CHEMICAL ABSORPTION INTO SLURRY IN GAS-SPARGED
STIRRED VESSEL UNDER CONTINUOUS OPERATION

HIROMITSU KOJIMA, MASAKI HAKUTA, KAZUHARU KUDOHO,
TSUKASA ICHINOSEKI AND HIROSHI MIDORIKAWA
Department of Chemical Technology, Kanagawa Institute of Technology,
Atsugi 243-02

Key Words: Absorption, Chemical Absorption, Absorption into Slurry, Chemical Reactor, Gas Sparged Stirred Vessel

The absorption rate into slurry in a gas-sparged stirred vessel under continuous operation was investigated experimentally and theoretically. The gas-liquid specific interfacial area and volumetric mass transfer coefficient were determined experimentally. The absorption rate of CO₂ into an aqueous slurry of Ca(OH)₂ particles and the power required for agitation were measured simultaneously in a gas-sparged stirred vessel under continuous operation.

A film theory model for the absorption rate was proposed, which was valid for the case where the concentration of the solute gas in the bulk of the slurry absorbent could not be assumed to be zero. The observed rates of absorption into the slurry agreed well with the predicted values by the present model both in the range of high solid concentration of Ca(OH)₂, where the model of Sada et al. is valid and in the range of low solid concentration where the modified enhancement factor is less than unity.

Introduction

The process of chemical absorption into a slurry containing solid particles as a reactant or a catalyst can be found in many practical processes such as hydrocracking of heavy oil, liquefaction of coal or hydrogenation of hydrocarbons.

Several experimental or theoretical studies have been reported on the mechanism of chemical absorption into a slurry with relatively high solid concentration. Uchida et al. modified the model of Ramachandran et al. for gas absorption with fast reaction into a slurry and pointed out that the enhancement of solid dissolution rate by chemical reaction is significant in the process of chemical absorption into a slurry.

Sada et al. presented a model for gas absorption into a slurry with a finite rate of chemical reaction, an extension of the model of Uchida et al. that takes into account the enhancement of solid dissolution by chemical reaction. They performed CO₂ and SO₂ absorption into a slurry containing Ca(OH)₂ particles and showed that their model agrees well with the experimental results.

Sada et al. predicted successfully the observed absorption rates of CO₂ into a slurry in the bubble column, using a film theory model incorporating the finite volume of the slurry.

No work has been published on the case where the solid concentration in a slurry is so dilute that a solute gas can penetrate into the bulk of the slurry phase.

In the present work, the model of Sada et al. is modified for application to the lower range of solid concentration where the assumption that the concentration of a solute gas in the bulk of a slurry is equal to zero does not hold. The observed absorption rates of CO₂ into the aqueous slurry of Ca(OH)₂ particles in a gas-sparged stirred vessel under continuous operation are compared with the values predicted by the present film theory model.

1. Analysis

1.1 Basic equations for the absorption rate

The chemical reaction equation and the reaction rate equation were assumed as follows.

\[ A + \nu B \rightarrow P \] (1)

\[ r_A = - \frac{dc_A}{dy} = k_A c_A c_B \] (2)

where \( c_A \) is the concentration of a solute gas \( A \) and \( c_B \) is the concentration of a reactant \( B \) dissolved from the solid particles. \( P \) denotes the product of reaction between \( A \) and \( B \). As the contact time between a bubble and liquid phase is generally short in a gas-sparged stirred vessel or in a bubble column, the thickness of the liquid film for mass transfer may become smaller than the particle size. Hence it was assumed as in the
model of Sada et al.\textsuperscript{10,11}) that no solid particles existed in the liquid film.

Material balance equations for $A$ and $B$ in the liquid film, Eqs. (3) and (4) and the relevant boundary conditions, Eqs. (5)–(7), become the same equations as in the model of Sada et al.\textsuperscript{10,11}:

\begin{align*}
\frac{d^2 A}{dx^2} &= MC_A C_B \tag{3} \\
\frac{d^2 B}{dx^2} &= MrqC_A C_B \tag{4} \\
X = 0 ; & \quad C_A = 1 \tag{5} \\
\frac{dC_B}{dx} &= 0 \tag{6} \\
X = 1 ; & \quad C_B = 1 + \left( \frac{qs_1 r}{\beta_B N} \right) \left( \frac{dC_A}{dx} \right) \bigg|_{x=0} \tag{7}
\end{align*}

