Continuous Processing of Rapid and Exothermic Reactions using Microstructured Devices

Madhvanand Kashid
Group of Catalytic Reaction Engineering (GGRC)
Swiss Federal Institute of Technology (EPFL)
Lausanne, Switzerland
EPF Lausanne is one of the two Federal technical universities in Switzerland (ETH & EPFL)

EPFL ranked **number 1 engineering school in Europe** in 2010 by Times Higher Education (THE)

More than 250 laboratories and research groups on campus

Emphasis: fundamental research and engineering applications.

Group of Catalytic Reaction Engineering (GGRC) focuses on the development of novel catalysts, catalytic reactors and microreactor technology
Process intensification (PI)

- ...innovative design aiming on reducing of chemical plants & reactors with drastic increase of (specific) efficiency (order of magnitude), compared to the existing ones (C. Ramshaw, 1986)

- ...drastic improvement of process performance by redesigning the process as a whole (including the development of new chemical routes) (A. Hüther et al., 2005)

- High specific performance
- Less energy consumption
- Increased selectivity
- Safer processes
- Shorter time to market
Microstructured devices (reactors)

- ... are miniaturized systems with dimensions (internal) in the sub-millimeter range

- micro-structured catalysts and reactors may be regarded as a Technology Push
  - opening process windows for new synthesis routes

- in fine chemicals and pharmaceutical industries
  - transformation of batch to continuous processes
  - high and reproducible product quality
  - accelerated process development
Outline

- Introduction
- Homogeneous systems
  - Mixing
  - Temperature control
- Multiphase systems
  - Flow regimes
  - Mass transfer
  - Separation (splitting)
- Reaction examples
  - PI cyclisation
  - Ionic liquid synthesis
  - MBY hydrogenation
- Conclusions
Process Intensification can be expected for characteristic reaction time $< 1 \text{ s}$.

- Fast (high temperature) reactions
- (Catalytic) reactions
- Chemical transformations
- Fluid dynamics and transport in conventional reactors

- Slow (biological) reactions

- Micro-reactors

- Kinetic regime

- Mass & heat transport limited
- Mass & heat transport influenced

Time scale, [s]
Outline

- Introduction
- Homogeneous systems
  - Mixing
  - Temperature control
- Multiphase systems
  - Flow regimes
  - Mass transfer
  - Separation (splitting)
- Reaction examples
  - PI cyclisation
  - Ionic liquid synthesis
  - MBY hydrogenation
- Conclusions
Importance of mixing – an example

Consecutive competitive reaction:

\[ A_1 + A_2 \xrightarrow{k_1} A_3 \]
\[ A_3 + A_2 \xrightarrow{k_2} A_4 \]

\[ k_2 / k_1 < < 1 \]

Overall balance: \( A_1 > A_2 \)
Local balance: \( A_1 < A_2 \)
Formation of \( A_4 \)

\[ M = \frac{c_{2,0}}{c_{1,0}} = 0.909 \]
\[ \frac{k_2}{k_1} = 0.05 \]
Homogeneous mixing – MSR characterization

Chemical method:

\[ A_1 + A_2 \rightarrow A_3 \] Instantaneous reaction

\[ A_4 + A_2 \rightarrow A_5 \] Fast reaction

Segregation Index \((X_S)\)

\[ X_S = \frac{Y}{Y_{CS}} \]

\[ Y = \frac{A_2 \text{ moles consumed by reaction 2}}{\text{total } A_2 \text{ moles fed}} \]

\[ Y_{CS} = Y \text{ at complete segregation} \]

\[ X_S = 1 \text{ complete segregation, } X_S = 0 \text{ complete mixing} \]

Villermaux – Dushman reaction

\([\text{I}^+] = 0.022 \text{ M, } [\text{I}]_0 = 0.0159 \text{ M, } [\text{IO}_3^-]_0 = 0.0033 \text{M, } T = 21 ^\circ \text{C}\)
Homogeneous mixing - Mixing time & power dissipation

Specific power dissipation [W/kg]: \( \varepsilon = \frac{Q \Delta P}{\rho V} \)

Correlation: \( t_m \propto \varepsilon^{-0.45} \)


© M. Kashid, EPFL, 2011
Homogeneous mixing - Effectiveness

Mixing performance → ratio of the reactor length \( (L_R) \) to the mixing length \( (l_m) \)

