

LIQUID FILM COEFFICIENTS OF EXTRACTION FOR SOLID CYLINDERS

by

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INTRODUCTION

Of the numerous operations by which physical changes may be produced in materials, those involving molecular diffusion are the most recent to be extensively investigated (4, 6, 8, 10, 12, 15). The diffusional processes such as humidification and dehumidification, drying, distillation, gas absorption, and extraction involve the transfer of material from one phase of a system to another by diffusion through films which exist at the interface of the two phases. These films are composed largely of the same substance as the phase itself and offer the resistance to the transfer of the material between phases.

Much work has been done during the past decade on mass transfer rates in the important processes of drying, distillation, gas absorption, and humidification. Now, since industry is adopting more widely the use of solvent extraction as a means for separation, research is being directed toward increased knowledge of mass transfer rates in extraction processes.

The design of equipment to be used in extraction and catalytic processes could be made a more efficient, economical undertaking if the factors which govern the rates of mass and heat transfer through liquid film resistances were known. The present work evaluated, to a limited degree, the variables which determine the rate of mass transfer through liquid films for the toluene-water system. The investigation can be extended to other systems and results compared by using generalized correlation relating properties of the components of the systems in such dimensionless groups as the Reynolds number, the Schmidt group, and the Colburn (2) group.

GENERAL THEORY OF MASS TRANSFER

The general theory of mass transfer is based on the concept that films which exist at the interface between different phases of a system offer high resistance to the diffusion of material between phases. The two films, one on each side of the interface, are assumed in equilibrium at the interface; and the overall rate at which material is transferred from one phase to another phase is controlled by the rate at which the substance being transferred diffuses through the films separating the bulk of the phases. It is known that the resistance offered by each film varies directly as the thickness of the film. The film thickness is dependent upon physical properties of the material and upon the conditions of flow. Turbulent flow decreases the film thickness thereby decreasing the resistance to transfer.

For mass transfer across films in gas-liquid absorption and in drying systems, the factors controlling the resistance of the gas film have been investigated extensively. For liquid-liquid systems, however, the scarcity of reliable data limits the knowledge of mass transfer through liquid films. In the absence of such knowledge, absorption data might be used to gain insight into the mechanism of the process and to predict experimental results.

In steady-state transfer across a fluid film, the basic rate equation is applicable and is most simply expressed as,

$$\text{Rate} = \frac{\text{driving force}}{\text{resistance}} \quad (1)$$

Application of the general rate equation to the rate of mass transfer across a film gives the expression

$$r = k a_v V [\Delta \epsilon]_m \quad (2)$$

where

r = rate of transfer

- k = mass transfer coefficient for the film
 a_v = effective transfer area per unit volume of packing
 V = volume of the reactor
 $[\Delta \mathcal{E}]_m$ = mean driving potential of transferable component across film

For diffusion in the gas film, the rate of mass transfer is

$$r = k_g a_v V [\Delta p]_m \quad (5)$$

where

- k_g = mass transfer coefficient for the gas film
 $[\Delta p]_m$ = mean partial pressure difference of the transferable component across the gas film

The mass transfer coefficient, k_g , requires a number of units for definition and, as expressed in the rate equation, is specific to the system being used. Therefore, it is not universally applicable. In their theoretical treatment for the transfer of gases within circular conduits, Colburn and Chilton (2) incorporated the mass transfer coefficient for the gas film, k_g , into a dimensionless mass-transfer factor defined as:

$$[j_d]_g = \frac{k_g p_{gf} M_m}{G} \left[\frac{\mu}{\rho D_v} \right]_f^{2/3} \quad (4)$$

where

- $[j_d]_g$ = mass-transfer factor for gases
 k_g = mass-transfer coefficient for the gas film
 p_{gf} = mean partial pressure of the non-transferable component in the gas film
 M_m = mean molecular weight of the gas
 G = superficial mass velocity of the flowing gas
 μ = absolute viscosity of the film
 ρ = density of the film
 D_v = diffusivity of the transferable component in the gas film

The mass-transfer factor is dimensionless and is therefore independent of the system.

In their studies of the vaporization of water from spheres and cylinders, Hougen, Gamson, and Thodos (6) obtained an empirical correlation between $[j_d]_g$ and a modified Reynolds number, $\frac{D_p G}{\mu}$, where D_p is the equivalent particle diameter of the packing, G the superficial mass velocity of the gas, and μ the absolute viscosity of the gas. The resulting relationships are:

$$[j_d]_g = 0.99 \left[\frac{D_p G}{\mu} \right]^{-0.41} ; \quad \text{for } \left[\frac{D_p G}{\mu} \right] > 350 \quad (5)$$

$$[j_d]_g = 1.82 \left[\frac{D_p G}{\mu} \right]^{-0.51} ; \quad \text{for } \left[\frac{D_p G}{\mu} \right] < 350 \quad (6)$$

The equivalent particle diameter, D_p , is the diameter of a sphere which has the same surface area as an average particle in the bed. Thus, for cylinders

$$D_p = \sqrt{a_p / \pi} \quad (7)$$

where

a_p = average surface area per particle

For mass transfer across liquid films in liquid-liquid systems, the general rate equation applies except that the potential difference term is expressed in terms of concentration instead of partial pressures. The rate equation then becomes

$$r = k_l a_v V [\Delta c]_m \quad (8)$$

where

k_l = mass-transfer coefficient for liquid film

$[\Delta c]_m$ = mean concentration difference of transferable component across liquid film