If the solid concentration of $B$ is very dilute, the solute gas will not be consumed completely by the chemical reaction in the liquid film $0 \leq X \leq 1$ and will penetrate into the bulk of a slurry. The solute gas in the bulk of a slurry will be consumed by the chemical reaction both in the bulk of liquid phase and in the liquid film around the solid particles. Hence the boundary condition for $A$ at $X = 1$ is written as Eq. (8).

\begin{align*}
X = 1 ; & \quad -dC_A/dx = (M/s_2)C_A C_B + \beta_A (N/s_1 r) C_A \tag{8}
\end{align*}

In the model of Sada et al.\textsuperscript{10,11} the boundary condition, $C_A = 0$, is imposed at $X = 1$ instead of Eq. (8) in the present model.

The enhancement factor, $\beta_B$, for the dissolution rate of $B$ and the modified enhancement factor, $\beta_A$, for the mass transfer rate of $A$ into the liquid film around the solid particles are obtained by the numerical solution of the following equations.

\begin{align*}
\frac{d^2 A}{dy^2} &= C_A C_B (\gamma_B / (rq)) \tag{9} \\
\frac{d^2 B}{dy^2} &= XC_A C_B \tag{10} \\
Y = 0 ; & \quad C_A = C_A \bigg|_{y=1} \tag{11} \\
C_B = C_B \bigg|_{y=1} \tag{12} \\
Y = 1 ; & \quad dC_A/dY = 0 \tag{13} \\
C_A = 1 \tag{14} \\
\beta_A &= -\left( \frac{dC_A}{dy} \right)_{y=0}/C_A \bigg|_{y=1} \tag{15} \\
\beta_B &= \left( \frac{dC_B}{dy} \right)_{y=1}/(1 - C_B \bigg|_{y=1}) \tag{16}
\end{align*}

The modified enhancement factor, $\phi$, for the absorption of $A$ into a slurry is defined as

\begin{equation}
\phi = -\left( \frac{dC_A}{dx} \right)_{x=0} \tag{17}
\end{equation}

The predicted values of absorption rate into a slurry in the stirred vessel can be obtained by solving numerically Eqs. (3)–(19).

2. Experimental Apparatus and Procedure

Figure 2 shows a schematic diagram of the experimental apparatus. The stirred vessel is a fully baffled standard vessel with an inner diameter of 179 mm. At the bottom of the stirred vessel a single nozzle with an inner diameter of 3.0 mm is fitted as a gas sparger. A six-blade flat-disk turbine with
diameter 60.0 mm is used as impeller. The slurry absorbents are fed into the vessel through an inlet 160 mm above the bottom and are allowed to flow out from the outlet near the bottom. The height of the gas-liquid contacting section is maintained at 179 mm by a constant-head device.

The absorption rate, the rotating speed and the required torque were measured simultaneously.

The absorption rate was determined by measuring the mole fraction of the solute gas (CO$_2$) in the influent and the effluent gas streams.

The gas-liquid interfacial area, $a$, was determined by measuring the absorption rate accompanied by the pseudo-1st order chemical reaction, for the system of NaOH aqueous solution- CO$_2$ and for the system of NaOH aqueous solution containing CaCO$_3$ particles- CO$_2$. Under the present experimental condition for the determination of gas-liquid interfacial area, it was confirmed that the absorption rates were proportional to the square root of NaOH concentration in the stirred vessel when the gas-sparging rate and the rotating speed were maintained constant. The values of $C_{\text{Al}}/k_{\text{Al}}$ decreased slightly from $1.47 \times 10^{-4}$ to $1.39 \times 10^{-4}$ with increase of NaOH concentration from 0.05 to 0.2 kmol/m$^3$. Hence it can be said that the absorption occurs in the pseudo-1st order chemical reaction regime.

The reaction rate constant for this system was estimated by the result of Pinsent et al.$^{79}$

The volumetric mass transfer coefficient, $k_{\text{Al}}a$, was determined by measuring the physical absorption rate for the systems of water-CO$_2$ and CaCO$_3$-slurry-CO$_2$.

The experiments on the chemical absorption into a slurry were performed for the system Ca(OH)$_2$-slurry-CO$_2$. CaCO$_3$ particles with diameter of 15.7 $\mu$m and Ca(OH)$_2$ with diameter of 25.9 $\mu$m were used as the solid particles.

