CHEMICAL ABSORPTION INTO SLURRY IN WETTED-WALL COLUMN

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The rate of absorption into a slurry absorbent under various conditions should be predicted to obtain a rational method for design of a three-phase reactor or an absorber.

We have proposed a model for chemical absorption into a slurry which has a large gas-liquid interfacial area.[3] It was shown in the previous paper[3] that the rate of absorption into a slurry in a gas-sparged stirred vessel with a gas-liquid interfacial area in the range from 10 to $70\,m^{-1}$ was predicted well by the present model, and that the model of Sada and Kumazawa[4] could be applied to predict the absorption rate if the dimensionless parameter, N, is greater than the value of s_1rq.

In the present paper, experimental data on the chemical absorption rate in a wetted-wall column having a gas-liquid interfacial area in the range from 2×10^3 to $5 \times 10^3\,m^{-1}$, were compared with the absorption rate predicted by the present model.

1. Application of Film Theory Model to Absorption into the Falling Film of a Slurry Absorbent

The falling film of a slurry was assumed to be partitioned into equal-sized small compartments of length Δz from the top toward the bottom of the column. The film theory model presented in the previous paper[3] was applied to these small compartments. Taking into account the mass balance for the solute gas, A, and the reactant, B, dissolved from solid particles in the i-th and the $(i-1)$-th compartments, the boundary conditions in the bulk phase of the slurry absorbent were modified as follows.

$$X=1: \quad -dC_A^i/dX=(M/s_2)C_A^iC_B^i+\beta_A\{N/(s_1r)\}C_A^i$$
$$+R(C_A^i-C_A^{i-1}) \qquad (1)$$

$$-dC_B^i/dX+(\beta_BN/s_1)(1-C_B^i)$$
$$=(Mrq/s_2)C_A^iC_B^i+Rr(C_B^i-C_B^{i-1}) \qquad (2)$$

The concentration of solid particles in the i-th compartment is related to that the $(i-1)$-th compartment by the following equation.

$$c_S^i=c_S^{i-1}+\{Q_L(c_A^i-c_A^{i-1})+(Q_L/v)(c_B^{i-1}-c_B^i)$$
$$-\phi^ik_Lc_{Ai}\pi D_T\Delta z\}\{100M_Wv/(\rho Q_Lv')\} \qquad (3)$$

where ϕ^i is the modified enhancement factor in the i-th compartment defined by the following equation.

$$\phi^i=-(dC_A^i/dX)_{x=0} \qquad (4)$$

Using Eqs. (1)–(4) and the film theory model presented in the previous paper[3], solid concentrations in each compartment are calculated successively in the direction of flow of the slurry film. Hence solid concentration, c_{S1}, solute gas concentration, c_{A1} and concentration of reactant dissolved from the solid particles, c_{B1}, at the bottom of the column are obtained numerically. The average value of the modified enhancement factor, ϕ, is obtained by the following equation.

$$\phi k_Lc_{Ai}\pi D_TZ_T=(c_{S2}-c_{S1})\rho Q_Lv'/(100M_Wv)$$
$$+Q_Lc_{Ai}+(Q_L/v)(c_{BS}-c_{B1}) \qquad (5)$$

2. Experimental

Wetted-wall columns of Pyrex glass tubes of 0.5 and 1.0 m in length with inner diameter of 12 mm were used as absorber.

Absorbents from the reservoir tank were fed into the top of the wetted-wall column after measuring the flow rate by a venturi tube flow meter and were allowed to fall vertically along the inside wall of the wetted-wall column.

The absorption rates were obtained from the difference in flow rates of the effluent and the influent solute gas, pure CO_2.

Tap water, $CaCO_3$–water slurry and $Ca(OH)_2$–water slurry were used as absorbents. The average diameters of the particles of $CaCO_3$ and $Ca(OH)_2$ were 15.7 μm and 25.9 μm, respectively.

Experimental conditions are summarized in Table 1.

3. Experimental Results and Discussion

An empirical equation for liquid-side mass transfer coefficients was obtained by the method of Fujita et al.[2]. H_L/Z_T was correlated with $1/P$ by Eqs. (6) and (7).

$$Z_T=0.5\,\mathrm{m}: \quad H_L/Z_T=0.113(1/P)^{0.815} \qquad (6)$$

Table 1. Experimental conditions

Height of wetted-wall section (Z_T) : 0.5, 1.0 m
Inner diameter of wetted wall column : 12 mm
Absorbent : Tap water,
      0.2–0.5 wt%$CaCO_3$-water slurry,
      0.2–0.5 wt% $Ca(OH)_2$-water slurry
Solute gas : pure CO_2
Volumetric flow rate of absorbents (Q_L) :
      $1.5\times10^{-6}-9\times10^{-6}\,\mathrm{m}^3/\mathrm{s}$
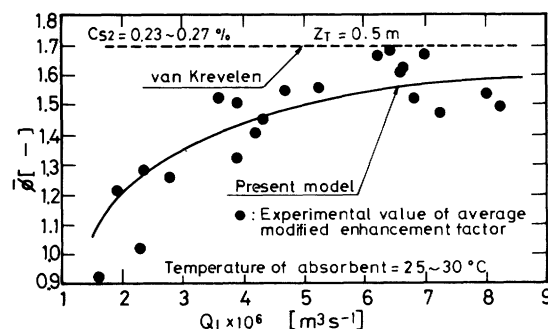Temperature of absorbents : 15–30°C

