Heterogeneous Catalysis Engineering

E. Klemm

Topical Workshop Catalysis
DFG Priority Program 1362
Stuttgart, April 12, 2011
Outline

• What is „Heterogeneous Catalysis Engineering“?

• Bulk Chemicals Manufacture
  • Space Time Yield
  • Selectivity-Conversion-Plots
  • Catalyst Life Time

• Fine Chemicals Manufacture
  • Space Time Yield
  • Atom Efficiency (E Factor)
  • Time-to-Market

• Bench Scale Reactors for Het. Cat. Eng.
What is “Heterogeneous Catalysis Engineering”? 

- **Time Scale**
  - Production Level
  - Process Engineering
  - Reaction Engineering
  - Surface Science

- **Length Scale**
  - Quality Control Longterm Stability
  - Separation units Recycle
  - Reaction Kinetics Reactor Modelling Scale-up
  - Operando Spectroscopy Quantum Mechanics / DFT
What is “Heterogeneous Catalysis Engineering”?

<table>
<thead>
<tr>
<th>Molecular Scale</th>
<th>Particle Scale</th>
<th>Reactor Scale</th>
<th>Process Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>E P+SP</td>
<td>E+P+SP</td>
<td>E</td>
</tr>
<tr>
<td>P</td>
<td>P+SP</td>
<td>SP</td>
<td>P</td>
</tr>
<tr>
<td>SP</td>
<td></td>
<td></td>
<td>Purge</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Active Site</th>
<th>Catalyst Pellet</th>
<th>Reactor</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity</td>
<td>Turnover Frequency</td>
<td>Effective Reaction Rate</td>
<td>Conversion / Space Time Yield</td>
<td>Process Conversion</td>
</tr>
<tr>
<td>Selectivity</td>
<td>Differential Selectivity on Active Site</td>
<td>Differential Selectivity on Pellet</td>
<td>Integral Selectivity</td>
<td>Process Selectivity</td>
</tr>
</tbody>
</table>

**Heterogeneous Catalysis Research**

**Heterogeneous Catalysis Engineering**
What is “Heterogeneous Catalysis Engineering”?

- Start of Production
- Commissioning
- Mechanical Completion
- Detailed Engineering
- Basic Engineering
- Front End Engineering
- Feasibility Study
- Bench Scale Experiments

**Heterogeneous Catalysis Engineering (Industry)**

- Space Time Yield, Selectivity/Conversion, catalyst life time etc.
- Market Analysis, Profitability (CAPEX, OPEX)
- Preliminary Flow Sheet, Technical Reactor Concept
- Detailed Flow Sheet, Dimensioning of Apparatuses, Expenditure Estimation (CAPEX, OPEX)
- Measuring and Control, Dimensioning of Pipes, Ordering
- Erection of Plant, Commissioning
- Start of Production

**Heterogeneous Catalysis Engineering (University/Industry)**

- Time
- Space Time Yield, Selectivity/Conversion, catalyst life time etc.
- Market Analysis, Profitability (CAPEX, OPEX)
- Preliminary Flow Sheet, Technical Reactor Concept
- Detailed Flow Sheet, Dimensioning of Apparatuses, Expenditure Estimation (CAPEX, OPEX)
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- Start of Production
What is “Heterogeneous Catalysis Engineering”?

„The bench scale results were so good that we by-passed the pilot-plant“

What is “Heterogeneous Catalysis Engineering”?

<table>
<thead>
<tr>
<th></th>
<th>Bulk Chemicals</th>
<th>Fine Chemicals</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plant Capacity</strong></td>
<td>&gt; 10,000 metric tons per year (usually: some 100,000 t/a)</td>
<td>&lt; 10,000 metric tons per year (usually &lt; 1,000 t/a)</td>
</tr>
<tr>
<td><strong>Space Time Yield</strong></td>
<td>1-10 kilogram per liter and hour</td>
<td>0.01-1 kilogram per liter and hour</td>
</tr>
<tr>
<td><strong>Processing</strong></td>
<td>continuous</td>
<td>batch-wise</td>
</tr>
<tr>
<td><strong>Phase</strong></td>
<td>gas (liquid)</td>
<td>liquid</td>
</tr>
<tr>
<td><strong>Reactor</strong></td>
<td>typically tube</td>
<td>typically stirred tank</td>
</tr>
<tr>
<td><strong>Plant</strong></td>
<td>dedicated</td>
<td>multi-purpose</td>
</tr>
<tr>
<td><strong>Product price</strong></td>
<td>&lt; 10 $/kg</td>
<td>&gt; 10 $/kg</td>
</tr>
<tr>
<td><strong>Lifecycle of product</strong></td>
<td>long</td>
<td>relatively short</td>
</tr>
<tr>
<td><strong>Added value</strong></td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td><strong>Raw materials quote</strong></td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td><strong>kg waste / kg product</strong></td>
<td>relatively low (&lt; 1-5)</td>
<td>high (5-50)</td>
</tr>
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Outline