### Fig. 3. Experimental results for gas-liquid interfacial area

**3. Experimental results and discussion**

**3.1 Gas-liquid interfacial area**

Figure 3 shows the experimental results for the gas-liquid interfacial area.

As shown in Fig. 3, the effect of solid concentration on the gas-liquid interfacial area was not significant. As an empirical equation for the gas-liquid interfacial area, Eq. (20) was obtained.

$$a = 1.04 \times 10^2 n^{0.54} \rho^{0.54}$$  \hspace{1cm} (20)

The present results agreed approximately with the estimated values from the results of Valentin et al.$^{13}$ and Yoshida et al.$^{14}$

**3.2 Liquid-side volumetric mass transfer coefficient**

Figure 4 shows experimental results for the volumetric mass transfer coefficient. As shown in Fig. 4, when tap water was used as an absorbent, the volumetric mass transfer coefficients are correlated by
Table 1. Experimental results of chemical absorption into a slurry and comparison with the computation

<table>
<thead>
<tr>
<th>$n \times 60$</th>
<th>$(W_A/c_d)_\text{exp} \times 10^5$ [m³/s]</th>
<th>$(W_A/c_d)_\text{cal} \times 10^5$ [m³/s]</th>
<th>$N \times 10^4$</th>
<th>$M$ [—]</th>
<th>$s \times 10^5$</th>
<th>$\gamma_b$ [—]</th>
<th>$\phi_{\text{exp}}$ [—]</th>
<th>$\phi_{\text{cal-1}}$ [—]</th>
<th>$\phi_{\text{cal-2}}$ [—]</th>
</tr>
</thead>
<tbody>
<tr>
<td>303</td>
<td>4.44</td>
<td>5.00</td>
<td>1.62</td>
<td>3.27</td>
<td>6.40</td>
<td>9.60</td>
<td>1.26</td>
<td>1.42</td>
<td>1.41</td>
</tr>
<tr>
<td>403</td>
<td>5.12</td>
<td>6.30</td>
<td>0.479</td>
<td>1.95</td>
<td>6.36</td>
<td>7.93</td>
<td>0.807</td>
<td>1.07</td>
<td>1.07</td>
</tr>
<tr>
<td>501</td>
<td>4.90</td>
<td>6.56</td>
<td>0.268</td>
<td>1.32</td>
<td>6.38</td>
<td>8.65</td>
<td>0.562</td>
<td>0.774</td>
<td>—</td>
</tr>
<tr>
<td>602</td>
<td>5.69</td>
<td>7.07</td>
<td>0.184</td>
<td>0.944</td>
<td>6.37</td>
<td>5.12</td>
<td>0.469</td>
<td>0.582</td>
<td>—</td>
</tr>
<tr>
<td>701</td>
<td>6.85</td>
<td>7.50</td>
<td>0.140</td>
<td>0.717</td>
<td>6.35</td>
<td>4.10</td>
<td>0.430</td>
<td>0.470</td>
<td>—</td>
</tr>
<tr>
<td>801</td>
<td>7.26</td>
<td>7.67</td>
<td>0.110</td>
<td>0.562</td>
<td>6.31</td>
<td>3.37</td>
<td>0.359</td>
<td>0.379</td>
<td>—</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$c_{SL} = 0.488-0.522%$</th>
<th>$Q_L \times 10^5 = 2.30-2.35$ m³/s</th>
<th>$X_1 = 0.415-0.430$</th>
<th>$v_g \times 10^3 = 4.65-5.07$ m/s</th>
<th>$q = 0.579-0.708$</th>
<th>$r = 1.13$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n \times 60$</td>
<td>$(W_A/c_d)_\text{exp} \times 10^5$ [m³/s]</td>
<td>$(W_A/c_d)_\text{cal} \times 10^5$ [m³/s]</td>
<td>$N \times 10^4$</td>
<td>$M$ [—]</td>
<td>$s \times 10^5$</td>
</tr>
<tr>
<td>302</td>
<td>6.32</td>
<td>6.41</td>
<td>5.80</td>
<td>3.66</td>
<td>8.29</td>
</tr>
<tr>
<td>404</td>
<td>7.89</td>
<td>9.25</td>
<td>2.23</td>
<td>2.17</td>
<td>8.29</td>
</tr>
<tr>
<td>506</td>
<td>9.50</td>
<td>11.8</td>
<td>0.924</td>
<td>1.43</td>
<td>8.16</td>
</tr>
<tr>
<td>607</td>
<td>9.74</td>
<td>14.2</td>
<td>0.466</td>
<td>1.03</td>
<td>8.15</td>
</tr>
<tr>
<td>705</td>
<td>10.0</td>
<td>14.3</td>
<td>0.377</td>
<td>0.792</td>
<td>8.26</td>
</tr>
<tr>
<td>805</td>
<td>15.8</td>
<td>16.9</td>
<td>0.262</td>
<td>0.611</td>
