LIQUID-LIQUID MASS TRANSFER IN AN AGITATED VESSEL WITH A FLAT INTERFACE

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Mass transfer between two phases was studied in an agitated vessel with a flat liquid-liquid interface for 30 systems, where physical properties varied in a wide range. The observed Sherwood numbers for the first-phase Sh_1 were correlated in terms of the first-phase Reynolds number Re_1 , modified second-phase Reynolds number Re_2' , Schmidt number Sc_1 , Capillary number Ca_1 and a function of viscosity ratio Φ . The correlation obtained represents all the data with an average deviation of 12.7%:

$$Sh_1 = 0.0119 Sc_1^{1/3} Ca_1^{6/13} [\Phi^4 Re_1^3 + Re_2'^{8/3}]^{1/4}$$

Introduction

It is necessary to understand exactly the role of diffusion in the kinetic analysis of heterogeneous liquid-liquid reaction and solvent extraction with chemical reaction. Agitated vessels with a flat liquid-liquid interface have widely been used since their original use by Lewis,⁸⁾ and Gordon and Sherwood,⁴⁾ for the study of liquid-liquid mass transfer. This type of apparatus has the advantage that its interfacial area is known and the amount of liquid required is comparatively small. On the other hand, it has the disadvantage that the mass transfer rate cannot be analyzed theoretically owing to ill-defined hydrodynamics near the interface. In predicting the mass transfer coefficients, therefore, one must use an adequate empirical correlation. Several studies^{2,8-12)} have been made on the correlation of the mass transfer coefficients, but the relevant physical properties were varied only within a limited range. Thus, it seems doubtful whether the proposed correlations are reliable.

The objective of the present study is to determine systematically the effects of the physical properties on the mass transfer rate over a wide range of values of these properties and to obtain a reliable correlation of the mass transfer coefficients.

1. Apparatus and Procedure

In our preliminary experiments, it was found that the Lewis cell, traditionally used for liquid-liquid systems, not only exhibited low mass transfer rate due to small interfacial area, but the interface was subject to breaking up even at low agitation speeds. In the present study, therefore, the agitation vessel shown in

Fig. 1 was used. It is basically similar to one used for gas-liquid systems.⁶⁾ It was possible to operate it without any break-up of the interface even at much higher agitation speeds. On the other hand, this agitated vessel was subject to surface wave motion. But the effect of surface wave motion on mass transfer rate seems to be negligible. This is because the dependence of mass transfer rate on agitation speeds was observed to be invariant with increase of the agitation speeds that enhanced the surface wave motion, and to be independent of the differing extent of surface wave motion in various experimental systems.

The present vessel consisted of an inner glass cylinder 80 mm in diameter and 160 mm high clamped between two flat stainless steel end plates. The annular space between inner and outer cylinders was used as a water jacket. Four equally spaced vertical glass baffles, 3.1 mm thick and one-tenth of the vessel diameter in width, were attached to the internal wall of the vessel. In both the upper and lower phases the liquid depth was kept equal to the vessel diameter and the vessel was completely filled with the liquids in order to ensure symmetrical configuration for both phases. In both phases, each stirrer was a glass paddle agitator with two flat blades, having a diameter and height of four-tenths and one-tenth of the vessel diameter respectively. The blades were placed at half of each liquid depth. The upper rotating shaft was extended through the interface to nearly half of the liquid depth in the lower phase to prevent vortex formation near the center of the interface.

All experiments were carried out at 25°C in batch operation. The mass transfer coefficients measured under the conventional contra-rotating conditions in the preliminary experiments, behaved as if the interface as a whole were not rotating for some com-

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Fig. 1. Agitated vessel.

binations of agitation speeds in each of the two phases. This suggests the difficulty of reasonably correlating the experimental data. Thus, the stirrers ran in the same direction in the present experiments.

The experimental conditions and systems used in this study are given in **Table 1**, in which the gas-liquid system used for comparison is also included. For the partially miscible binary liquid system of water-cyclohexanol, cyclohexanol in the upper phase was saturated with water, and water was partially saturated with cyclohexanol above 50% of its solubility. The necessity of this partial saturation is due to the fact that the density of the aqueous solution of cyclohexanol reaches maximum value at a concentration of between 25 and 50% of the solubility, and consequently, insufficient partial saturation might cause Rayleigh effect. For the ternary systems, the solvents in both phases were saturated with each other beforehand and then the solute was always added to the lower phase, which was aqueous except for the systems with chlorobenzene and with 1,1,2,2-tetrabromoethane. The mass transfer was controlled by aqueous-phase resistance in all the systems, because the equilibrium distributions of the solute strongly favored the organic phases.