• What is „Heterogeneous Catalysis Engineering“?

• Bulk Chemicals Manufacture
  • Space Time Yield
  • Selectivity-Conversion-Plots
  • Catalyst-Life-Time

• Fine Chemicals Manufacture
  • Space-Time-Yield
  • Atom Efficiency (E Factor)
  • Time-to-Market

• Bench Scale Reactors for Het. Cat. Eng.
Bulk Chemicals Manufacture

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Bulk Chemicals Manufacture

Process Profitability =
f(Reactor Costs, Separation Costs, Recycle Costs, Feedstock Costs…)

- **CAPEX**
  - Reactor Costs = f(Space Time Yield)
  - Feedstock Costs = f(Selectivity)

- **OPEX**
  - Recycle Costs = f(Conversion)
  - Separation Costs = f(Selectivity)
Bulk Chemicals Manufacture

Process Profitability = f(Selectivity-Conversion-Plot, …)

Educt → Product → Side Product

Molecular Scale:
• Turnover Frequencies
• Reducing Formation of Side Products

Particle Scale:
• Avoiding Film and Pore Diffusion Limitation
• Utilization of Shape Selective Effects

Reactor Scale:
• Avoiding Backmixing
• Avoiding Hot Spots

Process Scale:
• Recycle of Educt
• Integration of Separation
Bulk Chemicals Manufacture

- with increasing conversion the selectivity decreases
  -> feed-stock costs increase
- with increasing conversion less educt has to be separated and recycled
  -> energy costs decrease
Bulk Chemicals Manufacture

\[
\begin{align*}
\text{CH}_3\text{COOH} + \text{H}_2\text{C}=\text{CH}_2 + 0,5 \text{O}_2 & \xrightarrow{\text{Pd/Au}} \text{H}_3\text{C}=\text{O}\text{C}=\text{CH}_2 + \text{H}_2\text{O} \\
X_{\text{HAc}} &= 15-35 \% \quad X_{\text{C}_2\text{H}_4} = 8-10 \% \\
S_{\text{VAM,C}_2\text{H}_4} &= 88-96 \%
\end{align*}
\]
Bulk Chemicals Manufacture

Process Profitability = \( f(\text{Reactor Costs, \ldots}) \)

Reactor Costs
\( = f(\text{Space Time Yield}) \)
Bulk Chemicals Manufacture

Process Profitability = \(f(\text{Space Time Yield (STY)}, \ldots)\)

\[
STY = \frac{\dot{m}_P}{V_{\text{react}}} = \frac{\dot{V} \cdot c_{Eo} \cdot X_E \cdot S_{P,E} \cdot M_P}{V_{\text{react}}} = \]

\[
= \frac{c_{Eo} \cdot X_E \cdot S_{P,E} \cdot M_P}{\tau}
\]

Typical Values of STY:
1-10 kg product per 1 liter reaction volume and hour
# Bulk Chemicals Manufacture

**Space Time Yield (STY):**

<table>
<thead>
<tr>
<th>Type</th>
<th>Yield (kg/(l·h))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Het. Catalysis</td>
<td>1-10</td>
</tr>
<tr>
<td>Hom. Catalysis</td>
<td>0.01 – 1</td>
</tr>
<tr>
<td>Biocatalysis</td>
<td>0.001 – 0.01</td>
</tr>
</tbody>
</table>

The space time yield represents the rate at which product is generated per liter of reaction volume and hour of reaction time. The values indicate the efficiency of the catalytic processes in different environments.