<td>7.86</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$c_{SL} = 0.505-0.544%$</th>
<th>$Q_L = 2.35 \times 10^3$ m³/s</th>
<th>$X_1 = 0.503-0.505$</th>
<th>$v_g \times 10^3 = 5.46-5.79$ m/s</th>
<th>$q = 0.781-0.879$</th>
<th>$r = 1.13$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n \times 60$</td>
<td>$(W_A/c_d)_\text{exp} \times 10^5$ [m³/s]</td>
<td>$(W_A/c_d)_\text{cal} \times 10^5$ [m³/s]</td>
<td>$N \times 10^4$</td>
<td>$M$ [—]</td>
<td>$s \times 10^5$</td>
</tr>
<tr>
<td>300</td>
<td>7.87</td>
<td>6.52</td>
<td>5.58</td>
<td>3.88</td>
<td>9.22</td>
</tr>
<tr>
<td>404</td>
<td>8.84</td>
<td>9.21</td>
<td>1.87</td>
<td>2.26</td>
<td>9.14</td>
</tr>
<tr>
<td>502</td>
<td>8.85</td>
<td>10.9</td>
<td>0.695</td>
<td>1.53</td>
<td>9.18</td>
</tr>
<tr>
<td>603</td>
<td>10.7</td>
<td>11.8</td>
<td>0.454</td>
<td>1.04</td>
<td>9.03</td>
</tr>
<tr>
<td>704</td>
<td>12.4</td>
<td>12.7</td>
<td>0.343</td>
<td>0.822</td>
<td>8.97</td>
</tr>
<tr>
<td>804</td>
<td>13.8</td>
<td>13.1</td>
<td>0.261</td>
<td>0.645</td>
<td>8.90</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$c_{SL} = 0.243-0.258%$</th>
<th>$X_1 = 0.413-0.415$</th>
<th>$v_g \times 10^3 = 3.14-3.66$ m/s</th>
<th>$q = 0.500-0.736$</th>
<th>$r = 1.13$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_L \times 10^5 = 2.25-2.35$ m³/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q_L \times 10^3 = 1.18$ m³/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| $n \times 60$ | $(W_A/c_d)_\text{exp} \times 10^5$ [m³/s] | $(W_A/c_d)_\text{cal} \times 10^5$ [m³/s] | $N \times 10^4$ | $M$ [—] | $s \times 10^5$ | $\gamma_b$ [—] | $\phi_{\text{exp}}$ [—] | $\phi_{\text{cal-1}}$ [—] | $\phi_{\text{cal-2}}$ [—] |
| 302         | 4.12                                 | 4.43                                 | 0.838        | 3.28   | 6.37        | 8.78   | 1.18        | 1.27          | 1.26          |
| 401         | 5.08                                 | 6.01                                 | 0.422        | 1.96   | 6.30        | 7.35   | 0.877       | 1.04          | 1.04          |
| 500         | 6.02                                 | 6.85                                 | 0.264        | 1.31   | 6.25        | 6.05   | 0.700       | 0.798         | —             |
| 601         | 7.22                                 | 7.73                                 | 0.196        | 0.939  | 6.24        | 4.86   | 0.603       | 0.647         | —             |
| 703         | 8.08                                 | 8.23                                 | 0.149        | 0.705  | 6.19        | 3.76   | 0.512       | 0.521         | —             |
| 804         | 9.52                                 | 8.76                                 | 0.117        | 0.550  | 6.11        | 3.08   | 0.477       | 0.439         | —             |

$Q_L = 10^3 = 1.18$ m³/s

the following equation:

$$k_{Ld} = 8.68 \times 10^{-3} \cdot v_g^{0.44} \cdot n^{-1.4}$$

When the slurry containing CaCO₃ particles was used as an absorbent, the volumetric mass transfer coefficients in the range of the higher rotating speed became larger than those obtained when tap water was used as an absorbent. The empirical equation for the volumetric mass transfer coefficients using the slurry is given as Eq. (22).
Table 1. (continued)