Analogous to the grouping set down by Colburn and Chilton (2), Dougherty

(5) developed a mass-transfer factor for liquids. The mass-transfer factor for liquids is defined as

$$[j_d]_l = \frac{k_l c_{lf} M_m}{L} \left[\frac{\mu}{\rho D_l} \right]^{2/3} \quad (9)$$

where

$[j_d]_l$ = mass-transfer factor for liquids

k_l = mass-transfer coefficient for the liquid film

c_{lf} = mean concentration of nontransferable component in the liquid film

M_m = mean molecular weight of flowing liquid

L = superficial mass velocity of flowing liquid

μ = absolute viscosity of film

ρ = density of film

D_l = diffusivity of transferable component in the film

From the foregoing discussion, an empirical relationship between the mass-transfer factor for liquids, and the modified Reynolds number may be expected.

In addition to verifying the above relationship, it should be possible to determine whether or not there exists, for a solute-saturated, finely porous solid, a constant-rate period for extraction analogous to the constant-rate period for adiabatic drying. In drying, the rate of mass-transfer from a water-saturated porous solid is constant until a definite moisture content, known as the critical moisture content, is reached. The rate then decreases until the moisture content of the solid is in equilibrium with the moisture content of the gas. It is plausible that a similar event might take place in the transfer of solute matter held in pores of an inert solid, into a stream of unsaturated liquid solvent flowing over the solid.

This can be determined by observing the concentration of the effluent stream of liquid at intervals during an experiment performed under steady solvent flow conditions.

SCOPE OF PRESENT INVESTIGATION

In the present investigation, studies were made on one system only. The system consisted of two liquids, a solvent and a solute, having a limited mutual solubility. Small scale equipment was used to determine a procedure to be followed by subsequent investigations for the same and other systems on a larger scale. Furthermore, the use of small scale equipment reduced the expense and eliminated the problem of handling and storing large quantities of materials. As solvent flow was induced by gravity, only a narrow range of flow rates were possible. The effluent stream of solvent was analyzed chemically to determine the concentration of transferable component. Because of the very small solute solubility, a micro-analytical procedure was used.

Theoretically, there are two films present at the interface between the phases of a liquid-liquid diffusional process. One film is composed of a solvent-rich solution; the other, of a solute-rich solution. For solvent unsaturated with respect to solute and solute unsaturated with respect to solvent, counter-diffusion of solute and solvent occurs in the adjoining films. Thus the study of mass transfer rates through the individual films is complicated. The investigation can be simplified by reducing to zero, diffusion in one direction, thereby eliminating the solute-rich film. This can be done by soaking the packing with solvent-saturated solute. Since for solvent-saturated solute no concentration gradient exists, the solvent will not diffuse into the solute. Diffusion will take place in one direction only--the solute diffusing into the main stream of the solvent. One film is thus eliminated from consideration. This method was used in the present study.

EXPERIMENTAL STUDIES

Materials Used

In the system used in the present investigation, technical grade toluene was used as solvent, and distilled water as solute. These materials were chosen because of their low mutual solubility. The solubility of water in toluene is of the order of 0.450×10^{-5} lb per lb of toluene at ordinary room temperatures. If a material with higher water solubility had been used, the concentration gradient across the film would have been higher, resulting in such a high driving force that the porous solid would have been depleted of solute in a very short time. By using a solvent of low water solubility, there was maximum opportunity for the detection of a constant-rate of extraction, should one exist.

The packing used in the reactor was Calite 410 catalyst carrier pellets. The pellets, produced for commercial use by Johns-Manville, were made of a bonded diatomaceous earth in the form of cylinders. The internal void space was high (58 percent void volume), which was desirable for the study. Except for the extraction column proper, the experimental apparatus (Fig. 1) was constructed of metal and could be readily dismantled and cleaned. The glass tower was made of 0.50 in. diameter pyrex tubing in which the wet packing was supported.

Other equipment included a Fischer-Porter Flowrator for measuring the rates of flow, sample flasks, a stopwatch, a regulating valve, and a thermometer. The solvent supply tank was equipped with a constant-head device to provide a uniform rate of flow throughout the run.

