EXTRACTION RATES OF ZINC WITH AMMONIUM CHLORIDE SALTS OF AMBERLITE LA-2 IN A HORIZONTAL RECTANGULAR CHANNEL

FUMIYUKI NAKASHIO, KAZUO KONDO, YOSHINOBU KAWANO,
KATSUTOSHI INOUE AND HIROFUMI SATO

Department of Organic Synthesis, Kyushu University, Fukuoka 812

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Extraction rates of zinc with ammonium chloride salts of Amberlite LA-2 in hexane were measured in a horizontal rectangular channel. The experimental results were analyzed by considering the processes of diffusion in both solutions, adsorption and desorption to/from the interface and reactions at the interface for the species related as following steps;

The extraction rates of zinc was interpreted from the rate equation that the interfacial reaction between $(\text{BHCl})_2$ adsorbed at the interface and zinc chloride in the aqueous solution shown in step (2) is the rate-determining step. Some parameters of the rate equations were estimated.

Introduction

Solvent extraction of metals with high-molecular weight amines is now widespread in hydrometallurgy, and a large number of studies have been made. However, many of them were concerned with the distribution or aggregation of metal complexes formed.^{1,3,4,7,12)} Very few studies dealt with the extraction kinetics. Harada *et al.*⁵⁾ measured the extraction rates of ferric chloride with tri-*n*-octylamine in benzene using a stirred transfer cell, and concluded that the rate-controlling step of the extraction varied from reaction at the interface to diffusion of the species to the interface with increasing concentration of acid in the aqueous solution. Danesi *et al.* reported²⁾ the extraction rates of Cd(II) and Zn(II) through a liquid membrane consisting of triauryl ammonium chloride dissolved in trimethyl benzene impregnated in polypropylene film. In this system, the interfacial reaction rates were concluded to be faster than the diffusion rates of the species to the interface. One of the others⁸⁾ measured the extraction rate of zinc with ammonium chloride salt of Amberlite LA-2 in *n*-hexane by a single-drop method, and concluded that

the extraction rate is affected by the interfacial reaction rate between dimer of the ammonium chloride salt in the organic solution and chloro-zinc complex in the aqueous solution. However, detailed interfacial processes for related species were not examined in the analysis.

In the extraction of metals with ammonium chloride salts, the salts are likely to react with chloro-complex of the metal at the interface, because the salts and the complexes formed have very low solubilities in the aqueous solution. The interfacial kinetics of these species plays a significant role in the extraction rate of the metal. So it is necessary to define the interfacial conditions in analyzing the mass transfer rates. In the previous work,⁸⁾ using a single-drop method, the flow pattern inside and outside the drop made difficult the analysis of experimental results. In the present work, the extraction rate of zinc in acidic aqueous solution with ammonium chloride salt of Amberlite LA-2 (hereafter called ammonium salt) in *n*-hexane solution was measured by using a horizontal rectangular channel through which the aqueous and the organic solutions flow laminarily. The results were analyzed by considering the diffusion of the species from bulk solution to interface, the adsorption at the interface and the resulting reaction.

Received March 28, 1988. Correspondence concerning this article should be addressed to F. Nakashio. Y. Kawano is at Faculty of Eng., Miyazaki Univ., Miyazaki 889-21. K. Inoue is at Dept. Ind. Chem., Saga Univ., Saga 840. H. Sato is at Honsyu Paper Co. Ltd., Shiga 520-32.

1. Experimental Procedure

1.1 Reagents

Amberlite LA-2 (hereafter called amine) in *n*-hexane with a concentration of 1 mol/dm³ was washed alternately with 1 mol/dm³ hydrochloric acid and deionized water several times to remove water-soluble impurities,¹¹⁾ and then with an excess amount of hydrochloric acid to transform the amine into the ammonium salt. The solution was diluted with *n*-hexane to a required concentration. The aqueous zinc chloride solution was prepared by dissolving zinc chloride in aqueous sodium chloride solution containing a small amount of hydrochloric acid. In these procedures, hydrochloric acid, zinc chloride, sodium chloride and *n*-hexane of GR grade were used without further purifications.