<table>
<thead>
<tr>
<th>$n 	imes 60$ [1/s]</th>
<th>$\left(\frac{W}{c_{el}}\right)_{exp} \times 10^5$ [m²/s]</th>
<th>$\left(\frac{W}{c_{el}}\right)_{cal} \times 10^5$ [m²/s]</th>
<th>$N \times 10^4$</th>
<th>$M$</th>
<th>$s \times 10^5$</th>
<th>$\gamma_p$</th>
<th>$\phi_{exp}$</th>
<th>$\phi_{cal-1}$</th>
<th>$\phi_{cal-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>306</td>
<td>4.48</td>
<td>4.88</td>
<td>0.800</td>
<td>3.64</td>
<td>8.66</td>
<td>9.10</td>
<td>1.05</td>
<td>1.14</td>
<td>1.14</td>
</tr>
<tr>
<td>411</td>
<td>5.51</td>
<td>6.09</td>
<td>0.432</td>
<td>2.13</td>
<td>8.59</td>
<td>7.90</td>
<td>0.760</td>
<td>0.839</td>
<td></td>
</tr>
<tr>
<td>516</td>
<td>6.22</td>
<td>6.26</td>
<td>0.253</td>
<td>1.41</td>
<td>8.57</td>
<td>6.34</td>
<td>0.570</td>
<td>0.574</td>
<td></td>
</tr>
<tr>
<td>603</td>
<td>9.51</td>
<td>7.44</td>
<td>0.204</td>
<td>1.05</td>
<td>8.25</td>
<td>5.18</td>
<td>0.673</td>
<td>0.527</td>
<td></td>
</tr>
<tr>
<td>701</td>
<td>10.0</td>
<td>7.55</td>
<td>0.153</td>
<td>0.795</td>
<td>8.12</td>
<td>4.30</td>
<td>0.544</td>
<td>0.411</td>
<td></td>
</tr>
<tr>
<td>803</td>
<td>10.9</td>
<td>8.27</td>
<td>0.126</td>
<td>0.624</td>
<td>8.19</td>
<td>3.50</td>
<td>0.460</td>
<td>0.350</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$n 	imes 60$ [1/s]</th>
<th>$\left(\frac{W}{c_{el}}\right)_{exp} \times 10^5$ [m²/s]</th>
<th>$\left(\frac{W}{c_{el}}\right)_{cal} \times 10^5$ [m²/s]</th>
<th>$N \times 10^4$</th>
<th>$M$</th>
<th>$s \times 10^5$</th>
<th>$\gamma_p$</th>
<th>$\phi_{exp}$</th>
<th>$\phi_{cal-1}$</th>
<th>$\phi_{cal-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>304</td>
<td>4.41</td>
<td>4.89</td>
<td>0.990</td>
<td>3.88</td>
<td>9.52</td>
<td>11.4</td>
<td>0.999</td>
<td>1.11</td>
<td>1.11</td>
</tr>
<tr>
<td>403</td>
<td>5.96</td>
<td>5.73</td>
<td>0.487</td>
<td>2.29</td>
<td>9.36</td>
<td>9.52</td>
<td>0.811</td>
<td>0.780</td>
<td></td>
</tr>
<tr>
<td>505</td>
<td>6.67</td>
<td>6.62</td>
<td>0.320</td>
<td>1.53</td>
<td>9.40</td>
<td>8.13</td>
<td>0.512</td>
<td>0.561</td>
<td></td>
</tr>
<tr>
<td>602</td>
<td>6.72</td>
<td>6.56</td>
<td>0.233</td>
<td>1.11</td>
<td>9.42</td>
<td>6.84</td>
<td>0.442</td>
<td>0.431</td>
<td></td>
</tr>
<tr>
<td>701</td>
<td>6.75</td>
<td>6.79</td>
<td>0.179</td>
<td>0.848</td>
<td>9.46</td>
<td>5.65</td>
<td>0.336</td>
<td>0.338</td>
<td></td>
</tr>
<tr>
<td>804</td>
<td>6.32</td>
<td>6.88</td>
<td>0.142</td>
<td>0.661</td>
<td>9.45</td>
<td>4.84</td>
<td>0.246</td>
<td>0.268</td>
<td></td>
</tr>
</tbody>
</table>

![Diagram](image)

Fig. 4. Experimental results for volumetric mass transfer coefficient

$k_{L,A} = 4.89 \times 10^{-3} \rho_g^{0.44} n^{1.81}$ (22)

3.3 Absorption of CO₂ into the slurry containing Ca(OH)₂ particle

Experimental results for the absorption rate of CO₂ into the slurry containing Ca(OH)₂ particles are shown in Table 1. As shown in this table, the absorption rate decreases with decrease of the feed rate of the slurry and with decrease of Ca(OH)₂ concentration in the feed slurry.