When O_2 was used as the solute, the concentration variation of O_2 over time was monitored continuously by a DO meter. When caproic acid, I_2 , H_2 and cyclohexanol were used as solutes, on the other hand, the change in concentration of the solute over time was determined by analyzing liquid samples of 2 cm^3 withdrawn from the aqueous phase at intervals of 10–20 minutes. Caproic acid was determined by titration with the standard aqueous NaOH solution,

using phenolphthalein as an indicator, and I_2 was determined with the standard aqueous $Na_2S_2O_3$ solution. The concentration of H_2 was measured with a gas chromatograph and the concentration of cyclohexanol with a differential refractometer.

The physical properties of the systems are tabulated in Table 1, much of the data having been determined in this work. The systems provide a wide range of properties. The diffusivities of all the solutes in the aqueous solutions were estimated from the values for pure water at 25°C ,^{1,5,14,15} by correcting for the effect of the addition of sucrose or of saturation with the other phase according to the Stokes-Einstein relationship. The properties shown in Table 1 refer to those for the liquids in equilibrium with the other phases and containing the solute at the concentration level during the extraction processes. Interfacial tensions were measured by a capillary-rise method, and viscosities and densities by conventional techniques.

The mass transfer coefficients k_1 in the aqueous phase, denoted as the first phase below, were evaluated by the expression

$$\ln \frac{C_{1i} - C_{10}}{C_{1i} - C_1} = \frac{k_1 St}{V_1} \quad (1)$$

which is derived on the basis of the assumption of complete mixing of the first phase. The measured equilibrium concentration C_{1i} was used for the systems water-cyclohexanol, water- I_2 -chlorobenzene, and water- I_2 -1,1,2,2-tetrabromoethane, in which the solute transferred from the organic phase into the aqueous phase. In the other systems, in which the solute moved in the opposite direction, C_{1i} could be regarded as zero considering the distribution coefficient of the solute and the magnitude of mass transfer coefficients in both phases. In all cases, good straight lines were obtained by a semi-log plot of $(C_{1i} - C_{10})/(C_{1i} - C_1)$ against t .

2. Experimental Results and Discussion

2.1 Effects of Reynolds numbers of two phases

Firstly, the effects of the first-phase Reynolds number $Re_1 (= d^2 N_1 / \nu_1)$ and the second-phase Reynolds number $Re_2 (= d^2 N_2 / \nu_2)$ on the first-phase mass transfer coefficients k_1 were investigated. The experimental results for the water- O_2 - n -hexane system are shown in **Fig. 2**. It can be seen that k_1 is proportional to about 0.7 power of Re_1 when there is no agitation in the second phase. This is similar to the behavior in gas-liquid systems observed in a similar agitated vessel.⁶ When $Re_2 \neq 0$, on the other hand, k_1 approaches an asymptotic value which depends only on Re_2 at small values of Re_1 , but the effect of Re_2 diminishes with increasing Re_1 . It should be noted that if the agitation conditions correspond to the flat region of k_1 , the lack of effect of Re_1 on the overall

Table 1. Experimental conditions and physical properties of systems used [25°C]

