CHARACTERIZING THE KINETICS OF HETEROGENEOUS EXOTHERMIC REACTIONS

Kathrin Biskup¹, Heiko Bothe¹, Günther Hessel, Günther Hulzer¹, Holger Kryk, Wilfried Schmitt, Nurelegne Tefera

1. Introduction

In the pharmaceutical and fine chemical industry the knowledge of thermo-kinetic reaction parameters is of practical interest to the process optimization for economic and environmental reasons as well as to the risk management of exothermic reactions with a high hazardous potential. Since the thermo-kinetic data are mainly determined at the laboratory scale, the scale-up problem plays a crucial role when the results have to be adapted to the production plant. For this purpose, reaction calorimeters are a well-suited tool because they allow to work under conditions of stirred industrial tank reactors. In recent years the performance of calorimetric methods has been proven for homogeneous reactions. The aim of this paper is to present a set of experiments which allow to characterize exothermic reactions in heterogeneous systems. Results are described for the catalytic hydrogenation of a nitro aromatic compound.

2. Fundamentals of the heterogeneous process

The kinetics of homogeneous exothermic reactions can be characterized by the reaction enthalpy and the thermo-kinetic parameters such as the rate of reaction, the activation energy and the order of reaction. Due to multiphase reactions in heterogeneous systems, the reaction kinetics is additionally affected by the phase equilibrium and the mass transfer. Therefore, the gas solubility and the mass transfer coefficients have to be determined if they significantly affect on the reaction rate. As an example for complex heterogeneous reactions, the process kinetics of the catalytic hydrogenation of a substituted nitrobenzoate (SNBE) to a substituted aminobenzoate (SABE) is described in the following.

The three-phase process (gas-liquid-solid) of the catalytic hydrogenation is not only influenced by the reaction kinetics, but also by the hydrodynamics and the mass transfer. During the hydrogenation reactions which are catalysed by solids, the reactants must be transferred to the reaction site. The chemisorption onto the catalyst surface could be a rate determining step. Depending on the process conditions and the effects of the mass transfer, two pathways for the reduction of nitro compounds to amines are possible (Fig. 1). The first path a) proceeds from the sequential reduction of nitro compounds to nitroso compounds, next to hydroxylamine, and finally, to amine. This path a) is favoured when the reduction of nitro compounds is conducted with metals and mineral acids. The second path b) is possible under process conditions that lead to an increase of concentration of the intermediates nitroso and hydroxylamine. Both intermediates can combine to the azyoxy compound followed by reduction to the azo compound, hydrazo compound, and finally, to the amine (SABE). The kinetics of this pathway of the SABE formation is much slower. Due to the accumulation of intermediates, the

¹ Arzneimittelwerk Dresden GmbH (AWD)
hazardous potential of the catalytic hydrogenation is increased extremely since it can lead to side-reactions which are strongly exothermic. Furthermore, the azoxy formation, in contrast to the hydrogenation, cannot be controlled by the hydrogen supply because this side-reaction takes place without hydrogen uptake. Therefore, it is necessary to know whether accumulations of intermediates occurs.

Path a):

\[ R - \text{NO}_2 \xrightarrow{H_2} R - \text{NO} + H_2O \xrightarrow{H_2} R - \text{NHOH} \xrightarrow{H_2} R - \text{NH}_2 + H_2O \]

Path b):

\[ R - N = N - R + H_2O \xrightarrow{H_2} R - NH - NH - R \]

Fig. 1: Reaction pathways for the reduction of SNBE (nitro compound) to SABE (amine)

3. Measuring methods

3.1 Measurement of the gas solubility and mass transfer coefficient

To investigate the gas solubility and the volumetric mass transfer coefficient from the gas to liquid phase, the batch absorption of hydrogen in a stirred tank reactor was measured [1]. The advantage of this method is that both parameters can be determined without H₂-concentration measurements in real reaction mixtures. The pressure profile during the batch absorption of H₂ in the reaction mixture is depicted in Fig. 2. Before the reactor is pressurized with hydrogen, first the liquid must be degassed under agitation to reach an equilibrium at known pressure \( P_0 \) and temperature \( T \). Then the agitation is stopped and the reactor is pressurized with H₂ to the desired pressure \( P_m \). When the thermal equilibrium is reached, the stirrer is started. During starting the agitation, the gas absorption will be accelerated and the pressure continues to drop until the saturation point \( P_m \) is reached. The gas solubility \( \alpha \) can be determined by monitoring the initial and final pressures:

