Adhesion and agglomeration of catalyst particles in three phase reactors

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Citation for published version (APA):
Gas-solid adhesion and solid-solid agglomeration of carbon supported catalysts in three phase slurry reactors*

Abstract

In the study of three phase slurry reactors the slurry phase is conventionally treated as a quasi homogeneous liquid phase with altered sorption and reaction capacity due to the presence of catalyst particles. This approach may be utterly wrong in cases in which phase segregation of the solid takes place. This phenomenon is relatively little studied. This work will demonstrate that segregation may have a considerable impact on the operation of three phase reactors. Two examples of segregation, i.e. gas-solid adhesion and solid-solid agglomeration, will be discussed. Taking the example of carbon and alumina supported palladium catalysts, employed in the hydrogenation of methyl acrylate towards methyl propionate, the segregation of the catalyst phase by adhesion to gas bubbles is studied. A quantitative model is developed based on the film theory, the particle to bubble collision probability and the impact of the size of adhering particles on the effective film thickness. This model is used to describe adhesion under non-stagnant conditions and its impact on the overall G-L mass transfer rate. The conversion rate of a mass transfer limited model reaction, i.e. the hydrogenation of methyl acrylate to methyl propionate, is studied in a stirred tank reactor for two different catalysts (Pd/C and Pd/Al₂O₃) to verify the model. It is quantitatively demonstrated that particle to bubble adhesion will result in increased G-L mass transfer rates. The second, closely related, phenomenon studied is the segregation of the solid and liquid phase by agglomeration of the catalyst particles. This behaviour is of particular importance as it leads to a substantial increase in the effective particle size resulting in a decreased conversion rate.

2.1 Introduction

Three phase slurry reactors are widely used in chemical and biochemical industries. In most of these reactors a catalyst is present as a dispersed solid phase. The effect of the presence of catalyst particles on the hydrodynamic behaviour of a three phase slurry reactor, either on the mass transfer rate of the gaseous reactant to the catalyst surface or on the coalescence of bubbles, is still not well understood. This chapter focuses on the effect of two types of segregation phenomena, agglomeration and adhesion of catalyst particles, on the mass transfer processes and on the conversion rate of the key reactant.

The conversion rate of a gas-liquid mass transfer limited reaction may be enhanced by the presence of small catalyst particles adhering to gas bubbles. Vinke et al. (1991) showed with bubble pick up experiments that small hydrophobic particles will adhere to bubbles in an aqueous slurry, while hydrophilic particles will stay in the liquid phase. This adhesion may either affect the mass transfer rate by an increasing specific bubble surface $a_L$ and/or by an increasing mass transfer coefficient $k_L$. According to Lindner et al. (1988) the main reason for mass transfer enhancement is the increase of $a_L$, caused by a decreased bubble coalescence rate. Other authors suggest an increase in the value of $k_L$. Alper et al. (1980), Kars et al. (1968), Quicker et al. (1987) introduced the so called grazing or shuttle effect, where it is assumed that particles, smaller than the liquid side film thickness, penetrate into the gas-liquid boundary layer. Because of the high gas concentration in this layer compared to the bulk liquid, the adsorption rate from the gas phase increases. Catalyst particles saturated with gas can move back into the bulk liquid and increase the gas phase concentration there.

The new model introduced in this chapter is based on the presence of small catalyst particles in the liquid film around a gas bubble, which results in a decreased effective film thickness and an increased $k_L$. (See also Pal et al. (1982), Holstvoogd et al. (1990), Vinke et. al. (1993), Joly-Vuillemin et al. (1996)).
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To study the effects of the two types of segregation phenomena (adhesion and agglomeration) on the mass transfer rate in a three phase reactor, the hydrogenation of methyl acrylate is used as a model reaction.

2.2 Experimental

2.2.1 Hydrogenation of methyl acrylate.

A schematic representation of the glass slurry reactor used for our experiments is given in Figure 2.1. This thermostatted stirred tank reactor is designed according to a standard geometry as described by Forrester (1994).