1.2 Measurement of interfacial tension

n-Hexane solution of the ammonium salt of various concentrations were equilibrated with an excess amount of acidic zinc chloride aqueous solution. The interfacial tensions of these solutions were measured by drop-weight method.¹³⁾

1.3 Extraction rates of zinc in a horizontal rectangular channel

The experimental apparatus was the same as that shown in the previous paper.⁹⁾ The same type of rectangular channel described previously⁹⁾ was kept horizontal in an air bath at 30.0°C. Aqueous solution of zinc chloride and *n*-hexane solution of the ammonium salt were introduced into the cell through separate inlet, and contacted with each other at the end of a highly polished separating plate. Both solutions flowed laminary in the cell and were discharged separately from each outlet. The interface between the two solutions was kept at the height of half of the cell by each level controller during the runs. The concentration of zinc in the aqueous solution was measured by atomic absorption spectrophotometry. The concentration of the amine was determined by titration with hydrochloric acid in methanol-butanol mixed solution using bromocresol-green as an indicator.

2. Experimental Results

2.1 Interfacial adsorption equilibrium

As shown in the previous paper,⁶⁾ the ammonium salt (BHCl) and its dimer (BHCl)₂ are adsorbed at the interface, and the adsorption equilibrium constants K_{a01} and K_{a02} were obtained for monomer and dimer, respectively, as shown in Table 1. In the present work, to elucidate the adsorption equilibrium of zinc complexes formed in the organic solution, the interfacial tension of the solution involving the complexes was measured. Under the experimental conditions, the ammonium salts are converted to two

Table 1. Equilibrium constants and interfacial area occupied by the complex formed

[dm ³ /mol]			[cm ² /mol]	
$K_{a01}^{(6)}$	$K_{a02}^{(6)}$	K_{a12}	$K_{12}^{(10)}$	S_{12}
9.65×10^5	7.06×10^4	2.72×10^8	8.10	1.72×10^{10}

Fig. 1. Relation between interfacial tension and concentration of monomer of zinc ammonium chloride complex in the organic solution

kinds of complexes, (BH)₂ZnCl₄ and its dimer ((BH)₂ZnCl₄)₂, in the organic solution. However, in the range of C_{Znt} smaller than 10⁻³ mol/dm³ the formation of dimer is negligibly small compared with that of monomer.¹⁰⁾ So the interfacial tension, γ , is plotted against monomer concentration of the ammonium salt in the organic solution, C_{Znm} , in Fig. 1. Assuming that only monomer is adsorbed at the interface, the following interfacial adsorption equilibrium holds.

$$K_{a12} = \theta_{12} / \{C_{12}(1 - \theta)\} \quad (2)$$

where K_{a12} and C_{12} are the adsorption equilibrium constant and concentration in the organic solution of (BH)₂ZnCl₄, respectively, and θ_{12} is a fraction of the interfacial area occupied by (BH)₂ZnCl₄. The relation between the interfacial tension and the equilibrium concentration is given as follows;

$$d\gamma = RT \sum_{i=1}^n \{ \Gamma_i d \ln(C_i) \} \quad (i = 1, 2, \dots) \quad (3)$$

where Γ_i is an interfacial excess of solute expressed by θ_i/S_i , and S_i is an interfacial area occupied by unit mole of the species i adsorbed. The values of K_{a12} and S_{12} were estimated as shown in Table 1 by using Eqs. (2) and (3) and the experimental data. The solid line in Fig. 1 is the result calculated by using these values. Close agreement between observed and calculated values was obtained. As mentioned above, in the range of C_{Znm} greater than 10⁻³ mol/dm³ the formation of dimer cannot be neglected. However, the results of Fig. 1 suggest that adsorption of dimer is negligibly

small compared with that of monomer. Therefore, the adsorption behavior shown in Fig. 1 is interpreted by the adsorption of only one species, $(\text{BH})_2\text{ZnCl}_4$.

2.2 Extraction rates of zinc in a horizontal rectangular channel

The results of the extraction rates of zinc are shown in Fig. 2. The dimensionless extraction rate, Sh , is plotted against $\alpha\sqrt{\beta}$ for various concentrations of chloride ion at constant ammonium chloride salt concentration. Sh is defined by $(\Delta C_{At}/C_{At}^0)(\bar{u}_A h^2/D_A x)$ and α and β are respectively a dimensionless concentration, (C_{At}^0/C_{Bt}^0) , and a dimensionless diffusivity, (D_A/D_B) . The observed Sh value increased with concentration of chloride ion in the aqueous solution, and decreased with an increase in the value of $\alpha\sqrt{\beta}$. The dotted line in Fig. 2 is the calculated result by assuming that the equilibrium of the reaction between the ammonium salt and zinc chloride is attained immediately at the interface. Sh values on the dotted line are independent of chloride ion concentration, and are greater than those obtained experimentally. The results suggest that the rate of reaction at the interface is smaller than that of mass transfer from bulk phase to interface. The experimental results for various ammonium salt concentrations are shown as plots of Sh against $\alpha\sqrt{\beta}$ in Fig. 3. Under the condition, Sh values depend on ammonium salt concentration. Sh values when reaction equilibrium is attained at the interface were also calculated. Shown by the dotted line in Fig. 2, they were found to be larger than the experimental values. From the results above, the extraction rate of zinc in the horizontal rectangular channel may be affected by both the rate of reaction at the interface and the mass transfer from bulk phase to interface.