\[
\alpha = \frac{P_m - P_\infty}{P_\infty - P_0} \cdot \frac{V_G}{V_L} \cdot \frac{l}{RT} = \frac{l}{He}
\]

where

- \( V_G \) gas volume [l]
- \( V_L \) liquid volume [l]
- \( R \) general gas constant \( R = 8.31 \text{ kJ/(kmol} \cdot \text{K)} \)
- \( \alpha \) gas absorption coefficient [kmol/(m³ · kPa)]
- \( He \) Henry constant [(m³ · kPa)/kmol]
The integration of the mass balance between gas and liquid phase gives the following equation:

\[
\ln \left( \frac{P_m - P_m^\infty}{P - P_m^\infty} \right) = k_L a \frac{P_m - P_0}{P_m^\infty - P_0} \cdot t
\]  

(2)

where \( P \) is the pressure at the time \( t \).

Equation (2) shows that the value of the volumetric mass transfer coefficient \( k_L a \) as the product of the mass transfer coefficient and the specific boundary surface can be determined from the slope of the pressure drop (Fig. 2).

![Fig. 2: Pressure profile during the batch absorption of H₂](image)

### 3.2 Reaction enthalpy and thermo-kinetic parameters

Since the heat release rate \( \dot{Q}_r \) of exothermic reactions is proportional to the rate of reaction \( r \), to the volume of the reaction mixture \( V \), and to the enthalpy \( (-\Delta H_r) \), calorimetric methods can be used to determine the reaction enthalpy and the overall rate of reaction:

\[
\dot{Q}_r = rV(-\Delta H_r)
\]  

(3)

According to Arrhenius’ law, the rate of reaction \( r \) is an exponential function of temperature:

\[
r = k_0 \exp \left(-\frac{E_a}{RT}\right)C_{A0}^n (1-x)^n
\]  

(4)

where

- \( k_0 \) pre-exponential factor (unit depends on reaction order)
- \( E_a \) activation energy [kJ/kmol]
- \( C_{A0} \) initial concentration of reactant [kmol/m³]
- \( n \) reaction order.
- \( x \) conversion of reactant during the reaction
- \( r \) rate of reaction [kmol/(m³ · s)]
To determine the activation energy and the pre-exponential factor, a set of isothermal experiments at different temperatures have to be carried out in the reaction calorimeter.

4. Experimental equipment

The experiments were carried out in the METTLER high pressure reaction calorimeter RC1e/HP60 that was equipped with a high speed gassing-stirrer. To insure a good gas dispersion, the stirrer operated at 1000 rpm. This reaction calorimeter was mainly used to determine the reaction enthalpy with in situ high accuracy and to investigate the reaction kinetics. An FTIR spectrometer was applied to monitor the concentration profiles of reactants, products, and, if possible, of intermediates. The hydrogen uptake was monitored by gas flow measurements. The studies of mass transfer processes were carried out in the automatic laboratory reactor (ALR) that was additionally equipped with a fast-response pressure sensor.

5. Results

5.1 Gas solubility and mass transfer

According to equation (1), the H\textsubscript{2} solubility $\alpha_{\text{H}_2}$ was determined from the pressure values $P_m$, $P_a$, and $P_0$. The solubility measurements in the reaction mixture, consisting of isopropanol and SNBE without the catalyst, provided a mean solubility coefficient $\bar{\alpha}_{\text{H}_2}$ at 30 °C

$$\bar{\alpha}_{\text{H}_2, \text{mix}} = 4 \cdot 10^{-5} \frac{\text{kmol}}{m^3 \text{kPa}}$$

In isopropanol (tech), a little lower H\textsubscript{2} solubility at 30 °C was obtained

$$\bar{\alpha}_{\text{H}_2, \text{isop}} = 2.9 \cdot 10^{-5} \frac{\text{kmol}}{m^3 \text{kPa}}$$

As presented by the Arrhenius plot (Fig. 3) of the H\textsubscript{2} solubility in isopropanol (tech), there is an exponential dependence on the temperature of the liquid.