Mixing effectiveness:

\[
ME = \frac{L_R}{\frac{1}{u t_m} E u} = \frac{L_R}{\frac{\rho u^2}{u t_m} \Delta p}
\]

Graph showing mixing effectiveness vs. total flow rate [ml/min].
Temperature Profile - tubular reactors

Heat exchange area (A): \( \sim 100 \text{ m}^2/\text{m}^3 \)
Heat transfer coefficient (h): \( \sim 100 \text{ W/m}^2\text{K} \)

Hot-spot adversely effects:
- conversion
- selectivity
- safety
- catalyst lifetime
- choice of reactor material

\[
\frac{dX}{d\tau} = \frac{-R_1}{c_{1,0}} \quad \tau = \frac{z}{u}
\]
\[
\frac{dT}{d\tau} = \frac{(-R_1)}{c_{10}} \Delta T_{ad} - \frac{h \cdot 4 \cdot (T - T_c)}{d_t \cdot \rho \cdot \overline{c}_p}
\]

Isothermal Condition:
\[
\frac{dT}{d\tau} = 0
\]

\[
\Delta T = \left( \frac{h \cdot 4}{\rho \cdot \overline{c}_p \cdot \Delta T_{ad}} \right) \frac{d_t}{d_t} \frac{R_1}{c_{1,0}}
\]

function of axial position!

constant

must be varied with axial position!

not possible!!
Heat management – exothermic reaction

Design criteria: \( t_m \ll t_r \) (characteristics reaction time)

Design parameter for stable reactor operation (no run away):

\[
N = \frac{\text{char. reaction time}}{\text{char. cooling time}} = \frac{t_r}{t_c} = \frac{1}{k(T_c)c_1^{n-1}} \frac{U \cdot A}{\rho \cdot c_p \cdot V_r}
\]

Barkelew, 1959

\[
S' = \frac{\Delta T_{ad}}{T_c} \cdot \frac{E_a}{RT_c}
\]

Heat production potential

\[
\gamma = \frac{E_a}{RT_c}
\]

Arrhenius number

\[
N = \frac{\text{time to maximum rate}}{\text{char. cooling time}} = \frac{t_{mr}}{t_c} = \frac{RT_c^2}{E_a \cdot \Delta T_{ad}} \frac{1}{k(T_c)c_1^{n-1}} \frac{U \cdot A}{\rho \cdot c_p \cdot V_r}
\]

\[
S' = \frac{N}{1} = \frac{1}{Se}
\]
Stable operation in MSR

Stable reactor operation → no run-away (Renken’s criteria)

Temperature profile:

$$\Delta T' = \frac{T - T_c}{T} \frac{E_a}{RT_c}$$

Safe operation in microstructured reactors:
- decreasing diameter
- dilution of reactant
- multi-injection of reactant

$$\Delta T_{\text{max}}' \leq 1.2$$

$$N_{\text{min}} \geq \left( \frac{t_r}{t_c} \right)_{\text{min}} = 2.72 \cdot S' - B\sqrt{S'}$$

$B(n=0)=0, B(n=0.5)=2.6$

$B(n=1)=3.37, B(n=2)=4.57$
Outline

- Introduction
- Homogeneous systems
  - Mixing
  - Temperature control
- Multiphase systems
  - Flow regimes
  - Mass transfer
  - Separation (splitting)
- Reaction examples
  - PI cyclisation
  - Ionic liquid synthesis
  - MBY hydrogenation
- Conclusions
Flow regimes – microchannels

**MSR without structured internals**

- Slug
- Slug-drop
- Deformed interface

**MSR with structured internals**

- Annular
- Slug-dispersed
- Dispersed

**Generic flow pattern map**

Reynolds number: \( Re_i = \frac{\rho_i u_i d}{\mu_i} \)

Capillary number: \( Ca_i = \frac{\mu_i u_i}{\gamma} \)

Where, \( u_i \) is superficial velocity of \( i^{th} \) phase

(C-continuous, D-dispersed)

- Surface tension dominated
- Transition
- Inertia dominated

1. Concentric
2. PTFE capillary (Kashid and Agar, 2007)
3. T-rectangular (Jovanovic et al., 2011)
4. T-rectangular (Zhao et al., 2006)
5. T-square
6. Y-reactangular
7. T-rectangular (Salim et al., 2008)