![Figure 2.1. Schematic representation of the stirred tank reactor.](image)

The catalysts used are 5 wt% Pd/Al₂O₃ and 10 wt% Pd/C (Fluka Chemie AG) in a concentration range from γₜ = 0.1 to 1 kg m⁻³ (See also Table 2.1). The concentration methyl acrylate in distilled water is varied between 0.06 and 0.19 mol L⁻¹. Hydrogen is used as the gas phase. All experiments are performed at atmospheric pressure and a stirrer speed of 6.67 s⁻¹ (400 rpm). A typical experiment (C_m = 0.063 mol L⁻¹, γₜ = 0.5 kg m⁻³) is performed in the following way: the reactor is filled with 0.350 L distilled water, 2 mL methyl acrylate, and 0.17 g catalyst. The stirrer is started and the reactor is thermostatted at 303 K. Subsequently the reactor is degassed in vacuum. After degassing the reaction is started by filling the reactor with hydrogen. The hydrogen consumption is followed by using a graded tube sealed with a mercury ring.
2.2.2 Catalyst characterisation

Under equilibrium conditions, the distribution of the hydrogen adsorbed on the particles and dissolved liquid layer around the particle is described by a partition coefficient denoted as m. This parameter reflects the gas adsorption capacity of the solid particles and has been determined by Vinke et al. (1993). The average diameter of the particles or agglomerates, \( d_p \), is determined with a Coulter Counter. The density of the catalyst particles is calculated from the densities of carbon and alumina, obtained from mercury porosimetry, and the known density of palladium. The values of these properties are given in Table 2.1.

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Pd/C</th>
<th>Pd/Al₂O₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle or agglomerate diameter, ( d_p ) (µm)</td>
<td>6.0 ± 2.5</td>
<td>7.4 ± 5.9</td>
</tr>
<tr>
<td>Density, ( \rho_{sp} ) (kg m(^{-3}))</td>
<td>1344</td>
<td>2148</td>
</tr>
<tr>
<td>Partition coefficient, m</td>
<td>945</td>
<td>1520</td>
</tr>
</tbody>
</table>

*Table 2.1. Physical properties of the catalysts used.*

A light microscope is used to investigate agglomeration of particles under stagnant conditions. Five different solutions of methyl acrylate in distilled water are prepared: 0, 0.06, 0.09, 0.13, and 0.19 mol L\(^{-1}\). An amount of 0.025 g Pd/C catalyst is dispersed in 10 mL of each solution. These samples are observed and photographed at an enlargement factor of 40.

2.3 Model development

Vinke et al. (1991) reported that the adhesion of particles to bubbles in an aqueous solution is affected by the hydrophobicity of the catalyst. Hydrophobic particles show a higher bubble coverage than hydrophilic particles. In case of mass transfer limited reactions in aqueous solutions, the conversion rate of the reactant is enhanced as a result of the presence of the catalyst particles in the liquid film around gas bubbles. Therefore, the conversion rate increases for higher bubble coverage. A model based on adhesion, film theory, and the following assumptions describes the mass transfer rate enhancement resulting from particle to bubble adhesion:
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1. The particles are spherical and of equal size
2. The value of the specific bubble surface $a_L$ is not influenced by the particles present in the liquid phase
3. Adhering particles are much smaller than the gas bubbles ($d_p << d_b$). Therefore, the interface between the particles and the bubble surface can be considered as being flat. In case of adhering particles the effective film thickness is reduced to half the particle radius as described by Vinke et al. (1993) ($\delta_{\text{eff}} = d_p/4$), therefore $k_{LS}$ can be calculated by

$$k_{LS} = \frac{4 D_{AB}}{d_p}$$

4. The contribution of non-adhering particles to the enhancement factor is negligible small.

In the presence of adhering particles, the bubble is partly covered with particles (Figure 2.2).