$(\frac{W}{c_{el}})_{cal-1}$ in Table 1 is the absorption rate calculated by the present model. For the liquid-side mass transfer coefficient between liquid and gas phase, $k_{L,A}$, and the gas-liquid interfacial area, $a$, the calculated values by the present empirical equations Eqs. (20) and (22) were used to calculate the absorption rate. The liquid-side mass transfer coefficient between the liquid phase and the solid particle was estimated from the equation of Asai et al.₁,² by using the observed values of the energy dissipated per unit time in the stirred vessel.

The physical properties required to calculate the absorption rate are summarized in Table 2.

As shown in Table 1, the predicted values of the absorption rate calculated by the present model agree with the experimental values.

The experimental values of the modified enhancement factor, $\phi_{exp}$, defined by Eq. (17) are also shown in Table 1 and agree with the calculated values of the modified enhancement factor, $\phi_{cal-1}$, by the present model. The calculated values of the modified enhancement factor, $\phi_{cal-2}$, by Sada and Kumazawa's model are shown in the lower range of rotating speed and agree well with those by the present model. In the higher range of rotating speed, the modified enhancement factor was not obtained by Sada and Kumazawa's model under the present experimental condition, because $N$ became less than $q_{sr}$, ($N < q_{sr}$), and the concentration of the reactant, $B$, dissolved from the solid particles in the bulk of a slurry became...
equal to zero. The calculated values of the modified enhancement factor, \( \phi_{\text{cal}} - 1 \), by the present model agree with the experimental results in the whole range of \( N \) as shown in Table 1.

Under the condition of relatively higher solid concentration of 1.0%, the experimental values of the modified enhancement factor became greater than unity and coincided both with the present model and with Sada and Kumazawa’s model\(^{[10,11]}\).

**Conclusion**

A film theory model for the absorption into a slurry, an extension of Sada and Kumazawa’s model, was proposed to predict the absorption rate under the condition that the solid concentration is very low and consequently the concentration of the absorbed gas does not become zero in the bulk of a slurry.

Experimental values of the absorption rate obtained in a gas-sparged stirred vessel under continuous operation agreed well with the calculated values by the present model.