Key in Fig. 8	System First phase-Solute-Second phase	Phase	Re	$\mu \times 10^3$ [Pa·s]	ρ [kg/m ³]	$D \times 10^9$ [m ² /s]	$\sigma \times 10^3$ [N/m]
●	Water-I ₂ -20 vol% Paraffin oil	1	762- 4760	0.894*	997*	1.25	38.4
	+ 80 vol% <i>n</i> -Hexane	2	0- 4400	0.564	704		
○	Water-I ₂ -40 vol% Paraffin oil	1	762- 4760	0.894*	997*	1.25	38.5
	+ 60 vol% <i>n</i> -Hexane	2	1470- 4400	1.09	751		
◐	Water-I ₂ -60 vol% Paraffin oil	1	762- 4760	0.894*	997*	1.25	38.7
	+ 40 vol% <i>n</i> -Hexane	2	0- 1470	2.71	791		
◑	Water-I ₂ -80 vol% Paraffin oil	1	762- 4760	0.894*	997*	1.25	39.4
	+ 20 vol% <i>n</i> -Hexane	2	0- 180	11.8	832		
◒	Water-I ₂ -90 vol% Paraffin oil	1	762- 4760	0.894*	997*	1.25	41.4
	+ 10 vol% <i>n</i> -Hexane	2	0- 180	32.3	853		
□	Water-I ₂ -10 vol% Decalin	1	762- 3800	1.16	986	0.967	2.63
	+ 90 vol% <i>i</i> -Butanol	2	0- 1470	2.74	829		
▤	Water-I ₂ -50 vol% Decalin	1	762- 2500	1.14	987	0.979	4.11
	+ 50 vol% <i>i</i> -Butanol	2	0	2.20	855		
▥	Water-I ₂ -70 vol% Decalin	1	762- 2500	1.14	988	0.983	5.40
	+ 30 vol% <i>i</i> -Butanol	2	0	2.11	865		
▦	Water-I ₂ -80 vol% Decalin	1	762- 3000	1.08	988	1.03	7.00
	+ 20 vol% <i>i</i> -Butanol	2	0	2.09	872		
▧	Water-I ₂ -90 vol% Decalin	1	762- 3800	0.969	993	1.15	12.6
	+ 10 vol% <i>i</i> -Butanol	2	0- 351	2.19	882		
▨	Water-I ₂ -95 vol% Decalin	1	762- 3800	0.957	993	1.17	17.9
	+ 5 vol% <i>i</i> -Butanol	2	0	2.25	882		
◀	Water-I ₂ -Ethyl propionate	1	762- 3500	0.932	996	1.20	11.7
		2	0- 1470	0.538	880		
◁	Water-I ₂ -Ethyl <i>n</i> -butyrate	1	762- 3500	0.899	996	1.24	14.9
		2	0	0.639	868		
▽	Water-I ₂ -Ethylbenzene	1	762- 4000	0.876	997	1.28	32.9
		2	0	0.624	859		
■	Water-I ₂ - <i>i</i> -Butanol	1	762- 2080	1.18	986	0.945	1.96
		2	0- 351	2.84	833		
▷	Water-I ₂ - <i>n</i> -Pentanol	1	762- 2080	0.948	994	1.18	4.13
		2	0- 351	3.12	831		
►	Water-I ₂ - <i>n</i> -Hexanol	1	762- 3000	0.917	996	1.22	6.13
		2	0	3.95	832		
●	Water-I ₂ - <i>n</i> -Hexane	1	762- 4760	0.894*	997*	1.25	49.1
		2	0- 4400	0.305*	655*		
▼	Water-I ₂ -Toluene	1	762- 4000	0.894*	997*	1.25	32.3
		2	0	0.552	862		
◆	Water-I ₂ -Decalin	1	762- 4760	0.894*	997*	1.25	38.2
		2	0- 1470	2.25	885		
◇	Water-I ₂ -MIBK	1	762- 3500	0.917	994	1.22	10.2
		2	0	0.580	797		
▣	Water-I ₂ -1,1,2,2-Tetrabromoethane	1	759- 4740	0.899	999	1.24	34.6
		2	0- 1730	8.38	2970		
△	Water-I ₂ -Chlorobenzene	1	761- 3800	0.896	998	1.25	25.0
		2	0- 4520	0.794	1130		
▲	25 wt% Sucrose solution-I ₂ - <i>n</i> -Hexane	1	762- 3810	2.09	1100	0.534	47.5
		2	1470	0.351	660		
▲	40 wt% Sucrose solution-I ₂ - <i>n</i> -Hexane	1	762- 1900	5.11	1180	0.219	45.6
		2	1470	0.352	660		
▲	50 wt% Sucrose solution-I ₂ - <i>n</i> -Hexane	1	762	12.3	1230	0.0910	44.7
		2	0- 4400	0.352	660		
▲	Water-Caproic acid- <i>n</i> -Hexane	1	762- 4760	0.912	998	0.765	49.1
		2	0- 4400	0.332	666		
○	Water-O ₂ - <i>n</i> -Hexane	1	762- 6280	0.894*	997*	2.41	49.1
		2	0-12100	0.305*	655*		
△	Water-H ₂ - <i>n</i> -Hexane	1	762- 4760	0.894*	997*	4.80	49.1
		2	0- 4400	0.305*	655*		
①	Water-Cyclohexanol-Cyclohexanol	1	691- 3120	0.986	998	0.656	3.33
		2	0- 180	17.5	955		
+	Water-O ₂ -N ₂	1	1520- 8570	0.894*	997*	2.41	71.8
		2	0	0.0178*	1.15		