![Figure 2.2](image)

*Figure 2.2. Schematic representation the gas-liquid interfacial mass transfer in case of a partly covered bubble (dashed arrows: through the uncovered part of the bubble, full arrows: through the covered part of the bubble).*

In case of partly covered bubbles the mass transfer rate of the gaseous reactant is the result of a contribution from the mass transfer through the non-covered and through the covered part of the bubble, respectively (Figures 2.2, 2.3a and 2.3b).
The increase in the conversion rate under mass transfer limited conditions can be expressed in terms of an enhancement factor $E$, defined as the ratio between the conversion rate in presence of adhering particles $\Phi_\zeta$ and the conversion rate in absence of adhering particles $\Phi_{\zeta=0}$. A proper calculation of $E$ involves the use of similar hydrodynamic conditions and specific external catalyst surface area. The defining equations are:

$$E = \left[ \frac{\Phi_\zeta}{\Phi_{\zeta=0}} \right]$$  \hspace{1cm} (2.1)

In which

$$\Phi_\zeta = \zeta \Phi_c + \left(1 - \zeta \right) \Phi_u$$  \hspace{1cm} (2.2)

$$\Phi_{\zeta=0} = \Phi_u$$  \hspace{1cm} (2.3)

Under the assumption that the conversion rate is determined by the film mass transfer of the gaseous reactant, one may derive the following equation for the mass transfer rate through the uncovered part of the bubble for a first order reaction:
\begin{align}
\Phi_u &= k_L a_L V_L \left( C^* - C_B \right) \\
&= k_s a_s V_L \left( C_B - C_s \right) \\
&= k_r \eta \left( m V_L C_s \gamma_s / \rho_{pg} \right)
\end{align}

(2.4)

where

\[ a_s = \frac{6 \gamma_S}{d_p \rho_{pg}}, \quad k_s = \frac{2 D_{AB}}{d_p}, \]

and \( \eta \) is the effectiveness factor of the catalyst.

Elimination of \( C_B \) and substitution of \( a_s \) into equation (2.4) results in the following equation for the mass transfer rate through the uncovered part of the bubble.

\begin{align}
\Phi_u &= \frac{C^* V_L k_L a_L}{1 + k_L a_L \rho_{pg} \left( \frac{d_p}{\gamma_S} + \frac{1}{6 k_s + k_r \eta m} \right)} 
\end{align}

(2.5)

To obtain the values of \( k_L a_L \) and \( k_r \eta \) from a plot of \( \frac{C^* V_L}{\Phi_u} \) versus \( \frac{\rho_{pg}}{\gamma_S} \), equation (2.5) may be reformulated as:

\begin{align}
\frac{C^* V_L}{\Phi_u} &= \frac{1}{k_L a_L} + \left( \frac{d_p}{6 k_s} + \frac{1}{k_r \eta m} \right) \frac{\rho_{pg}}{\gamma_S} 
\end{align}

(2.5b)

For the covered part of the bubble the hydrogen flow rate is given by the following equation, using the assumption that \( C_S = 0 \), i.e. full mass transfer control (Westerterp et al. (1993)):

\begin{align}
\Phi_c &= k_{LS} a_L V_L C^*
\end{align}

(2.6)
Substitution of equations (2.2), (2.3), (2.5), and (2.6) into equation (2.1) leads to the following relation between the enhancement factor $E$ and the catalyst concentration $\gamma_s$.

$$E = 1 + \zeta \left[ \frac{k_{LS}}{k_L} + \frac{k_{LS} \rho_{ps} d_p}{\gamma_s} \left( \frac{1}{6k_S} + \frac{1}{k_s \eta_m} \right) - 1 \right]$$

(2.7)\]

Assuming that the probability of collision with a gas bubble is equal for each individual particle the following collision probability function may be derived:

$$\Phi d(\gamma_s) = e^{-\gamma_s} d(\gamma_s)$$

(2.8)\]