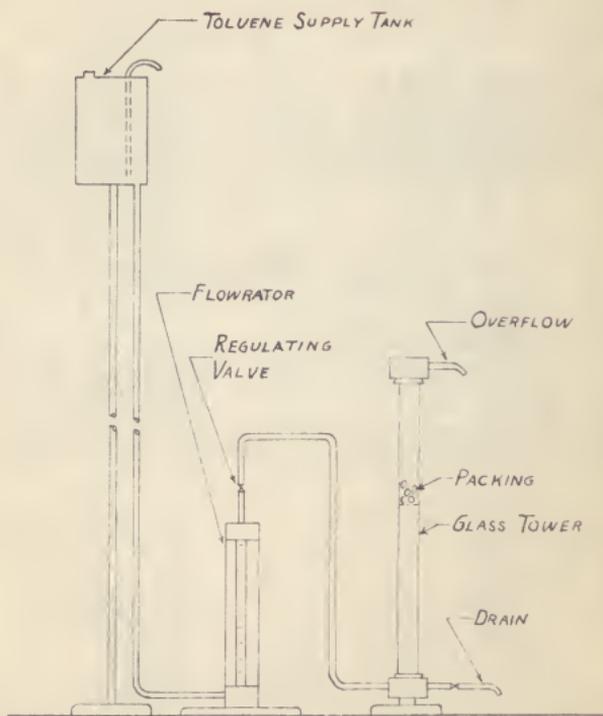


FIG. 1 SCHEMATIC DIAGRAM OF EXPERIMENTAL EQUIPMENT

Experimental Procedure

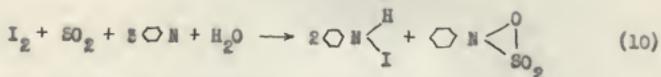
The initial water content of the technical grade toluene as received was nearly saturated with water and therefore required dehydration with silica gel prior to use in the experiment. The pellets were soaked in a solution of water saturated with toluene, for a period of several days before use. Excess surface moisture was drained from the soaked pellets, and the moistened pellets were placed in the extraction column. The packing was supported by a grid made of stainless steel and was located high in the chamber above the solvent entry point in order to assure streamlined flow. The dried toluene was then passed through the bed of pellets under steady-flow conditions and out the overflow pipe at the top of the tower. Samples of the overflow stream were taken in dried Erlenmeyer flasks which were immediately stoppered tightly.

The method of sampling consisted of catching the effluent stream at time intervals determined by the rate of flow. At the higher rates of flow, a 10-second sample was sufficient for analysis, while at lower rates a 15-second sample was necessary. The length of the runs varied from four minutes to about nine minutes. The solvent supply tank had a capacity of one quart, a quantity sufficient for a run of four minutes at the maximum flow rate.

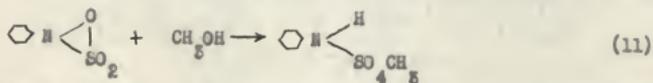
To preclude the possibility of moisture getting into the system from the air, the system was closed and guarded by drying tubes at all points through which air entered the system. The system was cleansed before use by rinsing with absolute alcohol and purging with dry, compressed air.

Analytical Method

The samples from the runs were analysed for water content by the Karl Fischer method (1, 11). This method employs the Karl Fischer Reagent, so named after the man who developed the method. The reagent, a mixture of iodine, pyridine, and sulfur dioxide made up according to formula (11), combines chemically with the water present in the sample. The reaction between water and the reagent is:



When all the water present is chemically combined, the addition of more reagent results in the presence of free iodine in the solution. If the water equivalent of the reagent is known, the volume of reagent used to combine with all the water in the sample is a quantitative measure of the water present. The water equivalent of the reagent is found by standardization with a standard water-in-methanol solution. The water in the standard reacts as in equation (10) above, and the methanol reacts as follows:



The Karl Fischer Reagent and the standard water-in methanol solution used for analysis in this investigation were purchased from Eimer & Amend, New York.

The detection of the endpoint in the titration may be accomplished by noting the color change from a straw yellow to the deep brown of free iodine. This method was used in the initial stages of the present work. The endpoint was readily detectable if small samples were used and mixing was complete. As the volume of the sample increased above 10 to 15 ml, the color change

became difficult to note. Since the samples to be analyzed were relatively large, the method was abandoned in favor of the electrometric titration method suggested by Almy, Griffin, and Wilcox (1).

The electrometric titration utilized a tungsten and a platinum electrode immersed in the solution. It had been shown (1) that the potential between the electrode pair changed from a zero potential when immersed in Karl Fischer Reagent to approximately 20 millivolts at the endpoint when the solution was titrated with the standard alcohol solution. The change was definite and very rapid. Using an instrument which noted the change in potential gave a sharp endpoint within a range of 0.05 ml of solution.

It was also demonstrated (1) that the instrument used had to be not only sensitive to note the small potential change, but, in order to prevent the electrodes from polarizing, the instrument could permit only a very small current to flow in the electrode circuit. A vacuum-tube type millivoltmeter was therefore desirable. Several different instruments were tried but discarded when results could not be reproduced. The instrument set-up which proved most satisfactory consisted of a Leeds & Northrup Co. amplifier, to which the electrodes and a continuous, recording potentiometer pyrometer manufactured by the Brown Instrument Co., were connected. The amplifier contained a resistance of the order of 10^6 ohms, and the current drawn from the electrodes was of the order of 10^{-12} amperes. The electrodes did not polarize noticeably. The amplifier made use of a small current which was fed to one side of a balanced bridge. When the potential between the electrodes changed at the endpoint, the bridge became unbalanced, and the Brown instrument, which was connected to the other side of the bridge, recorded the change. This arrangement gave reproducible results.