3. Analysis and Discussion

3.1 Equation of diffusion accompanied by interfacial reaction

Zinc chloride in the aqueous solution reacts with the ammonium salt at the interface to form the complex $(\text{BH})_2\text{ZnCl}_4$ by the following reactions:

In the organic phase, the species $(\text{BH})_2\text{ZnCl}_4$ dimerized itself to form $((\text{BH})_2\text{ZnCl}_4)_2$ and/or reacted with $(\text{BHCl})_2$ to form $(\text{BH})_4\text{ZnCl}_6$ as:¹⁰⁾

Under the experimental conditions, trimer and tetramer of the ammonium chloride salt can be ignored

Fig. 2. Plots of Sh values against $\alpha\sqrt{\beta}$ at constant C_{Bt}^0 for various C_{Cl-} .

Fig. 3. Plots of Sh values against $\alpha\sqrt{\beta}$ at constant C_{Cl-} for various C_{Bt}^0 .

compared with monomer and dimer of the salt.¹⁰⁾ As shown in the experimental results, all reactions taking place in the bulk phases are assumed to be equilibrated each other. The concentration of total unreacted ammonium salt, C_{Bt} , and total complexes formed, C_{St} , in the organic solution are given as follows:

$$C_{Bt} = C_{01} + 2C_{02} = C_{01} + 2K_{02}C_{01}^2 \quad (7)$$

$$C_{St} = C_{12} + C_{24} + C_{14} = C_{12} + K_{24}C_{12}^2 + K_{12}C_{02}C_{12} \quad (8)$$

where K_{ij} are equilibrium constants given in the previous paper,¹⁰⁾ and C_{ij} are the concentrations of $(\text{ZnCl}_n)_i(\text{BHCl})_j$ species.

To simplify the calculations, it is assumed that: (a) diffusion coefficients of the ammonium salts in the organic solution are identical to each other ($=D_B$); (b) diffusion coefficients of the complexes formed in the organic solution are identical to each other ($=D_S$); and (c) diffusion coefficients of chloro zinc complexes in the aqueous solution are identical to each other ($=D_A$). Under these conditions, mass balance equations for total unreacted ammonium salt, total complexes formed in the organic solution and total

zinc in the aqueous solution are written as follows:

$$u_B(\partial C_{Bt}/\partial x) = D_B(\partial^2 C_{Bt}/\partial y^2) \quad (0 < y < h) \quad (9)$$

$$u_B(\partial C_{St}/\partial x) = D_S(\partial^2 C_{St}/\partial y^2) \quad (0 < y < h) \quad (10)$$

$$u_A(\partial C_{At}/\partial x) = D_A(\partial^2 C_{At}/\partial y^2) \quad (-h < y < 0) \quad (11)$$

[B.C]

$$x < 0; 0 < y < h; C_{Bt} = C_{Bt}^o \quad (12)$$

$$; C_{St} = 0 \quad (13)$$

$$-h < y < 0; C_{At} = C_{At}^o \quad (14)$$

$$x > 0; y = 0; D_B(\partial C_{Bt}/\partial y) = -R_{Bt} \quad (15)$$

$$D_S(\partial C_{St}/\partial y) = -R_{St} \quad (16)$$

$$D_A(\partial C_{At}/\partial y) = R_{At} \quad (17)$$

$$y = h; (\partial C_{Bt}/\partial y) = 0 \quad (18)$$

$$(\partial C_{St}/\partial y) = 0 \quad (19)$$

$$y = -h; (\partial C_{At}/\partial y) = 0 \quad (20)$$

where x is the horizontal distance from the contact point of the two solutions, y is the perpendicular distance from the interface between the two solutions, and h is the height of each solution, while u_A and u_B are the linear velocities of the aqueous and the organic solutions, respectively, and are functions of y defined by the laminar flow pattern. R_{At} , R_{Bt} and R_{St} are the interfacial reaction rates for total zinc, total ammonium salts and total complexes formed. In the equations above, the following dimensionless terms can be defined;