Kashid and Kiwi-Minsker, Chemical Engineering and Processing, 50(10), 972-978, 2011
Mass transfer – MSR characterization

Rate of change of concentrations:

\[ \varepsilon_1 \frac{dC_1}{dt} = -k_L a \left( \frac{C_1}{K} - C_2 \right) \]

\[ \varepsilon_2 \frac{dC_2}{dt} = (1 - \varepsilon_1) \frac{dC_2}{dt} \]

\[ = k_L a \left( \frac{C_1}{K} - C_2 \right) \]

Where, \( \varepsilon_1 = \frac{Q_1}{Q_1 + Q_2} \)

Upon integration:

\[ k_L a = \frac{1}{\tau \left[ \frac{1}{K \varepsilon_1} + \frac{1}{1 - \varepsilon_1} \right]} \ln \left( \frac{C_2^* - C_2^{in}}{C_2^* - C_2^{out}} \right) \]

Where, Q – volumetric flow rate
K – partition coefficient

Flow rates: 1 - 18 ml/min
System: water (+ acetone) – toluene
Initial acetone in water: 3.5 wt%


© M. Kashid, EPFL, 2011
**Performance**

### $k_L a$ & $a$:

<table>
<thead>
<tr>
<th>Contactor</th>
<th>$a$ [m$^2$/m$^3$]</th>
<th>$k_L a$ [1/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agitated contactor</td>
<td>32-311</td>
<td>$(48-83) \times 10^{-3}$</td>
</tr>
<tr>
<td>Packed bed column</td>
<td>80-450</td>
<td>$(3.4 - 5) \times 10^{-3}$</td>
</tr>
<tr>
<td>Two impinging jets reactor</td>
<td>1000-3400</td>
<td>0.28</td>
</tr>
<tr>
<td><strong>Slug flow microchannel (ID = 0.5 – 1 mm)</strong></td>
<td><strong>830 – 3200</strong></td>
<td><strong>0.88 – 1.67</strong></td>
</tr>
</tbody>
</table>

### Energy input:

<table>
<thead>
<tr>
<th>Contactor Type</th>
<th>Energy Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agitated extraction column</td>
<td>0.5 – 190</td>
</tr>
<tr>
<td>Mixer-settler</td>
<td>150 – 250</td>
</tr>
<tr>
<td>Rotating disk Impinging Streams contactor</td>
<td>175 – 250</td>
</tr>
<tr>
<td><strong>Slug flow microchannel (ID = 0.5 – 1 mm)</strong></td>
<td><strong>0.2 - 20</strong></td>
</tr>
</tbody>
</table>
Flow separation – principle

- Phase separation in conventional contactors → density difference
- Laplace length for aqueous-organic system: $\lambda = \sqrt{\frac{\gamma}{\Delta \rho}} \cdot g \sim \text{mm}$
- Characteristic length of conventional system: $d_h \sim \text{m} >> \lambda$
- Characteristic length of microstructured devices: $d_h \sim \mu\text{m} < \lambda$

**Dimensionless number**

<table>
<thead>
<tr>
<th><strong>Definition</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Capillary number $Ca_i = \frac{\mu u}{\gamma}$</td>
</tr>
<tr>
<td>Weber number $We_i = \frac{u^2 d \rho_i}{\gamma}$</td>
</tr>
<tr>
<td>Bond number $Bo = \frac{(\Delta \rho) gd^2}{\gamma}$</td>
</tr>
</tbody>
</table>

→ drops can be guided through the microchannel — an important step in separation
Flow separation – preferential wettability

- Straightforward separation
- Well-defined reaction times
- Effective over slug flow regime
- Minor cross contamination

Outlet 2 – Teflon
Outlet 1 – steel

Inlet

Aqueous phase
Organic phase

Flow separation

Experimental (Water – iodine - kerosene)

Simulations (VOF) (Water – cyclohexane)

Outline

- Introduction
- Homogeneous systems
  - Mixing
  - Temperature control
- Multiphase systems
  - Flow regimes
  - Mass transfer
  - Separation (splitting)
- Reaction examples
  - PI cyclisation
  - Ionic liquid synthesis
  - MBY hydrogenation
- Conclusions
Example 1 — Cyclisation of Pseudoionone

- Cyclisation of pseudoionone (PI) to β-ionone (used in vitamin A & in perfumery)

\[ \text{PI} + \text{Acid} \rightarrow \beta\text{-ionone} \]