*Reaction temp.* and *Cat. conc.* refer to the reaction temperature and catalyst concentration, respectively.
Bulk Chemicals Manufacture

Process Profitability = f(Space Time Yield (STY), …)


Bulk Chemicals Manufacture

usually:
catalyst life time at least 8.000 hrs. (1 year)
Bulk Chemicals Manufacture (Example I)

Direct Ring Oxidation of Aromatics with N\textsubscript{2}O

(E. Klemm et al., Direct Ring Oxidation of Aromatics, in: G. Ertl, H. Knözinger, J. Weitkamp (Hg.), Handbook of Heterogeneous Catalysis, 2\textsuperscript{nd} edition, WILEY-VCH, Weinheim, 2008)

\[ \text{Benzene} + \text{N}_2\text{O} \xrightarrow{\text{ZSM-5, 300-500°C, 1bar}} \text{Phenol} + \text{N}_2 \]

Strong adsorption and slow diffusion of product compared to educt!
Bulk Chemicals Manufacture (Example II: DEMiS®)

\[
\text{gas} \quad \text{H}_2\text{O}_2/vapour \quad \text{TS-1 cat.} \quad \text{H}_2\text{O} + \text{olefin} \quad \Delta H_R = -220 \text{ kJ/mol}
\]

Lab Scale

Bulk Chemicals Manufacture (Example II: DEMiS®)

Bulk Chemicals Manufacture (Example II: DEMiS®)

\[
\text{Catalyst TS-1}
\]

<table>
<thead>
<tr>
<th>Reaction conditions</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>reaction temperature [°C]</td>
<td>100 - 150</td>
</tr>
<tr>
<td>reaction pressure [bar]</td>
<td>1</td>
</tr>
<tr>
<td>substrate/hydrogen peroxide</td>
<td>&gt;1</td>
</tr>
<tr>
<td>hydrogen peroxide in gas [vol%]</td>
<td>3 – 8</td>
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</table>

\[
\text{ΔH}_\text{R} = -220 \text{ kJ/mol}
\]

![Reaction conditions graph](image)

- Lab scale fixed bed (C3H6/H2O2=1,0)
- Lab scale micro reactor (C3H6/H2O2=1,4)
- Lab scale micro reactor (C3H6/H2O2=2,4)
- Pilot scale micro reactor (C3H6/H2O2=1,4)
- Pilot scale micro reactor (C3H6/H2O2=2,4)
Bulk Chemicals Manufacture (Example II: DEMiS®)

\[
\text{Catalyst TS-1}
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\[
\Delta H_R = -220 \text{ kJ/mol}
\]

\[
\text{Lab scale fixed bed (C}_3\text{H}_6/\text{H}_2\text{O}_2=1,0) \]
\[
\triangle \text{Lab scale micro reactor (C}_3\text{H}_6/\text{H}_2\text{O}_2=1,4) \]
\[
\text{Lab scale micro reactor (C}_3\text{H}_6/\text{H}_2\text{O}_2=2,4) \]
\[
\blacklozenge \text{Pilot scale micro reactor (C}_3\text{H}_6/\text{H}_2\text{O}_2=1,4) \]
\[
\blacksquare \text{Pilot scale micro reactor (C}_3\text{H}_6/\text{H}_2\text{O}_2=2,4) \]

\[
\begin{align*}
\text{S (propylene oxide, H}_2\text{O}_2) / \% & \quad \text{X (H}_2\text{O}_2) / \% \\
\end{align*}
\]

\[
\text{gas}\ H_2O_2/\text{vapour} \xrightarrow{\text{TS-1 cat.}} \text{H}_2\text{O} + \text{O} \]

23
Bulk Chemicals Manufacture (Example II: DEMiS®)

\[
\text{gas} \quad + \quad \text{vapour} \quad \xrightarrow{\text{TS-1 cat.}} \quad \text{H}_2\text{O} \quad + \quad \text{O}_2, \quad \Delta H_R = -220 \text{ kJ/mol}
\]

S. Heinrich, M. Plettig, E. Klemm,

T. Schwarz, S. Schirrmeister, H. Döring, E. Klemm,
*Herstellung von Wandkatalysatoren für Mikrostrukturreaktoren mittels der Niederdruckspritztechnologie*,

Katalytisch beschichtete Träger, Verfahren zu dessen Herstellung und damit ausgestatteter Reaktor sowie dessen Verwendung,