* Refers to pure solvent.⁷⁾

Fig. 2. Effects of Reynolds numbers Re_1 and Re_2 on mass transfer coefficients k_1 .
Water- O_2 - n -hexane system.

reaction rate in extraction with chemical reaction does not always mean that the rate process is of the reaction-controlling or fast pseudo m -th order reaction kinetics.

2.2 Effect of first-phase viscosity

Figure 3 presents the experimental results for the extraction of I_2 from aqueous sucrose solutions into n -hexane. The concentration of sucrose varied from 0 to 50 wt%, corresponding to a 14-fold change of the first-phase viscosity μ_1 . The upper limit of Re_1 for stable operation was observed to decrease with increasing sucrose concentration. It may be seen that k_1 is proportional to $Re_1^{0.8}$, independently of sucrose concentration, and varies inversely as $1/3$ power of μ_1 , inclusive of the variation of diffusivity of I_2 with μ_1 .

2.3 Effect of second-phase viscosity

The second-phase viscosity was varied over a wide range by changing the composition of the mixed solvent of paraffin oil and n -hexane, the interfacial tension remaining substantially constant. In Fig. 4, k_1 is plotted for the transfer of I_2 from water into such mixed solvents, against the second-phase viscosity μ_2 . In case of $Re_2 = 0$, the effect of μ_2 on k_1 was examined over about a 60-fold change of μ_2 . The effect is negligible in the region of small values of μ_2 , while at larger values of μ_2 , the mass transfer coefficients k_1 decrease gradually with increasing of μ_2 . In the case of $Re_2 = 1470$, on the other hand, k_1 increases rapidly with μ_2 . The results for the water- I_2 -Decalin system with a similar interfacial tension are also shown in Fig. 4 and are in accordance with those for the above mixed solvents.

2.4 Effect of diffusivity

Caproic acid, I_2 , O_2 and H_2 were used as the solutes in the water- n -hexane system to examine the dependence of k_1 on the diffusivity of the solute D_1 . This effect is shown in Fig. 5. Apparently, k_1 is found to depend on the $2/3$ power of D_1 over a 6-fold change of diffusivity. This dependency accords well with that for

Fig. 3. Effect of first-phase viscosity μ_1 on mass transfer coefficients k_1 .
Aqueous sucrose solutions- I_2 - n -hexane system.

Fig. 4. Effect of second-phase viscosity μ_2 on mass transfer coefficients k_1 .

Fig. 5. Effect of diffusivity D_1 on mass transfer coefficients k_1 .
First phase, water; second phase, n -hexane.

the gas-liquid systems.⁶⁾

2.5 Effect of density difference

Figure 6 shows the effect of density difference on k_1 for the case of $Re_2 = 0$, which has been studied using I_2 as a solute and water as the first phase. The solvents for the second phase were chosen so that the interfacial tensions might be kept approximately constant, but their viscosities changed greatly from system to system. Therefore, when the dependence of k_1

Fig. 6. Effect of density difference $\Delta\rho$ on mass transfer coefficients k_1 .
First phase, water; solute, I_2 .

on the second-phase viscosity was substantial, as expected in the region of large viscosity in Fig. 4, a correction factor Φ , which will later be defined by Eq. (7), was introduced. The density difference evidently has little effect on k_1 over a 16-fold change of $|\Delta\rho|/\rho_1$.

2.6 Effect of interfacial tension

To investigate the effect of the interfacial tension σ , experiments on the extraction of I_2 from the water phase into various organic phases were performed. In the case of chlorobenzene, however, I_2 transferred in the reverse direction. The results are illustrated in Fig. 7 for the case of $Re_2=0$. The second-phase viscosity and density difference are substantially different from system to system, but are within a range of little dependence of k_1 , as demonstrated in Figs. 4 and 6. Thus, Fig. 7 may be considered to show the effect of σ . It reveals that k_1 is proportional approximately to $\sigma^{-0.5}$ over a variation of σ of about 12 times. The same dependency was observed also for the case of $Re_2 \neq 0$.