![Fig. 3: Arrhenius plot of the H\textsubscript{2} solubility in isopropanol (tech.) using a gassing stirrer.](image-url)
From the Arrhenius plot (Fig. 3), the following dependence of the H$_2$ solubility on the temperature was determined

$$\alpha_{H_2, isop}(T) = 1.67 \times 10^{-5} \exp \left( \frac{1373}{RT} \right) \frac{kmol}{m^3 kPa}$$ (5)

Obviously, the low content of water in technical isopropanol seems to be responsible for the opposite dependence on the temperature [2].

The results of the $k_{L\alpha}$-determination, represented in Tab. 2, show that the H$_2$ transfer to the liquid phase of the isopropanol depends on the stirrer speed and on the temperature of the liquid. For comparison, the mass transfer coefficients for a three-blade stirrer are also given. The gassing stirrer provides higher $k_{L\alpha}$-values because the H$_2$ gas is well-dispersed into the liquid volume in small bubbles as observed in a glass reactor.

Table 2: Experimental $k_{L\alpha}$-values for the H$_2$ transfer into isopropanol (tech.) at different temperatures and two stirrer speeds of the gassing stirrer.

<table>
<thead>
<tr>
<th>$T_r$ [$^\circ$C]</th>
<th>n [1/min]</th>
<th>$k_{L\alpha}$ [1/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1000</td>
<td>0.26</td>
</tr>
<tr>
<td>40</td>
<td>1000</td>
<td>0.31</td>
</tr>
<tr>
<td>60</td>
<td>1000</td>
<td>0.57</td>
</tr>
<tr>
<td>30</td>
<td>600</td>
<td>0.021</td>
</tr>
<tr>
<td>60</td>
<td>600</td>
<td>0.036</td>
</tr>
<tr>
<td>30,0*</td>
<td>600</td>
<td>0.013</td>
</tr>
<tr>
<td>30,0*</td>
<td>1000</td>
<td>0.175</td>
</tr>
</tbody>
</table>

* 3-blades impeller stirrer

5.2 Reaction enthalpy

The overall heat $Q_r$ of the reaction was determined from isothermal experiments in the RC1 reaction calorimeter. The molar reaction enthalpy $\Delta H_r$ is defined by

$$\Delta H_r = \frac{Q_r}{n_{SNBE}}$$ (6)

where $n_{SNBE}$ is the amount of moles of SNBE. The experimental results for different reaction conditions and SNBE charges are listed in Tab. 3. Assuming a complete conversion of SNBE, an average value of the molar reaction enthalpy $\Delta \overline{H}_r$ can be calculated:

$$\Delta \overline{H}_r = -558 \text{ kJ/mol}_{SNBE}$$

This mean value is in good agreement with the known molar reaction enthalpy for nitrobenzene [3]:

$$\Delta H_r = -560 \text{ kJ/mol}$$

A significant dependence of the reaction enthalpy on the temperature was not found.
Table 3: Heat of reaction and molar reaction enthalpy for the hydrogenation of SNBE to SABE

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$T_r$ [°C]</th>
<th>$n_{SNBE}$ [mol]</th>
<th>$m_{cat}$ [g]</th>
<th>$Q_r$ [kJ]</th>
<th>$\Delta H_r$ [kJ/mol]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNBE02**b</td>
<td>30</td>
<td>1,5</td>
<td>0,75</td>
<td>-879,6</td>
<td>-586</td>
</tr>
<tr>
<td>SNBE18**a</td>
<td>30</td>
<td>0,25</td>
<td>0,75</td>
<td>-129,7</td>
<td>-519</td>
</tr>
<tr>
<td>SNBE20*a</td>
<td>30</td>
<td>0,25</td>
<td>0,75</td>
<td>-136,0</td>
<td>-544</td>
</tr>
<tr>
<td>SNBE24**</td>
<td>60</td>
<td>0,25</td>
<td>0,75</td>
<td>-149,4</td>
<td>-597</td>
</tr>
<tr>
<td>SNBE25**</td>
<td>30</td>
<td>0,25</td>
<td>2,25</td>
<td>-135,6</td>
<td>-542</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-557,8</td>
</tr>
</tbody>
</table>

* SNBE(new charge), ** SNBE(old charge)

a with after more than 15h hydrogenation, b concentrated SNBE, c catalyst 5% Pt in Carbon

5.3 Reaction rate

Experimental results show that the overall reaction rate $r$ and therefore the heat release rate $Q_r$ is directly proportional to the amount of the added catalyst. This is illustrated in Fig. 4 for 0,54 and 1,08 wt% Pt.