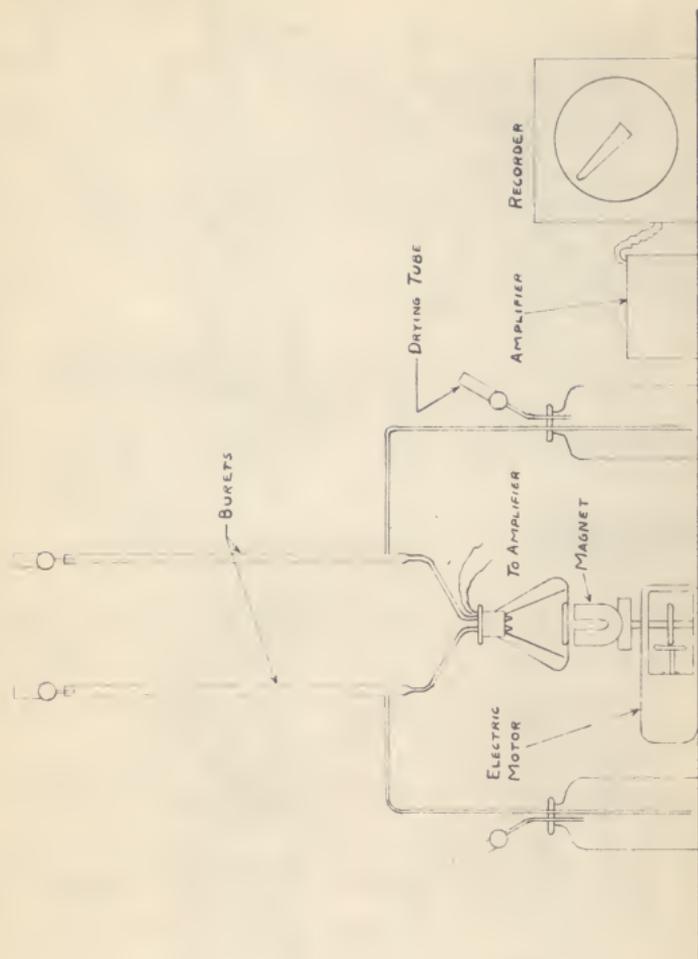


FIG. 2 ANALYTICAL EQUIPMENT

The toluene samples could not be titrated directly with Karl Fischer Reagent because the solutions are not mutually soluble; therefore, the water in the sample had to be extracted by some dehydrating agent which could be titrated. The dehydrating agent used was ethylene glycol. After the run, 25 ml of glycol was added to each sample, the glycol and the solution were thoroughly mixed, and the mixture was allowed to stand for several hours in the stoppered flask. The glycol layer was drawn off and titrated with Karl Fischer Reagent. The initial water content of the glycol was determined and subtracted from the total water titrated, and the difference was taken as the water content of the toluene sample.

A schematic diagram of the analytical apparatus is shown in Fig. 2. The Karl Fischer Reagent is somewhat sensitive to light and grows weaker with the passage of time. It was therefore necessary to standardize the reagent before each titration. The stock bottle was replenished with fresh reagent frequently.

In order to keep a completely air and water-vapor tight unit during titration, a magnetic stirring device was used. A small piece of soft iron wire was sealed in a glass tube and placed in the solution. A strong magnet, revolved under the bottom of the flask by an electric motor equipped with variable speed drive, caused the sealed soft iron wire in the solution to be revolved. The solution therefore was thoroughly agitated.

INTERPRETATION AND CORRELATION OF DATA

Data taken during the experimental studies was correlated according to the general theory of mass transfer through liquid films. Sample calculations for one run are included in the appendix.

Each sample taken during the run was analyzed for water content by the Karl Fischer method. Water introduced with the glycol was deducted from the total amount of water as indicated by the titration; the difference was the water content of the toluene sample. The composition of each sample was calculated and plotted on rectangular coordinate paper versus time elapsed during the run, as shown by the graph of Fig. 5. A line was drawn through the lower points of the group and extrapolated to time zero to determine the instantaneous composition of the stream entering the bed of packing at time zero, the moment at which transfer occurred at the maximum rate. The mean concentration difference, $[\Delta c]_m$, was calculated by the equation

$$[\Delta c]_m = \frac{[\Delta c]_1 - [\Delta c]_2}{\ln \frac{[\Delta c]_1}{[\Delta c]_2}}$$

where

$[\Delta c]_m$ = mean concentration difference

$[\Delta c]_1$ = concentration difference between saturated toluene and toluene entering the tower

$[\Delta c]_2$ = concentration difference between saturated toluene and effluent at time zero

The lower points were used to determine the line for extrapolation since the lower points were the more reliable. Should there have been leaks in the system, incomplete drying of the apparatus or sample flasks, or excess