2.7 Correlation of experimental data

Owing to the complexity of the hydrodynamic conditions near the liquid-liquid interfaces, no theoretical approach is possible. Thus, the relation between the mass transfer coefficients and the relevant variables was obtained by conventional dimensional analysis.

Figure 2 indicates that Re_1 and Re_2 cannot be combined in the form of a product. Therefore, assuming the independent effects of Re_1 and Re_2 on the first-phase Sherwood number Sh_1 , we use the following type of expression³⁾ for correlation of the experimental data:

$$Sh_1^n = F_1^n + F_2^n \quad (2)$$

where

$$F_j = \alpha_j Re_1^{a_j} Mo_1^{b_j} Sc_1^{c_j} Ar_1^{d_j} (\mu_2/\mu_1)^{e_j} \times (\rho_2/\rho_1)^{f_j} (|\Delta\rho|/\rho_1)^{g_j} \quad (j=1,2) \quad (3)$$

Fig. 7. Effect of interfacial tension σ on mass transfer coefficients k_1 .
First phase, water; solute, I_2 .

$$\left. \begin{aligned} Sh_1 &= k_1 L / D_1, \quad Mo_1 = g \mu_1^4 |\Delta\rho| / \rho_1^2 \sigma^3 \\ Sc_1 &= \nu_1 / D_1, \quad Ar_1 = d^3 \rho_1 g |\Delta\rho| / \mu_1^2 \end{aligned} \right\} \quad (4)$$

The coefficients and exponents in Eqs. (2) and (3) were determined by the Simplex method. The subsequent arrangement leads to the following simple correlation in its final form:

$$Sh_1 = 0.0119 Sc_1^{1/3} Ca_1^{6/13} [\Phi^4 Re_1^3 + Re_2'^{8/3}]^{1/4} \quad (5)$$

where

$$\left. \begin{aligned} Ca_1 &= (Ar_1^2 Mo_1)^{1/3} \rho_1 / |\Delta\rho| = g d^2 \rho_1 / \sigma \\ Re_2' &= Re_2 \nu_2 / \nu_1 = d^2 N_2 / \nu_1 \end{aligned} \right\} \quad (6)$$

$$\left. \begin{aligned} \Phi &= 1 \quad \text{for } \mu_2/\mu_1 \leq 7.0 \\ \Phi &= (\mu_2/7\mu_1)^{-1/5} \quad \text{for } \mu_2/\mu_1 > 7.0 \end{aligned} \right\} \quad (7)$$

The ranges of dimensionless groups covered in this experiment are as follows:

$$\begin{aligned} 690 < Re_1 < 6300, \quad 0 < Re_2' < 7600, \\ 190 < Sc_1 < 1.1 \times 10^5, \quad 200 < Ca_1 < 5100, \\ 0.029 < \mu_2/\mu_1 < 36. \end{aligned}$$

Figure 8 shows a comparison of the values of Sh_1 obtained in the present work with those calculated from Eq. (5). The keys used are shown in Table 1. The observed values of Sh_1 are in reasonable agreement with the calculated ones, with an average deviation of 12.7% and a maximum deviation of about 30%. Then, 80% of all 193 data points fall within $\pm 20\%$ of Eq. (5). It is seen that the measured values of Sh_1 do not depend on whether the first phase, the rate-determining one, is in the upper or lower position.

As the effects of Re_1 and D_1 on k_1 are analogous to those for gas-liquid systems obtained in a similar vessel,⁶⁾ it may be expected that Eq. (5) is also applicable to the gas-liquid systems. To ascertain this, experiments on the desorption of O_2 from water into

Fig. 8. Correlation of present results.

the N_2 stream were made using the present vessel. The Sherwood numbers Sh_1 obtained for $Re'_2=0$ are shown in Fig. 8, and can be seen to fall within approximately the same limits of error as that for the liquid-liquid systems. This means that the term including Re_1 in Eq. (5) is very insensitive to the physical properties of the second phase. On the other hand, Sh_1 values in the gas-liquid systems for $Re'_2 \neq 0$, not shown in Fig. 8, are essentially the same as those for $Re'_2=0$, owing to the very weak shear stress at the interface. Thus, they cannot be correlated by Eq. (5). This suggests that the term including Re'_2 should generally be a function of the second-phase properties, even if it is a very weak function for the liquid-liquid systems.