![Fig. 4: Influence of the catalyst concentration on the heat release rate.](image)

The influence of pH on the reaction rate was also studied. In the acidic solution (with HCl), the reaction rate is very slow, whereas in the basic solution (pH = 8) the reaction rate is very high. This result is in agreement with the investigation of Turek and Co-workers [4] for the hydrogenation of glucose.

Experimental investigation of another charge of SNBE (new charge) shows a higher reaction rate compared to the old charge at the same reaction conditions (see Fig. 5). FTIR spectroscopy of both SNBE charges gives the same result. There is only a slight difference in colour of the SNBE.
It is advisable to investigate whether path a) or path b) is favoured under the above experimental conditions. In a basic solution of an alcohol, the rate of the reaction between nitroso and hydroxylamine, forming the azoxy compound, is much higher than the reduction step. If this is true, the rate of formation of amine through path b) seems to be the probable mechanism. According to the information of the industrial partner (AWD), the reason for the azoxy formation lies in the type of SNBE that was used.

5.4 Reaction kinetics

To investigate the kinetics of the hydrogenation of SNBE to SABE, the following process model is assumed. The solubility of $H_2$ in the reaction mixture is modelled as follows

$$ H_2 \ (g) \ \overset{k_i}{\rightleftharpoons} \ H_2 \ (l) $$

(7)

$$ r_1 = k_1 P_{H_2}, \ \text{and} \ \ r_2 = k_2 [H_2 \ (l)] $$

(8)

The equilibrium condition is given by

$$ [H_2 \ (l)] = \frac{k_1}{k_2} P_{H_2} = \alpha_{H_2} P_{H_2} $$

(9)

Assuming that only Hydrogen is adsorbed onto the catalyst surface and that the adsorption/desorption of $H_2(l)$ onto the catalyst is the rate determining step, the following mechanism can be formulated:

- Adsorption/desorption of hydrogen onto the catalyst (E)

$$ H_2 \ (l) \ + \ E \ \overset{k_i}{\rightleftharpoons} \ H_2 - E $$

(10)

$$ r_3 = k_3 [H_2 \ (l)] [E] \ \text{and} \ r_4 = k_4 [H_2 - E] $$

(11)
• Intermediate formation (hydroxylamine) and desorption of the hydroxylamine

\[ R - NO_2 + 2(H_2 - E) \xrightarrow{k_5} R - NHOH + H_2O + 2E \]  \hspace{1cm} (12)

\[ r_5 = k_5 [R - NO_2][H_2 - E], \quad \Delta H_{r,5} \]  \hspace{1cm} (13)

• Product formation (amine): reaction between the adsorbed hydrogen and hydroxylamine from the liquid phase to amine and desorption

\[ R - NHOH + H_2 - E \xrightarrow{k_6} R - NH_2 + H_2O + E \]  \hspace{1cm} (14)

\[ r_6 = k_6 [R - NHOH][H_2 - E], \quad \Delta H_{r,6} \]  \hspace{1cm} (15)

The above equations are used to fit the experimental data of the heat release rate $\dot{Q}_r$ by means of the program RATE (BATCHCAD). To determine the model parameters, the molar reaction enthalpy should be known for each reaction step. In [3] the following molar reaction enthalpies were experimentally determined for the hydrogenation of nitrobenzene to aniline for path a):

$\Delta H_{r,5} = -320 \text{ kJ/mol}$ and $\Delta H_{r,6} = -225 \text{ kJ/mol}$

Using these molar reaction enthalpies, the model parameters $k_3$, $k_4$, $k_5$ and $k_6$ were adjusted with isothermal experiments. Fig. 6 shows experimental data $\dot{Q}_{\text{exp}}$ and model predictions $\dot{Q}_{\text{model1}}$ for the best fit using these enthalpies. There is a big discrepancy between the predicted and experimental values of $\dot{Q}_r$.