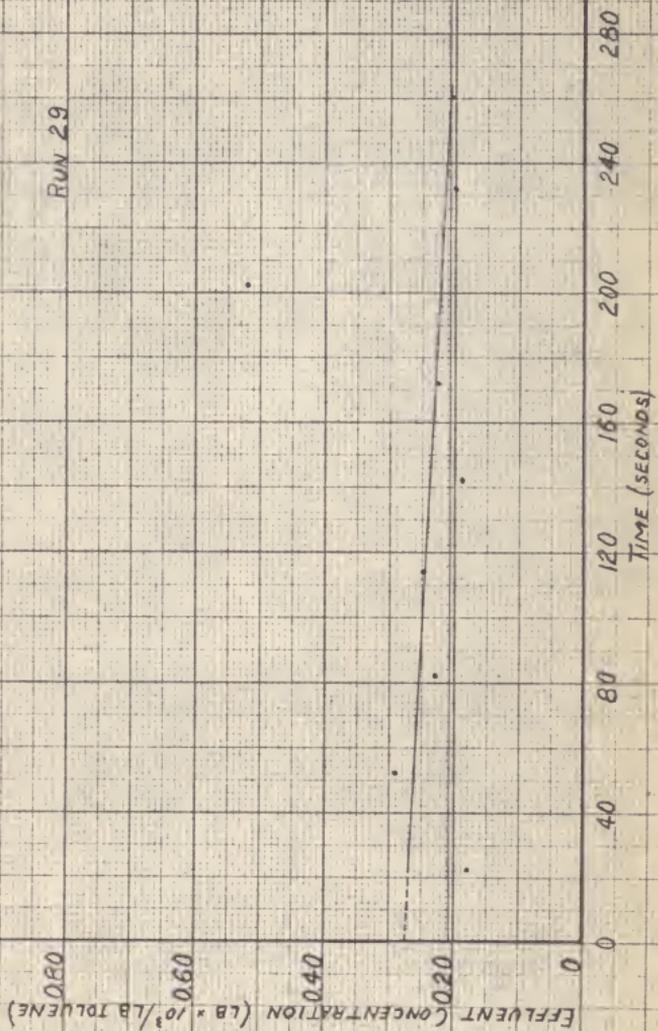


FIG. 3 EFFLUENT CONCENTRATION VS. TIME

moisture introduced on the pellets or the supporting grid, the experimental values of water content would have been high relative to the values obtained had no extraneous water been introduced.

The rate of transfer was the product of the rate of flow and the difference in concentration between the influent and effluent toluene streams. The mass-transfer coefficient, k_1 , was then calculated from equation (8) and the mass-transfer factor, $[j_d]_1$, from equation (9).

After calculating values for k_1 and $[j_d]_1$ for each of the runs made during the study, the values were plotted against the modified Reynolds number for each run. The resulting graphs are shown in Figs. 4 and 5.

To determine an equivalent particle diameter, D_p , each pellet used in the investigation was measured with a micrometer and the surface area calculated. From the summation of all the areas of all the particles, an average area was determined.

Observation of the slope of the line in the effluent composition versus time plot, Fig. 3, disclosed that the exit concentration gradually decreased as the run proceeded. If a constant-rate period for extraction existed for a brief interval during the run, the line should show initially a period of constant efflux composition. No such occurrence was evident in the data taken. It was apparent, then, that the surface of the pellets did not remain thoroughly wetted during the run, and that the boundary film through which the diffusion or transfer took place gradually receded into the pores of the solid. As the film disappeared toward the center of the particle, the area of the film decreased, and the rate of transfer decreased.

The correlation between the values of $[j_d]_1$ and the modified Reynolds number, and between k_1 and the modified Reynolds number were found