$$\eta = D_A x / \bar{u}_A h^2, \quad \xi = y/h, \quad a = C_{At}/C_{At}^o,$$

$$b = C_{Bt}/C_{Bt}^o, \quad s = C_{St}/C_{Bt}^o$$

$$\alpha = C_{At}^o/C_{Bt}^o, \quad \beta = D_A/D_B, \quad \beta_s = D_S/D_B,$$

$$\gamma = \bar{u}_A/\bar{u}_B, \quad u_A^* = u_A/\bar{u}_A, \quad u_B^* = u_B/\bar{u}_B$$

where $\bar{u}_A$ and $\bar{u}_B$ are the average linear velocities of each solution. Substituting these dimensionless terms into the fundamental equations above, Eqs. (9) to (20), give the following dimensionless equations:

$$u_B^*(\partial b/\partial \eta) = (\gamma/\beta)(\partial^2 b/\partial \xi^2) \quad (0 < \xi < 1) \quad (21)$$

$$u_B^*(\partial s/\partial \eta) = (\gamma \cdot \beta_s/\beta)(\partial^2 s/\partial \xi^2) \quad (0 < \xi < 1) \quad (22)$$

$$u_A^*(\partial a/\partial \eta) = (\partial^2 a/\partial \xi^2) \quad (-1 < \xi < 0) \quad (23)$$

[B.C]

$$\eta < 0; 0 < \xi < 1; b = 1 \quad (24)$$

$$s = 0 \quad (25)$$

$$-1 < \xi < 0; a = 1 \quad (26)$$

$$\eta > 0; \xi = 0; (\partial b/\partial \xi) = -(M \cdot R_{Bt}) \quad (27)$$

$$(\partial s/\partial \xi) = -(M \cdot R_{St})/\beta \quad (28)$$

Fig. 4. Interfacial transfer scheme

$$(\partial a/\partial \xi) = (M \cdot R_{At})/\beta \quad (29)$$

$$\eta > 0; \xi = 1; (\partial b/\partial \xi) = 0 \quad (30)$$

$$(\partial s/\partial \xi) = 0 \quad (31)$$

$$\varepsilon = -1; (\partial a/\partial \xi) = 0 \quad (32)$$

Eqs. (21)–(23) are numerically solved using the boundary conditions, if given, to obtain the dimensionless average extraction rate, Sh , defined by the following equation:

$$Sh = \frac{D_A x}{\bar{u}_A h^2} \int_{-1}^0 \{1 - a(\xi, \eta)\} d\xi \quad (33)$$

The Sh value calculated by Eq. (33) depends on C_{Bt}^o and the interfacial reaction rate and also on the constants, M , α , β and β_s . As these constants are fixed by the experimental conditions, the relation among Sh , C_{Bt}^o and $\alpha\sqrt{\beta}$ will depend only on the interfacial reaction rate.

3.2 Interfacial reaction rate

The reaction is assumed to proceed through the following steps:

- (1) adsorption of $(BHCl)_2$ to the interface (step 1)
- (2) reaction between $(BHCl)_2$ adsorbed and $ZnCl_4^{-(i-2)}$ in the aqueous solution (step 2)
- (3) desorption of formed $(BH)_2ZnCl_4$ from the interface (step 3), as shown in Fig. 4;

The interfacial reaction rate is determined by the rate of reaction expressed by Eqs. (34)–(36). In the case that each reaction step is a rate-controlling one, the interfacial reaction rate for total zinc was obtained by using an approximation method; that is, all steps except the rate-controlling one always attain equilibrium, and are shown in Table 2. In these equations, K_{12} is defined by the following equation with equilibrium concentrations, and was estimated previously¹⁰⁾ as shown in Table 1.

$$K_{12} = C_{12e}/(C_{Ate}C_{02e}) \quad (44)$$

Interfacial rate equations in which step 1 or step 3

Table 2. Interfacial reaction rate equations in cases where each step of Eqs. (34)–(36) is a rate-determining step