Next, the molar reaction enthalpies $\Delta H_{r,5}$ and $\Delta H_{r,6}$ were assumed to be proportional to the hydrogen uptake for each step and were set to be 2/3 of the overall reaction enthalpy for the formation of hydroxylamine and 1/3 for the formation of amine, respectively. The overall molar reaction enthalpy is $-560 \text{ kJ/mol}$ SNBE. Using these molar reaction enthalpies $\Delta H_{r,5} = -373 \text{ kJ/mol}$ and $\Delta H_{r,6} = -187 \text{ kJ/mol}$, the isothermal model parameters were estimated. The results are also plotted in Fig. 6 ( $\dot{Q}_{\text{model2}}$ ). This model provides a better approximation of the experimental data. Therefore, in this study $\Delta H_{r,5} = -373 \text{ kJ/mol}$ and $\Delta H_{r,6} = -187 \text{ kJ/mol}$ were adopted.

Fig. 6: Comparison between experimental data ( $\dot{Q}_{\text{exp}}$ ) and model ( $\dot{Q}_{\text{model1/2}}$ ) heat release rate.
Using the above molar enthalpies, the model parameters $k_3$, $k_4$, $k_5$ and $k_6$ were estimated for the isothermal hydrogenation of SNBE to SABE in the temperature range of 30°C to 60°C. The numerical values of the adjusted parameters are given in Table 4.

Table 4: Estimated parameters for the isothermal hydrogenation of SNBE to SABE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$30°C$</th>
<th>$40°C$</th>
<th>$50°C$</th>
<th>$60°C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_3$ [m$^3$/kg·s]</td>
<td>0.501343</td>
<td>0.741837</td>
<td>1.061190</td>
<td>1.279040</td>
</tr>
<tr>
<td>$k_4$ [1/s]</td>
<td>$4.47 \cdot 10^{-5}$</td>
<td>$4.47 \cdot 10^{-5}$</td>
<td>$4.47 \cdot 10^{-5}$</td>
<td>$4.47 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$k_5$ [m$^3$/kmol·s]</td>
<td>0.101043</td>
<td>0.202933</td>
<td>0.311271</td>
<td>0.769326</td>
</tr>
<tr>
<td>$k_6$ [m$^3$/kmol·s]</td>
<td>$5.4288 \cdot 10^{-4}$</td>
<td>$1.3739 \cdot 10^{-3}$</td>
<td>$3.8408 \cdot 10^{-3}$</td>
<td>$9.2715 \cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

The parameters $k_3$ and $k_4$ are the adsorption and desorption rate constants for hydrogen onto the catalyst. $k_4$ appears to be independent of the temperature and constant, where as $k_3$, $k_5$ and $k_6$ increase with the reaction temperature. The Arrhenius plot is illustrated in Fig. 7.

![Arrhenius plot of the reaction rate constants.](image-url)

**Fig. 7: Arrhenius plot of the reaction rate constants.**

The following dependencies on the temperature were found:

$$
\begin{align*}
    k_3 &= 2.058 \cdot 10^4 \exp\left(-\frac{26690}{RT}\right) \frac{m^3}{kg \cdot s} \\
    k_4 &= 4.47 \cdot 10^{-5} \text{ s}^{-1} \\
    k_5 &= 1.3708 \cdot 10^{10} \exp\left(-\frac{65430}{RT}\right) \frac{m^3}{kmol \cdot s} \\
    k_6 &= 3.6747 \cdot 10^{10} \exp\left(-\frac{80344}{RT}\right) \frac{m^3}{kmol \cdot s}
\end{align*}
$$

(16)

Figure 8 compares simulation and experimental results of the heat release rate at different temperatures. Now there is a good agreement between the model and experimental results. Qualitative analyses of the reaction product show that an intermediate product which seems to be the azoxy compound was produced. Therefore, the reaction mechanism given in path b)
(Fig. 1) should also be considered to model the hydrogenation of SNBE to SABE, especially if the overall reaction rate is low.

Fig. 8: Comparison of the heat release rate between simulation and experimental results.

6. Conclusions

The catalytic hydrogenation of SNBE to SABE is a complex exothermic process influenced by the competing effects of mass transfer and kinetics. In reaction calorimeters, several methods were applied to determine the parameters of kinetics and mass transfer under different process conditions. The reaction pathway is determined by the reactant quality and the process conditions. It was found that a bad quality of SNBE and disadvantageous process conditions can cause an accumulation of intermediates which probably desactivate the catalyst and lead to low process rates. Further work is necessary to investigate the gas solubility and mass transfer in the production plant as well as to simulate and to study the industrial conditions in the laboratory reactor.

References

[2] Landolt-Börnstein, 6. Aufl., Bd. II/2 b, pp 1-184