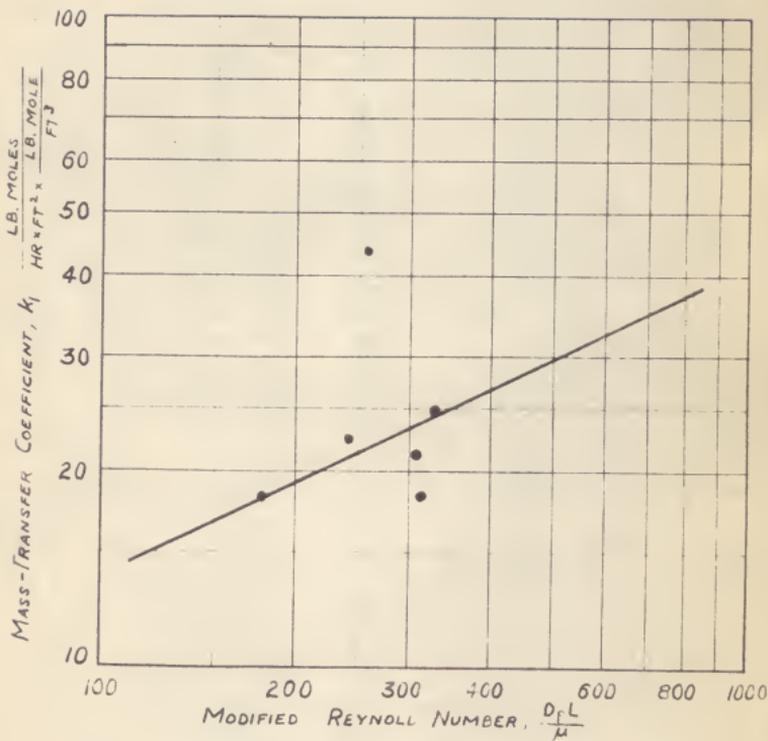


FIG. 4 MASS-TRANSFER COEFFICIENTS FOR LIQUIDS VS. MODIFIED REYNOLDS NUMBER

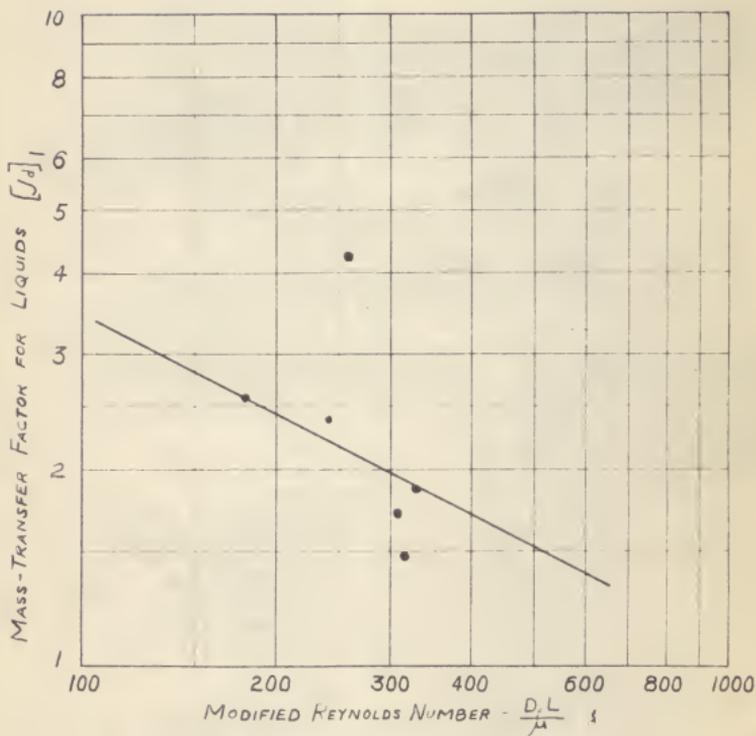


FIG. 5 MASS-TRANSFER FACTORS FOR LIQUIDS VS. MODIFIED REYNOLDS NUMBER

to be

$$[j_d]_1 = 55.95 \left[\frac{D_P L}{\mu} \right]^{-0.51} \quad (13)$$

$$k_1 = 1.48 \left[\frac{D_P L}{\mu} \right]^{0.485} \quad (14)$$

The results obtained in the present investigation were compared with those obtained by Hobson and Thodos (4) in their study of the systems water-isobutyl alcohol and water-methyl ethyl ketone and to those of Hougen, Ganson, and Thodos (6) for transfer rates in the gas film. The values of $[j_d]_1$ and k_1 found in the present work were higher, but of the same order of magnitude as those of the previous investigators. As compared with the correlation for gases developed by Hougen, Ganson, and Thodos and expressed by equation (8), the data from the present investigation yielded a line (see Fig. 5) which was higher but of the same slope. An examination of the Schmidt group, $\left[\frac{\mu}{\rho D} \right]$, of equation (9), which was used to calculate $[j_d]_1$, yielded some insight into the possible cause for the discrepancies.

In the calculation of the results in the present study, the value of the diffusivity coefficient, D_1 , was obtained from the values presented by Wilke (14). The value of D_1 for water diffusing in toluene is much larger than for more complex molecules, such as isobutyl alcohol, diffusing in water (the system used by Hobson and Thodos). The Schmidt group calculated from the film properties, therefore, is greatly influenced by the value of D_1 . When raised to the 2/3 power, the group has a marked effect on the calculated transfer numbers. Obviously, because of the variation in densities, viscosities, and especially molecular structures, the Schmidt group was largely responsible for the difficulty in obtaining agreement between j_d values for different systems.

CONCLUSIONS

Conclusions which may be drawn from the present work in regard to the factors governing the rate of mass-transfer through liquid films are:

1. Within the scope of this investigation, no constant-rate period of mass transfer was apparent. The boundary film moved toward the center of the particle during the extraction process.

2. The mass-transfer coefficients and mass-transfer factors were related to the modified Reynolds number. The transfer factors obtained in the present work vary to the same power of the Reynolds number as those found by other investigators, and are of the same order of magnitude. Discrepancies in magnitude were possibly due to large differences in diffusivity coefficients and, hence, Schmidt groups, for different systems. The mass-transfer factors varied as the - 0.51 power and the mass-transfer coefficients as the 0.485 power of the modified Reynolds number.

3. A mass-transfer factor for liquid films was defined as

$$[j_d]_l = \frac{k_1 c_{1f} M_m}{L} \left[\frac{\mu}{\rho D_1} \right]_f^{2/3}$$

By the correlation between the transfer factor and the modified Reynolds number, rates and coefficients of mass transfer may be predicted from rates of flow and physical properties of the components used in the system.

RECOMMENDATIONS FOR FUTURE WORK

It is recommended that the present work be extended to include the use of other liquids as solvents or solutes and to the use of a greater range of flow rates. Other variables to be investigated are the size and shape of the packing used to hold the solute. With water as the solute, the present analytical equipment using Karl Fischer Reagent gave reproducible results and was highly sensitive to small amounts of water. If another substance were used as solute, a different analytical method would be necessary.

Some refinements of the present procedure appear desirable. The use of a solvent which has a mutual solubility with Karl Fischer Reagent would obviate the need for a dehydrating agent, such as ethylene glycol, thereby eliminating one step and a potential source for error in the analysis.

The use of a completely closed system for extraction, sampling, and analysis, would eliminate the possibility of moisture entering from the surroundings. In the present method the sample flasks were opened twice before analysis; once to introduce the dehydrating agent and once to draw off the portion to be titrated. Two opportunities were thus presented for the entry of moisture into the sample.

A means of analyzing the effluent stream continuously would be, of course, most desirable since instantaneous concentrations then could be observed during the run. By this technique, the existence of a constant-rate period could be conclusively proved or disproved.

The present method was fundamentally reliable but possessed many weaknesses. It is believed that the above suggestions could be helpful in reducing or eliminating the remaining major shortcomings.

ACKNOWLEDGMENTS

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APPENLIX

Table 1. Experimental and calculated data

Sample Calculations

Table 2. Physical properties of packing

Table 3. Physical properties of toluene and water at 80°F.