E. Klemm, G. Mathivanan, T. Schwarz, S. Schirrmeister,

E. Klemm et al.,
*Method for Obtaining a Gaseous Phase From a Liquid Medium and Device for Carrying Out the Same*,

Virtual, but realistic example:

Fine chemical synthesis with \( Y_{P,E} = 80 \% \), \( c_{E_0} = 1 \text{ mol/l} \) and \( M_P = 100 \text{ g/mol} \)
(assuming stirred tank reactor with \( V_{reac} = 2 \text{ m}^3 \))

3-shift batch-wise operation:

\[
m_{\text{Product/day}} = 3 \cdot V_{reac} \cdot c_{E_0} \cdot Y_{P,E} \cdot M_P = \\
= 3 \cdot 2,000 \text{l} \cdot 1 \text{mol/l} \cdot 0.8 \cdot 100 \text{ g/mol} = \\
= 480 \text{ kg/day}
\]

Production Capacity: ca. 170 t / a
Space Time Yield: ca. 0.01 kg per liter and hour
Fine Chemicals Manufacture

Process Profitability = \( f(\text{Space Time Yield (STY)}, \ldots) \)

\[
STY = \frac{m_P}{V_{\text{Reac}} \cdot t} = \frac{V_{\text{Reac}} \cdot c_{Eo} \cdot Y_{P,E} \cdot M_P}{V_{\text{Reac}} \cdot t} = \frac{c_{Eo} \cdot Y_{P,E} \cdot M_P}{t} \left[ \frac{kg \ \text{Product}}{l_{\text{Reac}} \cdot h} \right]
\]

Process Time for batch-wise operation

Typical Values of STY:
0.01 – 1 kg product per 1 liter reaction volume and hour
### Fine Chemicals Manufacture

**Space Time Yield (STY):**

<table>
<thead>
<tr>
<th>Type of Catalysis</th>
<th>STY</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Het. Catalysis</td>
<td>1-10 kg/(l·h)</td>
<td></td>
</tr>
<tr>
<td>Hom. Catalysis</td>
<td>0.01 – 1 kg/(l·h)</td>
<td></td>
</tr>
<tr>
<td>Biocatalysis</td>
<td>0.001 – 0.01 kg/(l·h)</td>
<td></td>
</tr>
</tbody>
</table>

React. temp.

Cat. conc.
# Fine Chemicals Manufacture

<table>
<thead>
<tr>
<th>Plant Capacity</th>
<th>E Factor (kg waste / kg product)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Refining &gt; 1 Mio t / year</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Bulk Chemicals 10.000 t / year up to 1 Mio t / year</td>
<td>&lt; 1-5</td>
</tr>
<tr>
<td>Fine Chemicals &lt; 10.000 t / year</td>
<td>5-50</td>
</tr>
<tr>
<td>Pharmaceuticals &lt; 1 t / year</td>
<td>25-100</td>
</tr>
</tbody>
</table>


Process Development for the Reduction of the **E factor** in Fine Chemicals and Pharmaceuticals Manufacture due to …
… reduction of negative environmental impact
… reduction of cost of disposing of waste
Process time in batch-wise fine chemical manufacture is mostly limited by heat and mass, and not by the chemical reaction itself.

Due to increasing V and decreasing A/V, process time increases when scaling up from bench to production scale.
Fine Chemicals Manufacture

From: Dr. J. Lang, Evonik Degussa

Granulatspeicher ➔ Lösemittelpuffer
Granulatdosierung ➔ Flüssigdosierung
Zerkleinern/Feinmahlen ➔ Überhitzung
Feinkorndosierung ➔ Druckdosierung
Filtration ➔ Extraktion
Filterkuchenausstrag ➔ Rückstandspeicher
Produkt

310 ml
48 sec
23 L/h
204 tons/year

V = ca. 40 l
Fine Chemicals Manufacture

Shifting from batch-wise to continuous operation:

Fine chemical synthesis with $Y_{P,E}=80 \%$, $c_{E0} = 1 \text{ mol/l}$ and $M_P = 100 \text{ g/mol}$ (assuming continuous reactor with $V_{\text{reac}} = 40 \text{ l}$ and reaction time of 1 min):

$$m_{\text{Product}} = \frac{V_{\text{reac}} \cdot c_{E0} \cdot Y_{P,E} \cdot M_P}{\tau} =$$

$$= \frac{40 \text{ l} \cdot 1 \text{ mol/l} \cdot 0.8 \cdot 100 \text{ g/mol}}{1 \text{ min}} =$$

$$= 4,608 \text{ kg / day} = 4.6 \text{ t / day}$$

Production Capacity: ca. 1,533 t / a
Space Time Yield: ca. 4.8 kg per liter and hour

higher capacity or shorter time-to-market
Fine Chemicals Manufacture

Welcome to the 1st International Conference of The Flow Chemistry Society, held in Munich, Germany.

The conference was co-located with MediChem Europe, Pharma Outsourcing Congress and ADME/TOX Europe. Registered delegates also had access to these meetings ensuring a very cost-effective trip.

Make the most of your trip by also attending the co-located training course.

Keynote Speakers

Ian Baxendale
Professor
Cambridge University

Aaron Beeler
Professor
Boston University

Paul Watts
Senior Lecturer
University of Hull

Confirmed Speakers

Oliver Kappe Professor, University of Graz
Thomas Wirth Professor, Cardiff University
Chris Selvey Chief Technology Officer, Cyclophasic
Graham Sandford Professor, Durham University
Stefan Lobbecke Vice Director Energetic Materials, Fraunhofer Institute for Chemical Technology
Floris Rutjes Professor, Radboud University Nijmegen
Robert Woolton Senior Lecturer, Liverpool John Moores University
Chris Stevens Professor, Gent University
Fernando Albericio Group Leader, IIB Barcelona
Gilda Gasparini Continuous Reactor Manager, AM Technology
Willem Verboom Associate Professor, University of Twente
Haider Ali Lawati Assistant Professor, Sultan Qaboos University
Stevan Djuric Senior Director, Global Pharmaceutical Research and Development, AbbVie Laboratories
Andreas Kirschning Professor, Hannover University
Gregor Willa Senior Scientist, Sigma-Aldrich
Real Sach Senior Principal Scientist, Sigma-Aldrich
Gabor Szilvák Head of Chemical Laboratory, Thaliness
Alexander O’Brien PostDoc Researcher, Max Planck Institute of Colloids and Interfaces

Agenda Topics:

- Meso Flow Chemistry
- Microfluidic Flow Chemistry
- New Directions in Flow Chemistry

Sponsorship and Exhibition Opportunities

Aaron Woodley, Exhibition Manager
a.woodley@selectbiosciences.com
+44 (0) 1787 313129
Bench Scale Reactors for Heterogeneous Catalysis

Catalytic Wall Reactors

Tube Reactor

Recycle Reactor (Type Berty)

Stirred Autoclave Reactor

Slug Flow Reactor

Source:
Lehrstuhl Technische Chemie,
Universität Erlangen-Nürnberg
Universität Stuttgart
# List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Dimension</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{E,0}$</td>
<td>mol · m$^{-3}$</td>
<td>concentration of educt species E at the beginning of the reaction</td>
</tr>
<tr>
<td>$M_E$</td>
<td>g · mol$^{-1}$</td>
<td>molar mass of educt E</td>
</tr>
<tr>
<td>$\dot{m}_P$</td>
<td>kg · s$^{-1}$</td>
<td>productivity (mass flow of the product P)</td>
</tr>
<tr>
<td>$S_{P,E}$</td>
<td>-</td>
<td>selectivity to product P related to educt E</td>
</tr>
<tr>
<td>$t$</td>
<td>s</td>
<td>process time</td>
</tr>
<tr>
<td>$V_{\text{react}}$</td>
<td>m$^3$</td>
<td>reaction volume</td>
</tr>
<tr>
<td>$\dot{V}$</td>
<td>m$^3$ · s$^{-1}$</td>
<td>volumetric flow rate</td>
</tr>
<tr>
<td>$X_E$</td>
<td>-</td>
<td>conversion of educt E</td>
</tr>
<tr>
<td>$Y_{P,E}$</td>
<td>-</td>
<td>yield of product P related to educt E</td>
</tr>
<tr>
<td>$\tau$</td>
<td>s</td>
<td>residence time</td>
</tr>
</tbody>
</table>