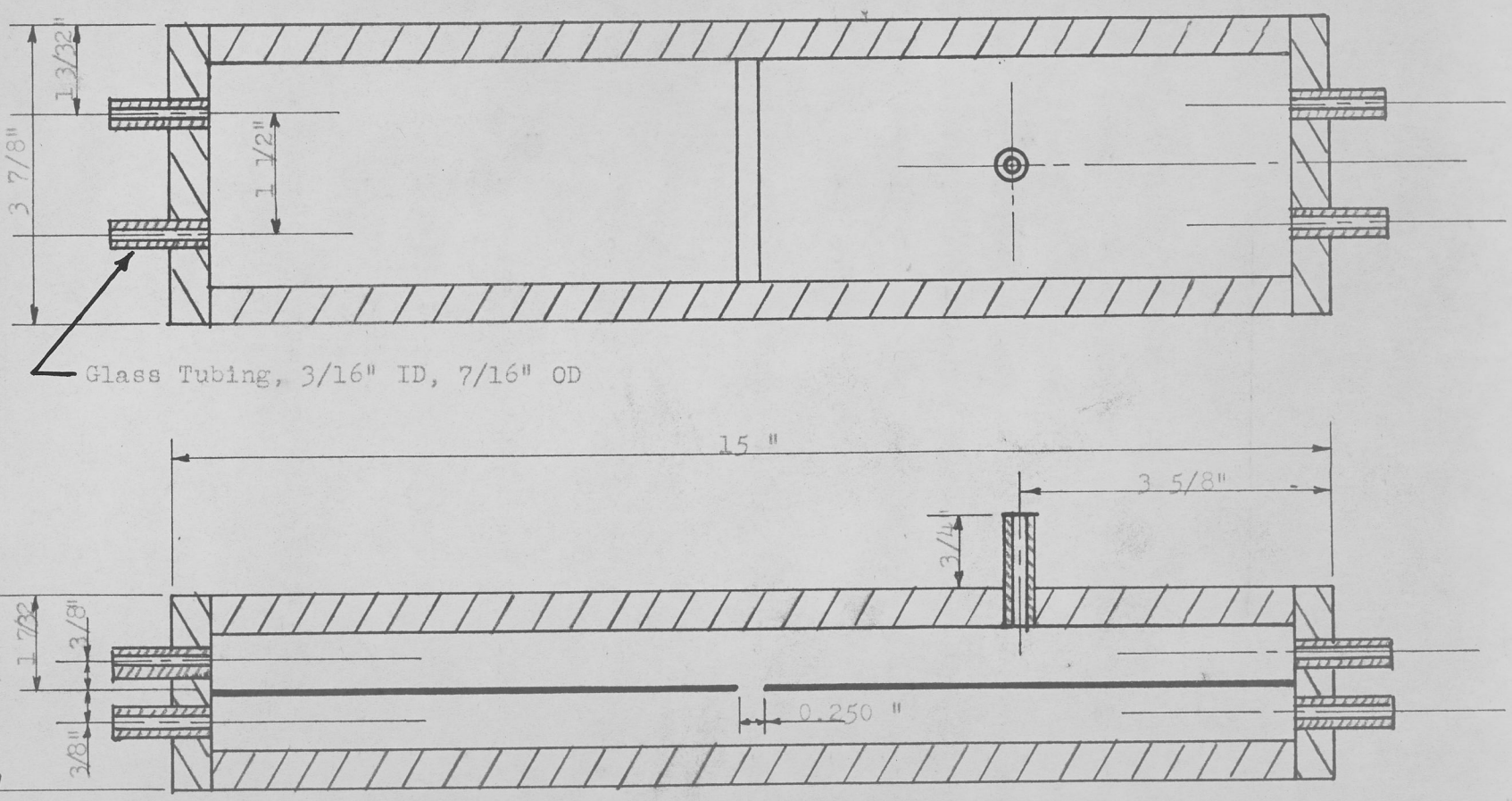

Figure 10

Detail of Contacting Device

APPENDIX C

MANOMETER CALIBRATIONS

Inorder to insure that the phases were flowing through their respective compartments at equal volumetric flow rates, the manometers had to be calibrated. The calibration data was obtained by measuring the volume of flow over a period of time as a function of the manometer pressure differential. The calibration curves are shown in Figures 10 and 11. The tabulated results are shown in Table II.