Fig. 6. Viscosity vs. Temperature for Toluene

Nomenclature

Table 1. Experimental and calculated data

Run :	Effluent stream composition :	L :	r :	$a_v v$:
:	at time zero :	lb./hr. (sq. ft.) :	lb. moles/hr. :	sq. ft. :
:	(lb. moles)/(cu. ft.) :	lb./hr. (sq. ft.) :	(lb. moles)/(hr.) :	(sq. ft.) :
25	0.00110	12,570	0.000154	0.00785
26	0.00117	8,712	0.000121	0.01570
27	0.00106	16,085	0.000180	0.01528
28	0.00096	15,081	0.000129	0.01125
29	0.00085	14,414	0.000074	0.00652
30	0.00098	11,061	0.000099	0.00906

Run :	Δc_m :	k_1 :	c_1^f :
:	(lb. moles)/(cu. ft.) :	(sq. ft.)(lb. mole)/(cu. ft.) :	(lb. moles)/(cu. ft.) :
25	0.00045	45.6	0.586
26	0.00039	16.3	0.586
27	0.00048	24.6	0.586
28	0.00054	21.2	0.586
29	0.00062	18.2	0.586
30	0.00049	22.4	0.586

Table 1 (concl.).

Run :	M_m :	$\frac{M}{\rho D_1}$:	$[j_d]_1$:	$\frac{D}{\mu}$:
:	lb./mole :	:	:	:
25	92.15	22.54	4.22	257
26	92.15	22.54	2.57	178
27	92.15	22.54	1.86	329
28	92.15	22.54	1.72	508
29	92.15	21.66	1.47	514
30	92.15	21.66	2.33	241

Sample Calculations

The following calculations were used for the data taken in run 29:

From Fig. 5, the extrapolated value of the concentration at time zero was 0.275×10^{-5} lb. water/lb. toluene. The mean concentration difference $[\Delta c]_m$ was found by the equation

$$[\Delta c]_m = \frac{(c_s - c_e) - (c_s - c_o)}{\ln \frac{(c_s - c_e)}{(c_s - c_o)}}$$

where

c_s = water concentration in saturated toluene, lb. moles/ft.³

c_e = water concentration in entering toluene, lb. moles/ft.³

c_o = water concentration in effluent stream at time zero, lb. moles/ft.³

for which the values were

$c_s = 1.35 \times 10^{-5}$ lb. moles/ft.³ (Table 2)

$c_e = 0.62 \times 10^{-5}$ lb. moles/ft.³ (Titration)

$c_o = 0.85 \times 10^{-5}$ lb. moles/ft.³ (Fig. 5)

Then

$$[\Delta c]_m = \frac{(0.00135 - 0.00062) - (0.00135 - 0.00085)}{\ln \frac{(0.00135 - 0.00062)}{(0.00135 - 0.00085)}}$$

$$[\Delta c]_m = 0.00062 \text{ lb. moles/ft.}^3$$

The rate of transfer per hr.-ft.² was found by

rate = $(c_o - c_e) \times$ rate of flow (ft.³/hr.)

rate = $(0.00085 - 0.00062)(0.36) = 0.000074$ lb. moles water/hr.

The mass-transfer coefficient, k_1 , was calculated by equation (8):

$$r = k_1 a_v V [\Delta c]_m$$

$$k_1 = \frac{0.000074}{(0.0065)(0.00062)} = 18.2 \frac{\text{lb. moles}}{\text{hr.} \times \text{ft.}^2 \times \text{lb. mole/ft.}^3}$$

The mass-transfer factor, $[j_d]_1$, was calculated by equation (9):

$$[j_d]_1 = \frac{k_1 c_{1f} M_m}{L} \left[\frac{\mu}{\rho D_1} \right]_f^{2/3}$$

$$[j_d]_1 = \frac{(18.2)(0.586)(92.12)}{14,414} \left[\frac{0.547 (2.42)}{(55.97)(0.000226)} \right]^{2/3}$$

$$[j_d]_1 = 1.47 \text{ (dimensionless)}$$

To calculate the modified Reynolds number:

$$D_p = \sqrt{a_p / \pi} = \frac{0.0025}{3.1416} = 0.027 \text{ ft.}$$

$$Re = \frac{D_p L}{\mu} = \frac{(0.027)(14,414)}{(0.547)(2.42)} = 314 \text{ (dimensionless)}$$

Table 2. Physical properties of packing (Celite 410)

Shape-----	cylindrical
Diameter-----	0.275 in.
Length-----	0.250 in.
Cold water absorption-----	58 gm./100 gm.
Packed density-----	54 lb./ft. ³
Temperature resistance-----	2,000 to 2,500°F.
Reaction-----	Slightly acid to normal
Compressive strength-----	2,200 lb./in. ²

Table 3. Physical properties of toluene and water at 80°F.

	<u>Toluene</u>	<u>Water</u>
Density-----	53.97 lb./ft. ³	62.22 lb./ft. ³ (5)
Viscosity-----	1.52 lb./ft.-hr.	2.09 lb./ft.-hr. (5)
Diffusivity-----		0.228×10^{-5} ft. ² /hr. (14)

Nomenclature

The following terms and symbols were used in the calculation of the data of the present work:

- a_v = effective surface area of packing per unit volume, $\text{ft.}^2/\text{ft.}^3$
 c = concentration of solute, $\text{lb. moles}/\text{ft.}^3$
 c_{1f} = concentration of solvent in film, $\text{lb. moles}/\text{ft.}^3$
 D_l = diffusivity of transferable component in liquid, $\text{ft.}^2/\text{hr.}$
 D_v = diffusivity of transferable component in gas, $\text{ft.}^2/\text{hr.}$
 D_p = equivalent particle diameter, ft.
 G = superficial mass velocity of flowing gas, $\text{lb.}/\text{hr.}-\text{ft.}^2$
 j_d = mass-transfer factor
 $[j_d]_g$ = mass-transfer factor for gases
 $[j_d]_l$ = mass-transfer factor for liquids
 k = mass-transfer coefficient for fluid film, $\text{lb. moles}/\text{hr.}-\text{ft.}^2$ -
 unit driving force
 k_g = mass-transfer coefficient for gas film, $\text{lb. moles}/\text{hr.}-$
 ft.^2 - atm.
 k_l = mass-transfer coefficient for liquid film, $\text{lb. moles}/\text{hr.}-$
 ft.^2 - $\text{lb. mole}/\text{ft.}^3$
 L = superficial mass velocity of flowing liquid, $\text{lb.}/\text{hr.}-\text{ft.}^2$
 M_m = mean molecular weight of flowing fluid, $\text{lb.}/\text{mole}$
 p = partial pressure of transferable component in gas film, atm.
 p_{g^*} = mean partial pressure of the non-transferable component in
 gas film, atm.
 r = rate of mass transfer, $\text{lb. moles}/\text{hr.}$
 Re = modified Reynolds number
 V = volume of packing, ft.^3

Greek:

Δ = symbol for difference

μ = absolute viscosity, lb./hr.-ft.

\mathcal{E} = driving force of transferable component expressed in any set of consistent units

ρ = density, lb./ft.³

Subscripts:

e = entering toluene

f = film

g = gas

l = liquid

m = mean

0 = time zero

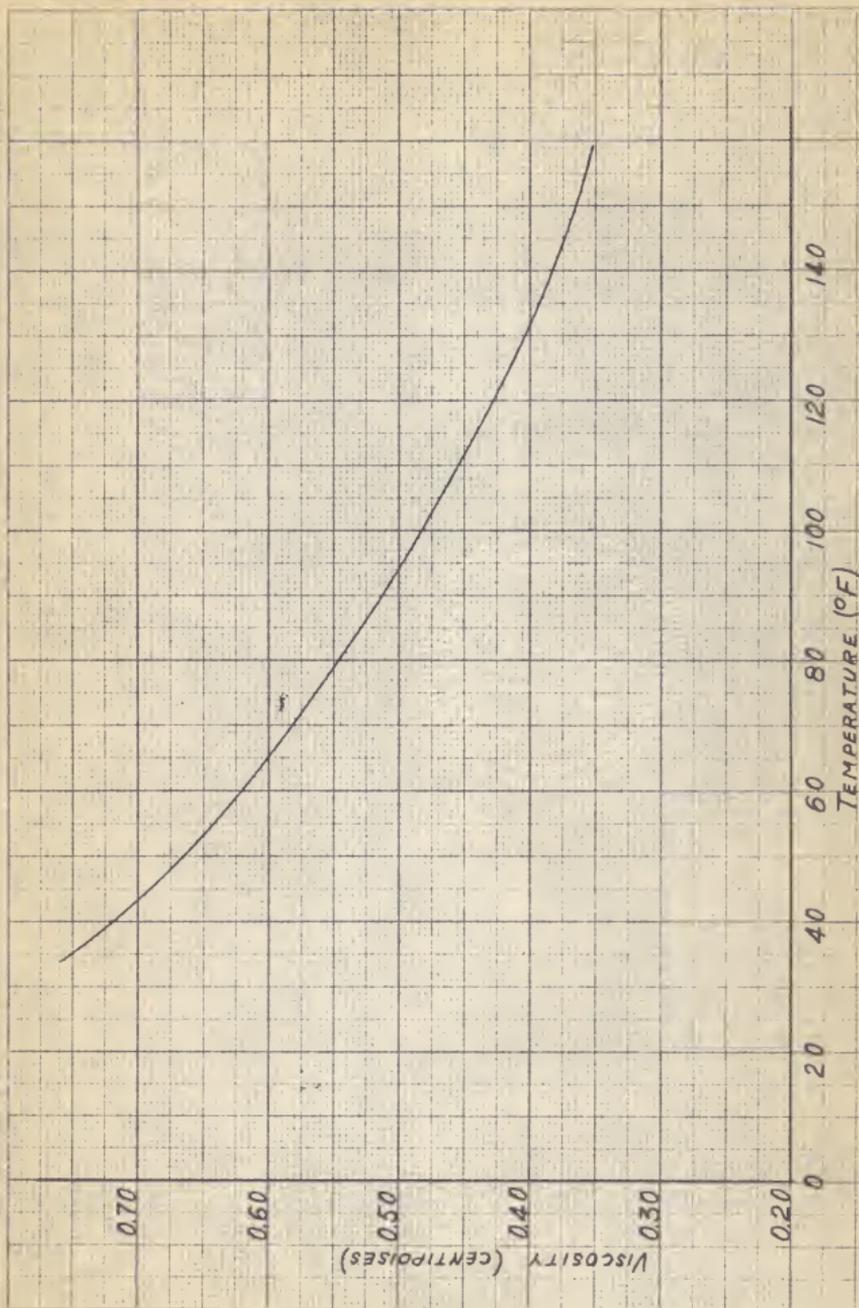


Fig. 6 Viscosity vs. Temperature for Toluene