The fraction $\zeta$ of the bubble covered by adhering particles as a function of the catalyst concentration $\gamma_s$ can be obtained from:

$$\zeta = \int_0^{\gamma_s} \Phi d(\gamma_s) = \int_0^{\gamma_s} e^{-\gamma_s} d(\gamma_s) = 1 - e^{-\gamma_s}.$$  

(2.9)\]

For $\gamma_s \to \infty$ the fraction $\zeta$ becomes $\zeta_{\text{max}}$, resulting in the following bubble coverage function:

$$\zeta = \zeta_{\text{max}} (1 - e^{-\gamma_s})$$

(2.10)\]

In equation (2.10) $\zeta_{\text{max}}$ represents the maximum bubble coverage for the specific three phases applied, which is observed at a high catalyst concentration in the slurry. $\zeta_{\text{max}}$ is a function of the hydrophobicity of the catalyst surface and the hydrodynamics in the reactor. However, below a critical catalyst concentration $\gamma_{s0}$, the number of adhering particles is assumed to be zero. This can be rationalised as below a certain catalyst concentration, particles do not adhere within a finite time scale. Taking into account this boundary condition, the following equation for the bubble coverage is obtained:
\[ \zeta = \zeta_{\text{max}} (1 - e^{-q(\gamma_{s} - \gamma_{s0})}) \quad \text{For } \gamma_{s} > \gamma_{s0} \quad (2.11) \]

\[ \zeta = 0 \quad \text{for } \gamma_{s} < \gamma_{s0} \quad (2.12) \]

The parameters \( q \) and \( \gamma_{s0} \) are constants which depend on the hydrodynamic conditions in the stirred tank reactor.

### 2.4 Experimental results and discussion

Previous experiments in our laboratory concerning the hydrogenation of methyl acrylate showed that, under the conditions used for the work presented in this paper, the conversion rate is first order in hydrogen, independent of the methyl acrylate concentration and dependent on the stirring rate. These results show that this reaction is hydrogen mass transfer rate limited.

#### 2.4.1 Determination of the parameters \( k_{L}, a_{L}, \) and \( k_{r} \eta \)

Vinke et al. (1991) observed that, for an aqueous slurry, Pd/C particles strongly adhere to hydrogen bubbles while Pd/Al\(_{2}\)O\(_{3}\) particles do not. Hence, the conversion rate under mass transfer limited conditions in presence of Pd/Al\(_{2}\)O\(_{3}\) particles represents the conversion rate at zero coverage \( \Phi_{\zeta=0} \) (See equation (2.1)). The conversion rate measured in the current study for the hydrogenation of methyl acrylate to methyl propionate in presence of Pd/Al\(_{2}\)O\(_{3}\) particles is shown in Figure 2.4. The corresponding values of \( k_{L}a_{L} \) and \( k_{r}\eta \) for the Pd/Al\(_{2}\)O\(_{3}\) system are obtained from the intercept and slope of a plot of \( C^{*}V_{L}/\Phi_{u} \) versus \( \rho_{pg}/\gamma_{s} \) using equation (2.5b) (See Figure 2.4).

From a best-fit procedure we found the following values for \( k_{L}a_{L} \) \((2.0\cdot10^{-2} \text{ s}^{-1})\) and \( k_{r}\eta \) \((0.38 \text{ s}^{-1})\). The observed gas holdup \( \varepsilon \) and bubble diameter \( d_{b} \) are 0.01-0.015 and \( 1.5\cdot10^{-3}-2\cdot10^{-3} \text{ m} \) respectively. This results in an approximate value for \( a_{L} \) of 40 \text{ m}^2 \text{ m}^{-3} \(

\[ a_{L} = \frac{6 \varepsilon}{d_{b}}. \]
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Figure 2.4. $C^* V L \Phi_u^{-1}$ versus $\rho_{pg} \gamma_s^{-1}$ for the mass transfer limited hydrogenation of 0.06 mol L$^{-1}$ methyl acrylate in presence of Pd/Al$_2$O$_3$ catalyst particles ($C^* = 0.76$ mol m$^{-3}$). The markers (■) represent the experimental data, the solid line is the result of a best-fit procedure (equation 2.5b).