**Nomenclature**

\[
\begin{align*}
a & = \text{gas-liquid interfacial area} \quad [\text{m}^2/\text{m}^3] \\
A_s & = \text{solid-liquid interfacial area} \quad [\text{m}^2/\text{m}^3] \\
C_A & = \text{dimensionless concentration of the solute gas} A, \text{defined as} \, c_A/c_{A,0} \quad [\text{--}] \\
C_B & = \text{dimensionless concentration of the reactant} B \text{ dissolved from the solid particles, defined as} \, c_B/c_{B,0} \quad [\text{--}] \\
c_A & = \text{concentration of solute gas} A \text{ in liquid phase} \quad [\text{kmol/m}^3] \\
c_{A,0} & = \text{concentration of solute gas} A \text{ at the gas-liquid interface} \quad [\text{kmol/m}^3] \\
c_{A,2} & = \text{concentration of solute gas in the effluent absorbent stream from the stirred vessel} \quad [\text{kmol/m}^3] \\
c_B & = \text{concentration of the reactant} B \text{ dissolved from the solid particles} \quad [\text{kmol/m}^3] \\
c_{B,0} & = \text{concentration of the reactant} B \text{ at the solid-liquid interface} \quad [\text{kmol/m}^3] \\
c_s & = \text{solid concentration in the slurry absorbent} \quad [\text{wt}%] \\
c_s & = \text{solid concentration in the effluent absorbent stream from the stirred vessel} \quad [\text{wt}%] \\
c_{s,0} & = \text{solid concentration in the effluent absorbent stream from the stirred vessel} \quad [\text{wt}%] \\
\mathcal{D}_A & = \text{diffusivity of solute gas} A \text{ in the liquid phase} \quad [\text{m}^2/\text{s}] \\
\mathcal{D}_B & = \text{diffusivity of reactant} B \text{ in the liquid phase} \quad [\text{m}^2/\text{s}] \\
k_L & = \text{liquid-phase mass transfer coefficient for gas-liquid interface} \quad [\text{m/s}] \\
k_{L,0} & = \text{volumetric mass transfer coefficient for gas-liquid interface} \quad [\text{1/s}] \\
k_r & = \text{reaction rate constant} \quad [\text{m}^3 \text{ s}^{-1} \text{ kmol}^{-1}] \\
k_e & = \text{mass transfer coefficient for solid particle dissolution} \quad [\text{m/s}] \\
M & = \text{dimensionless parameter defined as} \, k_A c_{A,0} \delta_A^2 / \mathcal{D}_A \quad [\text{--}] \\
M_s & = \text{molecular weight of solid particles} \quad [\text{kg/mol}] \\
N & = \text{dimensionless parameter defined as} \, k_e A_s \delta_A^2 / \mathcal{D}_A \quad [\text{--}] \\
n & = \text{rotating speed of impeller} \quad [\text{1/s}] \\
Q_L & = \text{volumetric feed rate of absorbent} \quad [\text{m}^3/\text{m}] \\
q & = \text{dimensionless parameter defined as} \, v c_{A,0} / \mathcal{D}_A \quad [\text{--}] \\
r & = \text{ratio of diffusivity for absorbent gas} A \text{ and for the reactant} B \quad (= \mathcal{D}_A / \mathcal{D}_B) \quad [\text{--}] \\
s_1 & = \text{dimensionless parameter defined as} \, a \cdot \delta_A \quad [\text{--}] \\
s_2 & = \text{dimensionless parameter defined as} \, a \cdot \delta_A (1 - a \cdot \delta_A - A_s \delta_A - \varepsilon_s) \quad [\text{--}] \\
V & = \text{volume of gas-liquid-solid contacting section in the stirred vessel} \quad [\text{m}^3] \\
\nu_T & = \text{superficial gas velocity} \quad [\text{m/s}] \\
W_s & = \text{absorption rate in the stirred vessel} \quad [\text{kmol/s}] \\
X & = \text{dimensionless coordinates defined as} \, x / \delta_A \quad [\text{--}] \\
X_1 & = \text{mole fraction of the solute gas in the influent gas stream into the stirred vessel} \quad [\text{m}] \\
Y & = \text{dimensionless coordinates defined as} \, y / \delta_A \quad [\text{--}] \\
Y_s & = \text{coordinates in the liquid film around the solid particles} \quad [\text{m}] \\
\delta_L & = \text{thickness of liquid film adjacent to gas} \quad (= \varepsilon_s / \delta_A) \quad [\text{m}] \\
\delta_s & = \text{thickness of liquid film around solid particle} \quad (= \delta_A / 2 \varepsilon_s) \quad [\text{m}] \\
\varepsilon_s & = \text{volume fraction of solid particles in a slurry absorbent} \quad [\text{--}] \\
\gamma & = \text{dimensionless parameter defined as} \, v c_{A,0} \delta_B / k_e^2 \quad [\text{--}] \\
\beta_A & = \text{modified enhancement factor for the mass transfer rate of solute gas A into the liquid film near the solid particle} \quad [\text{--}] \\
\beta_s & = \text{enhancement factor for the solid dissolution rate} \quad [\text{--}] \\
\nu & = \text{stoichiometric coefficient in Eq. (1)} \quad [\text{--}] \\
\nu' & = \text{moles of B per unit mole of solid particle} \quad [\text{--}] \\
\rho_L & = \text{apparent density of slurry} \quad [\text{kg/m}^3] \\
\phi & = \text{modified enhancement factor for the absorption rate into a slurry absorbent defined by Eq. (17)} \quad [\text{--}] \\
\phi_{\text{cal}} - 1 & = \text{calculated value of} \, \phi \text{ by the present model} \quad [\text{--}] \\
\phi_{\text{cal}} - 2 & = \text{calculated value of} \, \phi \text{ by the model of Sada and Kumazawa} \quad [\text{--}] \\
\langle \text{Subscripts} \rangle \\
\exp. & = \text{experimental value} \\
cal. & = \text{calculated value by the present model}
\end{align*}
\]

**Literature Cited**