Step	Interfacial reaction rate equation
Eq. (34)	$R_{d12} = k_{d12} \{C_{02} - C_{12}/(K_{12}C_{At})\}(1-\theta) \quad (37)$ $(1-\theta) = 1/[1 + K_{a01}C_{01} + C_{12}(K_{a02}/K_{12}C_{At}) + C_{12}K_{a12}] \quad (38)$
Eq. (35)	$R_{d12} = k_{d12} \{C_{02}C_{At} - C_{12}/K_{12}\}(1-\theta) \quad (39)$ $(1-\theta) = 1/[1 + K_{a01}C_{01} + K_{a02}C_{02} + C_{02}C_{At}(K_{12}K_{a12})] \quad (40)$
Eq. (36)	$R_{r12} = k_{r12}g_1(\text{Cl}^-)\{C_{02}C_{At} - C_{12}/K_{12}\}(1-\theta) \quad (41)$ $(1-\theta) = 1/[1 + K_{a01}C_{01} + K_{a02}C_{02} + K_{a12}C_{12}] \quad (42)$ $g_1(\text{Cl}^-) = \beta_1[\text{Cl}^-]^i / \left\{ 1 + \sum_{j=1}^4 (\beta_j[\text{Cl}^-]^j) \right\} \quad (43)$

is a rate-determining one are independent of chloride-ion concentration in the aqueous solution. As shown in Fig. 2, the extraction rates of zinc depend markedly on chloride-ion concentration in the aqueous solution. From these interfacial reaction rates it is difficult to interpret the experimental results of the extraction rate of zinc. The interfacial reaction rate defined by Eq. (41) depends on chloride ion concentration in the aqueous solution, and has a dependency of the extraction rate on chloride ion concentration similar to that of the experimental results. The formation rates of total zinc, R_{At} , total ammonium salt, R_{Bt} , and total complexes R_{St} , are expressed by the following equations:

$$-R_{At} = R_{12} + 2R_{24} + R_{14} = R_{r12} \quad (45)$$

$$-R_{Bt} = 2R_{12} + 4R_{24} + 4R_{14} = 2R_{r12} + 2R_{14} \quad (46)$$

$$R_{St} = R_{12} + R_{24} + R_{14} = R_{r12} - R_{24} \quad (47)$$

where R_{12} , R_{24} and R_{14} are the formation rates of the complexes of $(\text{BH})_2\text{ZnCl}_4$, $(\text{BH})_2\text{ZnCl}_4)_2$ and $(\text{BH})_4\text{ZnCl}_6$, respectively. Concentrations of these complexes are expressed as a function of C_{Bt} and C_{St} using Eqs. (7) and (8). Then R_{24} and R_{14} are written as follows:

$$R_{24} = g_{24B} \cdot R_{Bt} + g_{24S} \cdot R_{St} \quad (48)$$

$$R_{14} = g_{14B} \cdot R_{Bt} + g_{14S} \cdot R_{St} \quad (49)$$

where $g_{ijB} = (\partial C_{ij}/\partial C_{Bt})$ and $g_{ijS} = (\partial C_{ij}/\partial C_{St})$. Solving Eqs. (46) to (49) gives

$$R_{Bt} = \frac{2(g_{14S} + g_{24S} + 1)R_{r12}}{2g_{24B}g_{14S} - (2g_{14B} + 1)(g_{24S} + 1)} \quad (50)$$

$$R_{St} = \frac{R_{r12} - g_{24B}R_{Bt}}{(1 + g_{24S})} \quad (51)$$

At the interface, both species ZnCl_2 and ZnCl_3^- react with the adsorbed ammonium salts, $(\text{BHCl})_2$, according to Eq. (35). Then the interfacial reaction rate for total zinc chloride is given by the summation of reaction rates of each chloro-zinc complex as follows:

$$R_{r12} = \{k'_{r12}g_2(\text{Cl}^-) + k''_{r12}g_3(\text{Cl}^-)\} \times \{C_{02}C_{At} - C_{12}/K_{12}\}(1-\theta) \quad (52)$$

3.3 Comparison of experimental results and calculated results

By utilizing Eqs. (45), (50) and (51) along with Eq. (52), the fundamental equations of mass balances, Eqs. (21)–(23), were solved numerically to obtain the concentration distribution for total chloro-zinc complexes in the aqueous solution at $\eta = \eta_L$. The dimensionless extraction rate constant, Sh , for various values of k'_{r12} and k''_{r12} was calculated by Eq. (33) using the concentration distributions of total chloro-zinc complexes. To check the fit between the results calculated by the above model and the experimental ones, the standard deviations, SD , for Sh values were calculated for all experimental conditions by the following equation;