In the following sections the influence of the Pd/C catalyst concentration and methyl acrylate concentration on the enhancement factor will be presented for the hydrogenation of methyl acrylate to methyl propionate.

2.4.2. Effect of catalyst concentration

Figure 2.5 shows the experimental results for the enhancement factor as a function of the catalyst concentration, as calculated by equation (2.1), in which $\Phi_\zeta$ is the measured conversion rate of methyl acrylate in presence of a Pd/C catalyst and $\Phi_{\zeta=0}$ is derived from the measured conversion rate in presence of a Pd/Al$_2$O$_3$ catalyst for the same value of the specific external catalyst surface. The methyl acrylate concentration is 0.06 mol L$^{-1}$ for all experiments.
Figure 2.5. The enhancement factor \( E \) as a function of the catalyst concentration \( \gamma_s \).

- : Ratio of the experimental conversion rates in presence of Pd/C particles and the experimental conversion rate in the presence of Pd/Al\(_2\)O\(_3\) particles as defined by equation (2.1). The solid line is calculated from equations (2.7), (2.11), and (2.12) using the values of \( \zeta_{\text{max}} \), \( q \), and \( \gamma_{s0} \) given in Table 2.2.

The solid line through the markers is calculated using equations (2.7), (2.11), and (2.12) after substitution of the appropriate values of \( \zeta_{\text{max}} \), \( q \), and \( \gamma_{s0} \) (See Table 2.2) obtained from a best-fit procedure.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \zeta_{\text{max}} ) ((-))</td>
<td>0.2</td>
</tr>
<tr>
<td>( \gamma_{s0} ) ((\text{kg m}^{-3}))</td>
<td>0.075</td>
</tr>
<tr>
<td>( q ) ((\text{m}^3 \text{ kg}^{-1}))</td>
<td>46</td>
</tr>
</tbody>
</table>

*Table 2.2. The values of \( \zeta_{\text{max}} \), \( \gamma_{s0} \), and \( q \) obtained by a best-fit procedure of the data points in Figure 2.5.*

From the experimental data represented in Figure 2.5 it can be seen that the value of \( \gamma_{s0} \) lies in a small interval with the boundary values 0.07 and 0.078 kg m\(^{-3}\). From flotation experiments under non-stagnant conditions (Chapter 3) \( \zeta_{\text{max}} \) was found to
range from 0.1 to 0.25. This value of $\zeta_{\text{max}}$ is in good agreement with the value obtained by a best-fit procedure (Table 2.2).

2.4.3. Impact of the methyl acrylate concentration on catalyst agglomeration

Under stagnant hydrodynamic conditions the agglomerate size of Pd/C catalyst particles decreases for higher methyl acrylate concentrations (Figure 2.6). The captions in Figure 2.6 also give the surface tension $\sigma_{\text{LG}}$ of the liquid phase. The agglomeration behaviour of Pd/Al$_2$O$_3$ is also investigated by microscopic imaging, but no significant change in agglomeration is observed.

![Microscopic images](image)

Figure 2.6. Microscopic images (125×200 µm) of Pd/C slurry for different methyl acrylate concentration ($C_{\text{ma}}$) in water and the corresponding surface tension $\sigma_{\text{LG}}$ of the liquid phase.

If similar agglomeration behaviour of both catalysts would occur under non-stagnant reactor conditions, an increase in the conversion rate with increasing concentration methyl acrylate is expected due to the decreasing effective particle diameter. The
results of the hydrogenation of methyl acrylate at different methyl acrylate concentration using Pd/C catalyst particles are presented in Figure 2.7. This figure clearly shows the expected increase of the conversion rate for increasing concentration methyl acrylate.