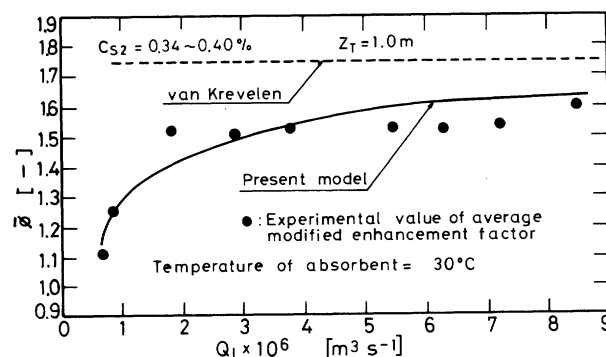**Fig. 1.** Comparison of experimental and calculated values for average modified enhancement factor

Fig. 2. Comparison of experimental and calculated values for average modified enhancement factor

$$Z_T=1.0\,\mathrm{m}: \quad H_L/Z_T=0.300(1/P)^{0.674} \qquad (7)$$

Experimental values of the modified average enhancement factor were obtained as the ratio of the observed absorption rate to $k_La\,c_{Ai}$, where k_L, a and c_{Ai} are liquid-side mass transfer coefficient, gas-liquid interfacial area and saturated concentration of solute gas respectively. The gas-liquid interfacial area can be equal to $1/l$, where l is the thickness of falling liquid film.

$$a=1/l \qquad (8)$$

$$l=\{(3\mu_L\Gamma)/(\rho_L^2g)\}^{1/3} \qquad (9)$$

Examples of the experimental values of the average modified enhancement factor are plotted against the feed rate of slurry absorbent in **Figs. 1** and **2**. Comparison of the experimental values with the values predicted by the present model is also made in

Table 2. Physical properties required for calculation of the modified enhancement factor

Physical property	Temperature [°C]		
	15	25	30
Solubility of $Ca(OH)_2$ [mol dm^{-3}] $\times 10^2$	2.44	2.29	2.16
Solubility of CO_2 into absorbent c_{Ai} [mol dm^{-3}] $\times 10^2$	4.37	3.26	2.81
Diffusivity of CO_2 $\mathscr{D}_A$ [m^{2}s^{-1}] $\times 10^9$	1.41	1.81	2.04
Diffusivity of OH$^-$ $\mathscr{D}_B$ [m^{2}s^{-1}] $\times 10^9$	1.38	1.83	2.08
Reaction rate constant k_r [mol^{-1}dm^{3}s^{-1}] $\times 10^{-3}$	4.05	8.77	12.6

these figures.

Physical properties required to calculate the modified enhancement factor are summarized in **Table 2**. For the solid-liquid mass transfer coefficient, the values predicted by the equation of Asai et al.[1] were used.

As shown in Figs. 1 and 2, in the region of relatively high feed rate of the slurry absorbent the experimental values approach those of the present model and the model of van Krevelen et al.[5]. In the region of relatively low feed rate of the slurry absorbent, where the value of N becomes less than the value of $s_1 rq$ and the boundary condition, $x = \delta_L : c_A = 0$, becomes inconsistent, the present model agrees well with the experimental results.

Conclusion

A model for absorption into a slurry absorbent was proposed on the basis of film theory, taking into account the finite volume of absorbent and the finite rate of reaction between the solute gas and the dissolved solid species both in the film at the gas-liquid interface and in the bulk of a slurry absorbent.

Experimental values of the absorption rate obtained in a wetted-wall column agreed well with the values predicted by the present model over the whole range of feed rate of absorbent under the present experimental condition.