$$SD = \sqrt{\sum_{i=1}^N \{(Sh_{i,exp} - Sh_{i,cal})/Sh_{i,cal}\}^2 / N} \quad (53)$$

where $Sh_{i,exp}$ and $Sh_{i,cal}$ are the experimental and the calculated Sh values respectively. The minimum value of SD ($=0.21$) was obtained at $k'_{r12} = 2.5 \times 10^7 \text{ cm}^4 \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$ and $k''_{r12} = 2.1 \times 10^6 \text{ cm}^4 \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$. The solid lines in Figs. 2 and 3 are the calculated results using the reaction rate constants above. These solid lines agreed well with the experimental values obtained under various conditions. The interfacial reaction rate depends on the values of $k'_{r12}g_2(\text{Cl})$ and $k''_{r12}g_3(\text{Cl})$ for the reactions of ZnCl_2 and ZnCl_3^- species. The ratio of these values varied from 0.11 to 1.1 with an increase in $[\text{Cl}]$ under the experimental conditions. This result indicates that the contribution of ZnCl_3^- species on the interfacial reaction can be ignored at low $[\text{Cl}]$, but both reactions with ZnCl_2 and ZnCl_3^- species must be accounted for the analysis of the extraction rate of zinc in the aqueous solution in the high $[\text{Cl}]$ range. In the previous paper,⁸⁾ the effect of the interfacial adsorption of the related species on the kinetics was not considered in the analysis. That is, the term $\{k'_{r12}g_2(\text{Cl}) + k''_{r12}g_3(\text{Cl})\}(1-\theta)$ in Eq. (52) was assumed to be constant. The rate equation shown in the previous paper cannot be used to interpret the experimental results in this work. In the present work, the interfacial mass transfer rate was analyzed by considering the rate and/or equilibrium of interfacial processes such as adsorption, desorption and reaction at the interface. The rate of reaction

between $(\text{BHCl})_2$ adsorbed and chloro-zinc complexes in the aqueous solution was found to be smaller than those of adsorption of $(\text{BHCl})_2$ at the interface and of desorption of zinc-ammonium chloride salt complex from the interface. The interfacial reaction rate was derived as a function of parameters with respect to adsorption and desorption. This point is different from the previous paper.⁸⁾

Conclusion

The extraction rates of zinc with the ammonium chloride salts of Amberlite LA-2 were measured in a horizontal rectangular channel at 30.0°C. The results were analyzed by considering the processes of diffusion in the solution, adsorption and desorption of the species at the interface and reaction at the interface. It was found that the extraction rates of zinc are controlled by the interfacial reaction rates between the ammonium chloride salt adsorbed at the interface and chloro-zinc complex in the aqueous solution. The rate constants of the interfacial reactions were obtained.

Nomenclature

a	= dimensionless concentration defined by (C_{At}/C_{At}^0)	[—]
b	= dimensionless concentration defined by (C_{Bt}/C_{Bt}^0)	[—]
C_{ij}	= concentration of species A_iB_j	[mol/dm ³]
C_{ije}	= equilibrium concentration of species A_iB_j	[mol/dm ³]
D	= diffusion coefficient	[cm ² /sec]
h	= height of solution	[cm]
Gz	= Graetz number defined by $(\bar{u}_A h^2 / D_A x)$	[—]
K_{ij}	= equilibrium constants	[dm ³ /mol]
K_{aij}	= adsorption equilibrium constant of species A_iB_j	[dm ³ /mol]
k	= reaction rate constant	[(cm ⁴ /mol)/sec]
R	= reaction rate	[mol/cm ² ·sec]
S	= interfacial area occupied by unit mole	

	of the species	[cm ² /mol]
s	= dimensionless concentration defined by (C_{St}/C_{Bt}^0)	[—]
Sh	= Sherwood number defined by $((\Delta C_{At}/C_{At}^0)Gz)$	[—]
u	= linear velocity of solution	[cm/sec]
$\bar{u}$	= average linear velocity of solution	[cm/sec]
x	= horizontal distance from contact point	[cm]
y	= perpendicular distance from interface	[cm]
α	= (C_{At}^0/C_{Bt}^0)	[—]
β	= (D_A/D_B)	[—]
θ	= fraction of vacant active site	[—]
γ	= $(\bar{u}_A/\bar{u}_B)$	[—]
Γ	= interfacial excess of solute	[mol/cm ²]
η	= $(D_A x / \bar{u}_A h^2)$	[—]
ξ	= (y/h)	[—]

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