![Figure 2.7. The conversion rate for the hydrogenation of methyl acrylate under mass transfer limited conditions as a function of methyl acrylate concentration (Pd/C, $\gamma_s = 0.5 \text{ kg m}^{-3}$).](image)

Under the assumption that the increased conversion rate at increasing concentration of methyl acrylate is only caused by de-agglomeration, i.e. by a decreasing effective particle diameter, equation (2.7) can be used to calculate this effective catalyst particle diameter $d_{\text{eff}}$. The result of this calculation is given in Table 2.3 and Figure 2.8.

<table>
<thead>
<tr>
<th>$C_{\text{ma}}$ (mol L$^{-1}$)</th>
<th>$d_{\text{eff}}$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06</td>
<td>6.0</td>
</tr>
<tr>
<td>0.09</td>
<td>4.3</td>
</tr>
<tr>
<td>0.13</td>
<td>3.6</td>
</tr>
<tr>
<td>0.16</td>
<td>3.2</td>
</tr>
<tr>
<td>0.19</td>
<td>3.0</td>
</tr>
</tbody>
</table>

*Table 2.3. The calculated effective particle diameter under non-stagnant conditions for various methyl acrylate concentrations ($\gamma_s = 0.5 \text{ kg m}^{-3}$, $\xi_{\text{max}}$, $\gamma_{50}$, and $q$: see Table 2.2).*
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To obtain the enhancement factor $E$, the value of $\Phi_{Pd/Al_2O_3}$ is calculated at the specific external catalyst surface for the different effective catalyst particle diameters (See Table 2.3). The enhancement factor obtained in this way and the corresponding effective particle diameters are plotted in Figure 2.8. The solid line represents the enhancement factor calculated from equations (2.7), (2.11), and (2.12) and the appropriate values of $\zeta_{\text{max}}$, $q$, and $\gamma_{S0}$ (Table 2.2) using the values of the effective particle diameter at the various methyl acrylate concentrations.

![Figure 2.8](image)

*Figure 2.8.* The enhancement factor $E$ and the effective particle diameter $d_{\text{eff}}$ as a function of the methyl acrylate concentration ($\gamma_s = 0.5 \text{ kg m}^{-3}$, $\zeta_{\text{max}}$, $\gamma_{S0}$, and $q$: see Table 2.2). ●: The measured value of $E$; —: The model; · · ▲ · ·: The calculated values of $d_{\text{eff}}$ (right hand axis)).

Several possible explanations for the observed increase in conversion rate as a function of the concentration methyl acrylate could be put forward, e.g. an increasing specific bubble surface and a change in the bubble coverage. For the surface tensions used for the experiments the change in the specific bubble surface will not exceed 5% (Perry), which cannot explain the change in the conversion rate. Figure 2.8 shows that the observed increased enhancement can be explained by a decreasing effective particle diameter. This suggests that the agglomeration behaviour of the catalyst particles is an important reason for the observed enhancement. This hypothesis is supported by the fact that the calculated values of the effective particle diameter under non-stagnant reactor conditions, represented in Table 2.3, show a similar trend with the concentration as the agglomerates under stagnant hydrodynamic conditions.
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represented in Figure 2.6. This effect of methyl acrylate on agglomeration can be caused by three different phenomena. The first possible explanation is the effect of the surface tension. The other two possible explanations are both based on adsorption of methyl acrylate on the carbon surface: i.e. an effect on hydrophobicity and on the interparticle forces. Probably the surface plays the most important role.

2.5 Conclusions

A new model has been developed which describes the enhancement of the conversion rate of the hydrogenation of methyl acrylate caused by an increase in hydrogen transfer rate owing to adhesion of catalyst particles to gas bubbles. This model is based on the gas-liquid film theory, particle to bubble collision probability and the effect of the particle diameter of adhering particles on the effective film thickness.