- Highly exothermic reaction
- Product are extracted by diluting reaction mixture with water → an exothermic step

Definitions:
- Conversion = \( \frac{C_{0\text{PI}} - C_{f\text{PI}}}{C_{0\text{PI}}} \)
- Yield = \( \frac{C_{\alpha+\beta}}{C_{0\text{PI}}} \)

NP-PI-H$_2$SO$_4$

- Single phase to two phases

Workshop on Continuous & Intensified Processes for Specialty Chemicals, NCL, Pune, 19.12.2011

© M. Kashid, EPFL, 2011
Kinetics in batch

**π→α** – quasi-instantaneous

α→β - moderate

**Arrhenius plot**

**β-ionone formation**

$E_a/R = 7962$ K

$\ln k_0 = 25.14$

$R^2 = 0.99$

**α-ionone transformation**

$E_a/R = 7791$ K

$\ln k_0 = 24.30$

$R^2 = 0.98$

Average

$E_a/R = 7876$ K

$\ln k_0 = 24.72$

$Ea \sim 65$ kJ/mol

Concentration profile (NP – 102g, H$_2$SO$_4$ – 61g, PI – 5g, T = -12°C)

**α-ionone** (NP – 102g, H$_2$SO$_4$ – 61g, PI – 1g)


© M. Kashid, EPFL, 2011
**Cyclisation in T-type MSR**

### Operating conditions
- **Temperature:** 273-323 K
- **Total flow rate:** 20-100 ml/h
- **Residence time:** 1-37 sec
- **Initial conc. of PI in organics:** 0.4 M – 2.5 M
- **H\textsubscript{2}SO\textsubscript{4}:PI (mol) ratio:** 4.8 - 10

### Experimental set-up
- Ionone productivity in MSR is \( \sim 10^5 \text{ kg/m}^3\text{h} \) compared to laboratory semi-batch reactor \( \sim 10^2 \text{ kg/m}^3\text{h} \) \( (\Delta T \sim 5\text{K}) \)
- Process intensification by > 2-3 orders of magnitude

**Hot spot is relatively small compared to \( \Delta T\textsubscript{ad} \) (=17 K)**
PI cyclisation – important points

- PI-to-α transformation
  - Instantaneous & exothermic
  - Fast mixing
  - Reaction heat evacuation
  - Hot-spot distribution*
  - Scale-up/Numbering-up
- α-to-β isomerization
  - Rate limiting & endothermic
  - Tubular reactor
- Extraction of sulphuric acid
  - Exothermic
  - Fast mass transfer
  - Heat removal
  - Scale-up/Numbering-up

* Haber et al., Industrial and Engineering Chemistry Research, in press

© M. Kashid, EPFL, 2011

Workshop on Continuous & Intensified Processes for Specialty Chemicals, NCL, Pune, 19.12.2011
Example 2 — Ionic Liquid Synthesis

\[ \text{MIM} \quad + \quad \text{DES} \quad \rightarrow \quad \text{1-ethyl-3-methylimidazolium ethylsulfate} \]

- methyl imidazole
- diethyl sulfate

**Difficult temperature control**

Temperature > 100°C leads to colored products!

4-times addition by syringes

50 ml flask, 50°C

Renken et al., Chemical Engineering & Technology, 2007
Continuous process

Characteristics:
- \( \Delta H_r = -100 \text{ kJ/mol} \)
- \( \Delta T_{ad} = 173 \text{K} \) (\( C_0 = 4.8 \text{ kmol/m}^3 \), no solvent)
- \( E_A = 86 \text{ kJ/mol} \)
- \( k(40^\circ\text{C}) = 1.9 \times 10^{12} \text{ m}^3/\text{kmol/s} \) (2\text{nd} order)

Characteristic reaction time (\( t_r \)) = \( \frac{1}{k(T)C_0} \)

\[ t_r = 10 \text{ s at 300 K} \]

Mixing:
- Design of a laminar micro mixer: \( t_m << t_r \)
- Caterpillar mixer:
  - Mixing time \( \rightarrow 0.02 \text{ – 0.2 s} \)
  - Suitable for high flow rates

Reaction & heat exchange:
- Combined micro-channels for reaction with heat exchanger (water cooling)
  - \( \rightarrow \) Enhances heat transfer
Final process design