TABLE II

TABULATED FLOW DATA FOR METHYL*ISOBUTYL KETONE AND FOR WATER

Manometer Pressure Differential cm.		Flow Rate cc per min.		Reynold's Number	
Water	Ketone	Water	Ketone	Water	Ketone
42.1	37.7	149	190	65.1	147.1
32.4	29.6	123	168	53.7	130.0
27.1	15.2	110	109	48.0	84.4
20.6	8.8	92	77	40.2	59.6
11.6	5.0	62.5	51.5	26.3	39.9
8.2	2.7	49	34	21.4	26.3
4.0		27		12.0	
2.6		19		8.3	

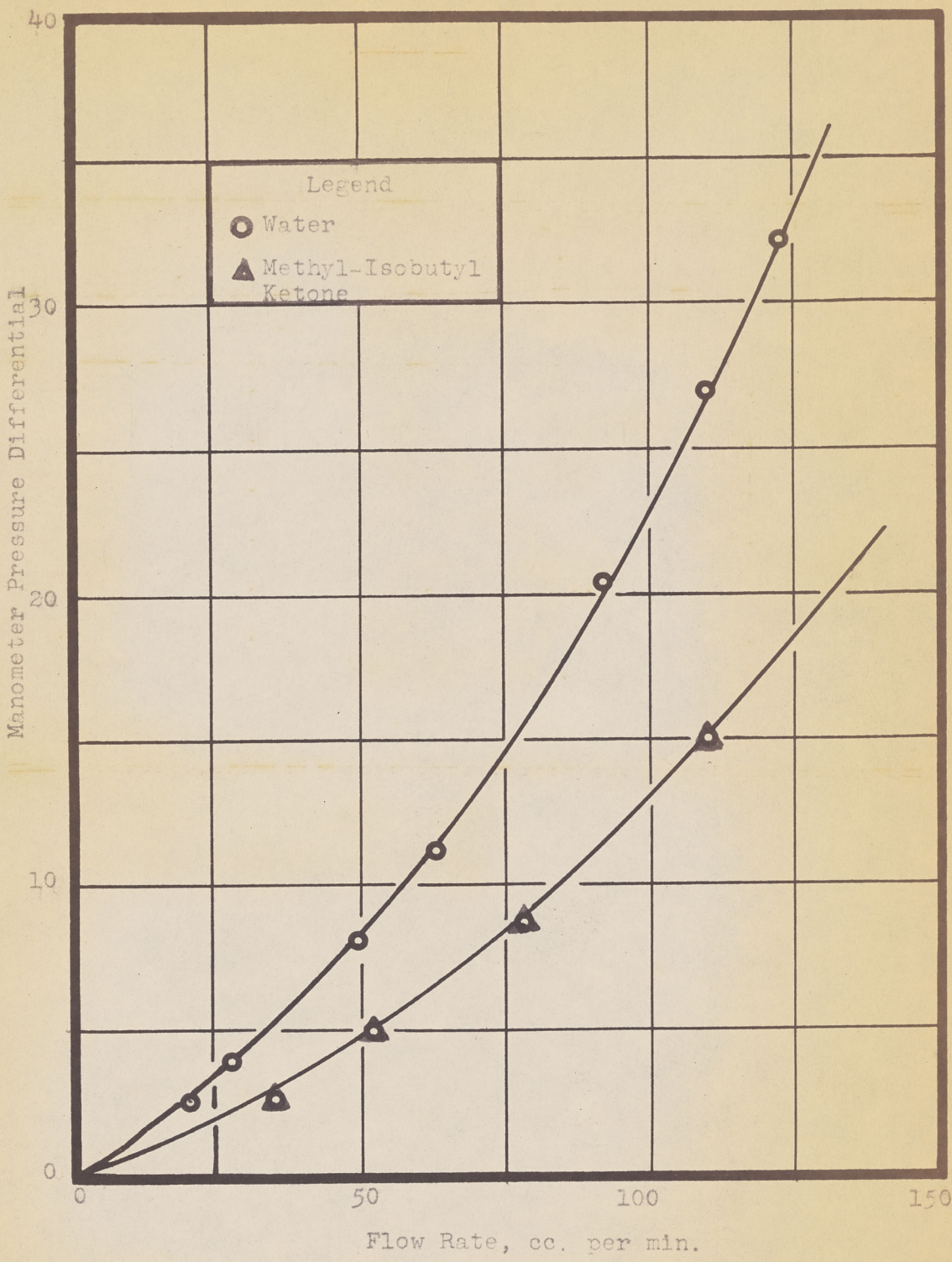

Figure 11

Manometer Pressure Differential as a Function of the Flow Rate

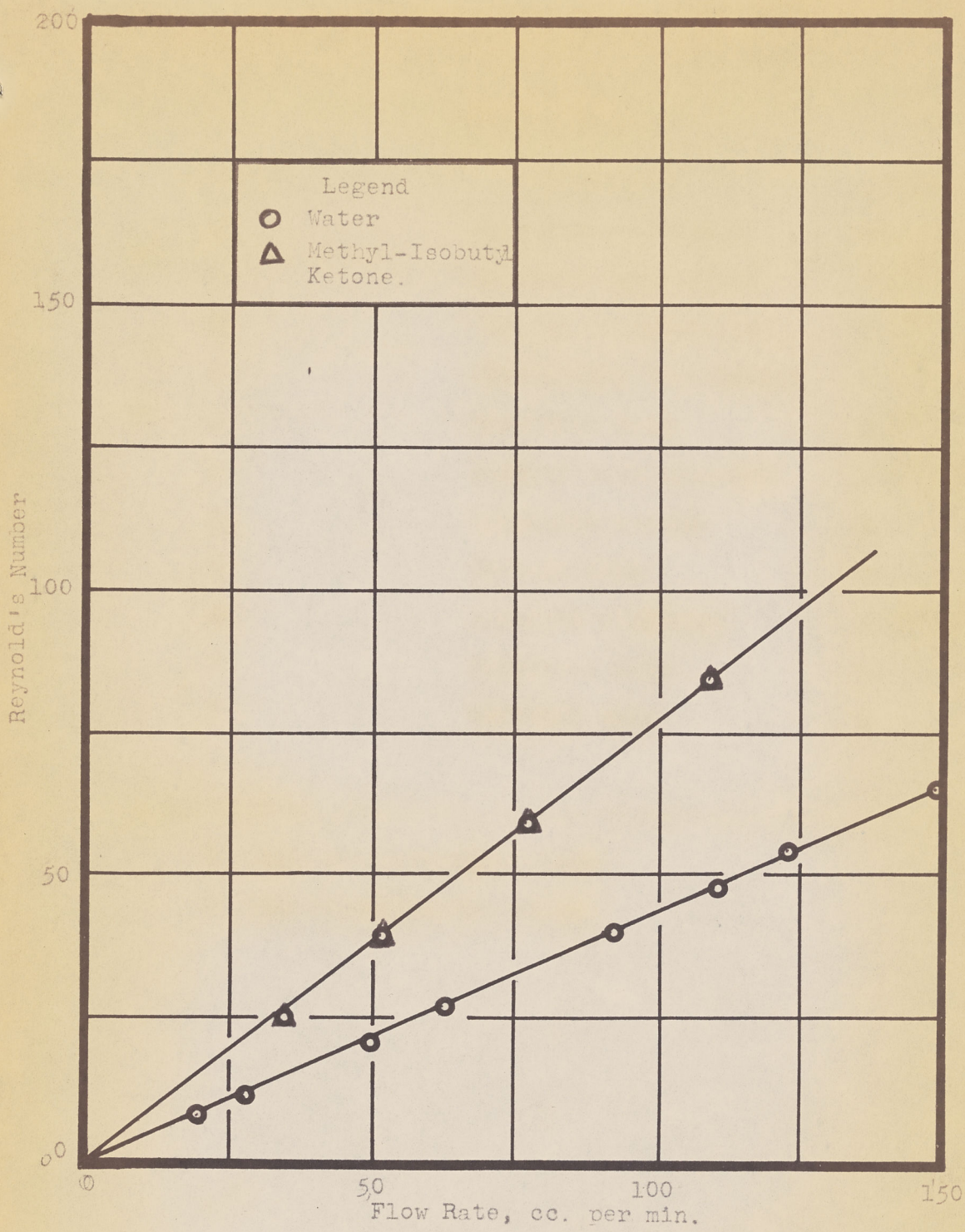

Figure 12

Reynold's Number Through the Compartment as a Function of the Flow Rate.

NOMENCLATURE

SYMBOL	DEFINATION	DIMENSION
a	Constant coefficient	Dimensionless
b	Constant coefficient	$M L^{-3}$
C	Liquid concentration	$M L^{-3}$
D	Diffusivity Coefficient	$M L^{-1} \theta^{-1}$
Q	Mass flow rate	$M \theta^{-1}$
R	Rate of mass transfer	$M L^{-3} \theta^{-1}$
R_H	Hydraulic radius	L
t	Contact time	θ
u	Absolute viscosity	$M L^{-1} \theta^{-1}$
X	Horizonal axis	L
Y	Vertical axis	L

SUBSCRIPTS

1 High concentration phase

2 Low concentration phase

APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval that the undersigned does not necessarily endorse or approve any statement made, opinions expressed or conclusions drawn herein, but approves the thesis only for the purpose for which it is submitted.

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