The inclusion of Ca_1 is probably closely connected with the surface wave motion. It should be noted that apart from the inclusion of Ca_1 , the dependence of Sh_1 on Re_1 , Re'_2 and Sc_1 is analogous to that in the familiar correlations for turbulent mass transfer to a stationary or rotating rigid surface.

2.8 Comparison with previous correlations

Various empirical correlations for the mass transfer coefficients in agitated vessels with a flat interface, especially in the Lewis cell or in modified cells, have been proposed by several investigators.^{2,8-12)} Their correlations are shown in Table 2. Coefficients $\alpha_1, \alpha_2, \dots$ depend on the dimensions and the geometrical configuration of the vessel and of the agitator blade. The present vessel is so different in configuration and dimensions from those of the previous workers that it may be quite impractical to attempt a quantitative comparison of the mass transfer coefficients measured in the present work with the previous correlations. Thus, here the behavior of k_1 or Sh_1 with respect to the relevant variables is briefly compared.

The qualitative behavior of k_1 due to Re_1 and to

Re_2 , or Re'_2 shown in Fig. 2, might be expected from the correlations of McManamey *et al.*,^{11,12)} and Bulíčka and Procházka.²⁾ Nitsch and Kähni¹³⁾ also observed similar behavior. However, the exponents of Re_1 and Re'_2 by this work, $3/4$ and $2/3$ respectively, are significantly smaller than those by McManamey *et al.*, $3/2$ and $3/2$, and are comparable to the $3/4$ and $3/4$ by Bulíčka and Procházka.

The present experimental fact that k_1 at $Re'_2=0$ is independent of the second-phase viscosity μ_2 in the region of comparatively low viscosity and decreases gradually with high values of viscosity accords well only with the prediction from the correlation of Bulíčka and Procházka. On the other hand, the fact that there is no appreciable effect of μ_2 in the case of $Re_1 \ll Re'_2$ was also observed by Lewis and McManamey *et al.*

There has been a lack of agreement about the influence of molecular diffusion on the mass transfer process in agitated vessels. McManamey *et al.* based their correlation on the Levich model. Bulíčka and Procházka based theirs on the surface renewal model associated with the turbulent theory of Kolmogorov. Their correlations both involve the dependence of Sh_1 on $Sc_1^{1/2}$ as a natural consequence of their models. The other previous empirical correlations resulted in the effect of Sc_1 varying with the power of 1.0 to 0.63, indicating that k_1 is proportional to $D_1^0 - D_1^{0.37}$, which has no plausible theoretical basis. In these studies, however, few experiments have been carried out to test their validity directly. The values of D_1 were mainly varied by changing the viscosity of the liquids. The only exception was the experiments of McManamey *et al.*, in which the dependence of Sh_1 on $Sc_1^{0.36} - Sc_1^{0.53}$ was found by changing the solutes. The exponent of Sc_1 obtained in the present work, $1/3$, is smaller than any previous exponent.

The effect of the interfacial tension σ was taken into account only by McManamey *et al.*^{11,12)} in terms of the Levich approach. Their correlation yields the relations of $k_1 \propto \sigma^{-1/2}$ for $Ca_1 |\Delta\rho|/\rho_1 \ll 178$ and of $k_1 \propto \sigma^0$ for $Ca_1 |\Delta\rho|/\rho_1 \gg 178$. However, these relations appear not to have been experimentally verified. The present experimental evidence that the relation $k_1 \propto \sigma^{-6/13}$ holds for $Ca_1 |\Delta\rho|/\rho_1 \ll 178$ accords well with their model correlation. But it was difficult to choose systems to verify experimentally the lack of dependence of k_1 on σ for the opposite limit.