μ-mixer
\[ Q = 7 \text{ mL/min} \]
\[ T = 323 \text{ K} \]

μ-reactor
\[ V_{\text{MSR}} = 10.8 \text{ mL} \]
\[ T_c = 323 \text{ K} \]
\[ d = 1.8 \text{ mm} \]
\[ V_{t,1} = 6.7 \text{ mL} \]

Tubular reactor
\[ V_{t,2} = 13.8 \text{ mL} \]
\[ T_c = 323 \text{ K} \]
\[ T_c = 368 \text{ K} \]

Residence time: 4.6 min
Production: 0.5 kg/h
Performance: 4.4 kg m\(^{-3}\) s\(^{-1}\)

Isothermal tubular reactor*
Residence time: 240 min
Performance: 0.08 kg m\(^{-3}\) s\(^{-1}\)

* A. Grosse-Böwing & A. Jess, 2007

© M. Kashid, EPFL, 2011
Workshop on Continuous & Intensified Processes for Specialty Chemicals, NCL, Pune, 19.12.2011
Example 3 - Selective hydrogenation of alkynes

- Important step in fine chemical synthesis
- 2-Methyl-3-butyn-2-ol hydrogenation: vitamin E synthesis

\[
\text{2-methyl-3-butyn-2-ol} \xrightarrow{+ H_2} \text{2-methyl-3-butyn-2-ol} \xrightarrow{+ H_2} \text{2-methyl-3-butyn-2-ol}
\]

\[
\text{2-methyl-3-butyn-2-ol} \xrightarrow{+ H_2} \text{2-methyl-3-butyn-2-ol} \xrightarrow{+ H_2} \text{2-methyl-3-butyn-2-ol}
\]

- Highly exothermic
- Solvent free hydrogenation: $\Delta T_{ad} = \text{above 500 K}$
- Yield for MBE: $> 96\%$; temperature $< 85^\circ C$
Intensive heat transfer

Integrated catalyst / cross flow heat exchanger


© M. Kashid, EPFL, 2011

Workshop on Continuous & Intensified Processes for Specialty Chemicals, NCL, Pune, 19.12.2011
Cross-flow micro heat-exchange element

**Characteristics**

- 40mm internal column diameter
- 17 slits of ~ 0.3mm width
- Total slit length: 530 mm
- Total heat exchange area:
  - Cooling water side: ~ 17 cm²
  - Reaction side: ~ 78 cm²
- Total free volume per stage (reaction side) : ~ 3.7 cm³
  (slits + 2mm free space above) => 39% porosity
Hydrogenation results

- Combination of **structured metal fiber** catalyst with **integrated micro heat exchanger**
- Heat transfer performance (per stage): 3 – 13 W K\(^{-1}\)
  \[\rightarrow 700 – 3500 \text{ kW m}^{-3} \text{ K}^{-1}\]
- Narrow residence time distribution due to cascading effect
  \[\rightarrow\] important for continuous operation
- Reactor performance:
  \[L_p > 12000 \text{ kg m}^{-3} \text{ h}^{-1} \text{ MBE for } \Delta T = 15K\]
  \[L_p \sim 125 \text{ kg m}^{-3} \text{ h}^{-1}\] conventional slurry reactor
- Process intensification by > 2 orders of magnitude
Final Conclusions

**Microstructured reactor systems:**
- High heat transfer performance
- Short diffusion times, short mixing times
- High mass transfer rate
- Low pressure drop, narrow RTD
- Increased specific surface area by surface treatment for heterogeneous catalytic reactions

**Microstructured reactors allow:**
- Safe micro scale operation for hazardous / toxic chemistry
- Require minimal quantity of material for analysis
- Integration into automated instrumentation
- Integrated sensors for fast process optimization
- Multiplexed reactors for parallel synthesis
- Readily scaled up production
Acknowledgements

TU Dortmund
• Prof. D. W. Agar
• Prof. S. Turek

EPFL
• Prof. A. Renken
• Prof. L. Kiwi-Minsker
• I. Yuranov
• M. Grasemann
• A. Fattet
• O. Detraz
• J. Haber

Project partners
• IMM, Germany
• Givaudan, Switzerland
• WUT, Warsaw, Poland
• PILLS consortium

Financial support:
Swiss National Science Foundation
(Swiss) Comission for Innovation and Technology
European framework project (FP7)

THANK YOU FOR YOUR ATTENTION