Nomenclature

a	= gas-liquid interfacial area per volume of absorbent	[m^2/m^3]
A_P	= solid-liquid interfacial area per volume of absorbent	[m^2/m^3]
C_A	= dimensionless concentration of the solute gas, A, defined as c_A/c_{Ai}	[—]
C_B	= dimensionless concentration of the reactant, B, dissolved from the solid particles, defined as c_B/c_{BS}	[—]
c_A	= concentration of solute gas, A, in liquid phase	[kmol/m^3]
c_{Ai}	= concentration of solute gas, A, at the gas-liquid interface	[kmol/m^3]
c_B	= concentration of the reactant, B, dissolved from the solid particles	[kmol/m^3]
c_{B1}	= concentration of the reactant, B, at bottom of wetted-wall column	[kmol/m^3]
c_{BS}	= concentration of the reactant, B, at solid-liquid interface	[kmol/m^3]
c_S	= solid concentration in the slurry absorbent	[wt%]
c_{S1}	= solid concentration in the slurry absorbent at the bottom of wetted-wall column	[wt%]
c_{S2}	= solid concentration in the slurry absorbent at the top of wetted-wall column	[wt%]
$\mathscr{D}_A$	= diffusivity of solute gas in liquid phase	[m^2/s]
$\mathscr{D}_B$	= diffusivity of reactant, B, in liquid phase	[m^2/s]
D_T	= inner diameter of wetted-wall column	[m]
g	= acceleration of gravity	[m/s^2]
H_L	= HTU defined as $\Gamma/\rho k_L$	[m]
k_L	= liquid-phase mass transfer coefficient for gas-liquid interface	[m/s]
k_r	= reaction rate constant for the second-order reaction	[m^{3}s^{-1}kmol^{-1}]
k_s	= mass transfer coefficient for solid particle dissolution	[m/s]
M	= dimensionless parameter defined as $k_r c_{BS} \delta_L^2/\mathscr{D}_A$	[—]
M_w	= molecular weight of solid particle	[kg/kmol]
N	= dimensionless parameter defined as $k_s A_P \delta_L^2/\mathscr{D}_B$	[—]
P	= dimensionless number defined as $(1/0.341)(4\Gamma/\mu)^{-4/3} Sc^{-1} (\mu^2/\rho^2 g Z_T^3)^{-1/3}$	[—]
Q_L	= volumetric feed rate of absorbent	[m^3/s]
q	= dimensionless parameter defined as $v c_{Ai}/c_{Bs}$	[—]
R	= dimensionless parameter defined as $Q_L \delta_L/(\pi D_T \Delta z \mathscr{D}_A)$	[—]
r	= dimensionless parameter defined as $\mathscr{D}_A/\mathscr{D}_B$	[—]
s_1	= dimensionless parameter defined as $a\delta_L$	[—]
s_2	= dimensionless parameter defined as $a\delta_L/(1 - a\delta_L - A_P \delta_S - \varepsilon_P)$	[—]
X	= dimensionless coordinates defined as x/δ_L	[—]
x	= coordinates perpendicular to the axis of wetted-wall column	[m]
Y	= dimensionless coordinates defined as y/δ_S	[—]
y	= coordinates in the liquid film around the solid particles	[m]
z	= coordinates along the wetted wall	[m]
Z_T	= height of wetted-wall column	[m]
δ_L	= thickness of liquid film adjacent to gas-liquid interface ($= \mathscr{D}_A/k_L$)	[m]
δ_S	= thickness of liquid film around solid particles ($= \mathscr{D}_B/k_S$)	[m]
ε_P	= volume fraction of solid particles in a slurry absorbent	[—]
Γ	= mass flow rate of absorbent per unit periphery	[kg m^{-1} s^{-1}]
γ_B	= dimensionless parameter defined as $v k_r c_{Ai} \mathscr{D}_B/k_s^2$	[—]
β_A	= modified enhancement factor for the mass transfer rate of solute gas, A, into the liquid film near the solid particle	[—]
β_B	= enhancement factor for the solid dissolution rate	[—]

v = stoichiometric number for unit mole of A in the chemical reaction between the solute gas, A, and the reactant dissolved from solid particle, B [—]

v' = moles of B per unit mole of solid particles [—]

μ = viscosity of absorbent [Pa s]

ρ = specific density of absorbent [kg m^{-3}]

ϕ = modified enhancement factor for the absorption rate into a slurry absorbent defined by Eq. (4) [—]

$\bar{\phi}$ = average modified enhancement factor for the absorption rate into a slurry absorbent [—]

⟨Superscripts⟩

i = the i-th compartment of slurry absorbent

Literature Cited

1) Asai, S., Y. Konishi and Y. Sasaki: *J. Chem. Eng. Japan*, **21**, 107 (1988).
2) Fujita, S., A. Tanimoto, M. Tamura and K. Yamamoto: *Kagaku Kogaku*, **18**, 474 (1954).
3) Kojima, H., M. Hakuta, T. Ichinoseki and H. Midorikawa: *J. Chem. Eng. Japan*, **22**, 621 (1989).
4) Sada, E., H. Kumazawa and C. H. Lee: *Chem. Eng. Sci.*, **38**, 2047 (1983).
5) van Krevelen, D. W. and P. J. Hoftijzer: *Rec. Trav. Chim.*, **67**, 563 (1948).