The density ratio ρ_2/ρ_1 appears in all previous correlations for given values of Re'_2 , but the variation of ρ_2/ρ_1 of less than 2.5 times in these studies is not great enough to accurately clarify the effect. The present study revealed no appreciable effect of ρ_2/ρ_1 on Sh_1 over a 5.5-fold change of density ratio. On the other hand, our experimental results support the lack of appreciable effect of density difference on Sh_1

Table 2. Previous correlations for mass transfer coefficient

Lewis ⁸⁾	$Sh_1 = \alpha_1 Sc_1 \left[\left(Re_1 + Re_2' \frac{\rho_2}{\rho_1} \right)^{1.65} + 1.48 \times 10^5 \right]$
McManamey ¹⁰⁾	$Sh_1 = \alpha_2 Sc_1^{0.63} Re_1^{0.9} \left(1 + \frac{Re_2' \rho_2}{Re_1 \rho_1} \right)$
Mayers ⁹⁾	$Sh_1 = \alpha_3 Sc_1^{5/6} (Re_1 Re_2)^{1/2} \left(\frac{\mu_2}{\mu_1} \right)^{1.9} \left(0.6 + \frac{\mu_2}{\mu_1} \right)^{-2.4}$
McManamey <i>et al.</i> ^{11,12)}	$Sh_1 = \alpha_4 \left[\frac{Sc_1}{Ar_1} \frac{Ca_1 \Delta\rho /\rho_1}{1 + 0.00562 Ca_1 \Delta\rho /\rho_1} (Re_1 + Re_2') \left(Re_1^2 + Re_2'^2 \frac{\rho_2}{\rho_1} \right) \right]^{1/2}$
Bulička and Procházka ²⁾	$Sh_1 = \alpha_5 Sc_1^{1/2} Re_1^{3/4} \left[\frac{1 + \left(\frac{Re_2'}{Re_1} \right)^3 \left(\frac{\mu_2 \rho_2}{\mu_1 \rho_1} \right)^{1/2}}{1 + \left(\frac{\mu_2}{\mu_1} \right)^{3/2} \left(\frac{\rho_1}{\rho_2} \right)^{1/2}} \right]^{1/4}$

indicated by the previous correlations.

The disagreement regarding the influence of various variables on the mass transfer coefficients among the correlations has been pointed out above. It may be partly attributed to the fact that the properties used for the previous correlations varied over a fairly narrow range. In fact, the previous correlative expressions are widely different, in spite of the fact that the majority of data used for the correlations, except in the work of Bulička and Procházka, is the same data, those of Lewis.

Conclusion

Liquid-liquid mass transfer in a very simple vessel with a flat interface was studied systematically over a wide range of physical properties. Measured mass transfer coefficients could be correlated with reasonable accuracy by Eq. (5). This correlation is not only useful in estimating the role of mass transfer in extraction with chemical reaction, but also gives important information about the transport phenomena in turbulent mass transfer across a liquid-liquid interface.

Nomenclature

Ar	= Archimedes number, $d^3 \rho g \Delta\rho /\mu^2$	[—]
$a_j, b_j, \dots$	= exponents	[—]
C	= concentration of solute	[kmol/m ³]
Ca	= Capillary number, $gd^2\rho/\sigma$	[—]
D	= diffusivity of solute	[m ² /s]
d	= diameter of stirrer blade	[m]
F_j	= function defined by Eq. (3)	[—]
g	= gravitational constant	[m/s ²]
k	= mass transfer coefficient	[m/s]
L	= diameter of vessel	[m]
Mo	= Morton number, $g\mu^4/ \Delta\rho \rho^2\sigma^3$	[—]
N	= agitation speed	[1/s]
n	= exponent	[—]
Re	= Reynolds number, d^2N/ν	[—]
Re_2'	= modified second-phase Reynolds number, d^2N_2/ν_1	[—]
S	= cross-sectional area of vessel	[m ²]

Sc	= Schmidt number, ν/D	[—]
Sh	= Sherwood number, kL/D	[—]
t	= time	[s]
V	= volume of liquid in vessel	[m ³]
α_j	= coefficients	[—]
$\Delta\rho$	= density difference, $\rho_1 - \rho_2$	[kg/m ³]
μ	= viscosity	[Pa·s]
ν	= kinematic viscosity, μ/ρ	[m ² /s]
ρ	= density	[kg/m ³]
σ	= interfacial tension	[N/m]
Φ	= correction factor defined by Eq. (7)	[—]

<Subscripts>

i	= interface
0	= initial
1	= first phase
2	= second phase

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