The enhancement factor E obtained from hydrogenation experiments at different catalyst concentrations (\( \gamma_S = 0.1-1 \text{ kg m}^{-3} \)) and several methyl acrylate concentrations (\( C_{ma} = 0.06-0.19 \text{ mol L}^{-1} \)) are in excellent agreement with the results of the introduced model.

An important phenomenon is the agglomeration of Pd/C catalyst particles. A decrease in agglomerate size with increasing concentration of methyl acrylate is observed under stagnant conditions and is likely to hold under non-stagnant conditions. Agglomeration of catalyst particles results in a decreased conversion rate and enhancement factor. With the developed enhancement model accurate prediction of the impact of agglomeration on the rate of conversion can be calculated.
2.6 Nomenclature

- $a_L$: bubble surface per unit of slurry volume, $m^2 m^{-3}$
- $a_S$: external catalyst surface per unit of slurry volume, $m^2 m^{-3}$
- $C_g$: concentration of the gaseous reactant in gas phase, mol $m^{-3}$
- $C^*$: concentration at the film side of the gas-liquid interface, mol $m^{-3}$
- $C_B$: concentration of the gaseous reactant in the bulk liquid, mol $m^{-3}$
- $C_S$: concentration of the gaseous reactant at the liquid side of the solid-liquid interface, mol $m^{-3}$
- $C_{ma}$: concentration methyl acrylate, mol $L^{-1}$
- $D_{AB}$: binary diffusion coefficient, $m^2 s^{-1}$
- $d_p$: particle diameter, m
- $E$: enhancement factor, -
- $k_L$: liquid-side mass transfer coefficient for the uncovered part of the bubble surface, m $s^{-1}$
- $k_{LS}$: liquid-side mass transfer coefficient for the covered part of the bubble surface, m $s^{-1}$
- $k_S$: mass transfer coefficient from the bulk liquid to the surface of the catalyst, m $s^{-1}$
- $k_r$: reaction rate constant, $s^{-1}$
- $m$: partition coefficient defined as the ratio between the amount of gas phase reactant molecules per unit volume catalyst and the amount of gas phase reactant molecules per unit volume liquid, -
- $q$: constant used in equation (6.11), $m^3 kg^{-1}$
- $V_L$: volume of the solid-liquid suspension in the reactor, $m^3$

Greek symbols

- $\gamma_S$: catalyst concentration in the slurry, kg $m^{-3}$
- $\gamma_{S0}$: critical catalyst concentration, kg $m^{-3}$
- $\delta$: liquid-film thickness at the uncovered part of the bubble, m
- $\delta_{eff}$: effective liquid-film thickness at the covered part of the bubble, m
- $\varepsilon$: gas holdup, volume gas per total volume of suspension and gas, $m^3 m^{-3}$
- $\zeta$: fraction of bubble surface covered by adhering particles, -
- $\zeta_{max}$: maximum bubble coverage, -
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\[ \eta \quad \text{effectiveness factor of the catalyst, } - \]
\[ \rho_{pg} \quad \text{density of a dried catalyst with gas filled pores, } \text{kg m}^{-3} \]
\[ \sigma_{LG} \quad \text{static surface tension between gas phase and liquid phase, } \text{N m}^{-1} \]
\[ \Phi \quad \text{collision probability function, } - \]
\[ \Phi_c \quad \text{gaseous mass transfer rate for the covered part of the bubble, } \text{mol s}^{-1} \]
\[ \Phi_u \quad \text{gaseous mass transfer rate for the uncovered part of the bubble, } \text{mol s}^{-1} \]
\[ \Phi_\zeta \quad \text{conversion rate in presence of adhering particles, } \text{mol s}^{-1} \]
\[ \Phi_{\zeta=0} \quad \text{conversion rate in absence of adhering particles, } \text{mol s}^{-1} \]
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2.7 References


