Business in Micro Reactor Technology

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I would like to . . .

Share with you the industrial perspective on MRT application

- PI as engine for innovation
- Business value
- Dynamics of innovation
- Micro reactor principles
- Hurdles towards industrial application
PI as engine for innovation

PI ‘thinking’ pushes the development of highly productive new technologies

existing process technologies

PI
Emerging needs

New needs emerged at the end of the 20th century
• Sustainability requirements
• Transition to new energy sources
• Transition to renewable raw materials
• Flexibility, agility towards change

Creating new lines of thinking
Conventional chemical engineering

Applies the ‘unit operation’ as a key paradigm

- Structured the science
- Framework for abstract knowledge
- Building block for process design

Which is a blessing but also a curse

- We connect automatically with the existing equipment
- This restricts our solution space to a limited number of available well-known ready solutions
Process intensification is a new approach

Start the problem solving from the solution  (in analogy with TRIZ)
What does the chemistry need?

- product removal
- supply of raw materials
- transfer of reaction heat
Is there an optimal pathway?

Imagine a fluid element and a chemical conversion

\[ A + B \rightarrow P \rightarrow Z \]

- Within the fluid element there are no gradients
- Chemical reaction $\rightarrow$ change of composition $\rightarrow$ change of optimal conditions
- We optimize conditions by manipulating the outer fluxes (heat, mass)
- If fluxes are not limited we will find the optimal pathway
- This optimum is **independent of existing equipment**

fit the equipment to the requirements

Our current PI toolbox

Selection criteria
- High technology readiness level
- Responding to DSM’s needs

Technological drivers
- Surface to volume ratio
- Centrifugal force

Micro reactor
Intensified tube reactor
Oscillating flow reactor
Rotating contactor
Micro separation
What business value can PI bring to us?
Efficiency due to intensification

The impact of intensification on cost drivers
Break through solutions

Disrupt the normal pattern of thought
Overcome mental blocks, pre assumptions

Product learning curve

Conventional
(optimization, economy of scale)

2e Generation
(process intensification)

€/kg

∑ production

Break through solution
New operational domains

Expanding capabilities

- Operate close to decomposition temperature
- Short reaction time (flash chemistry)
- Unlock hazardous chemistries (diazomethane, phosgene)
- Energy harvest (extract heat at useful temperature)
- Enable new products (not possible with conventional)

- Heating(cooling) rate > 100°C/sec
- Mixing time < 1 msec
- Productivity 10,000 – 100,000 kg/m³h
Enable new process concepts

• Asset light (low invest per unit of production capacity)
• Faster cash conversion cycle (higher NPV of project)
• Follow the market in capacity and location (flexible)
• Easier adoption to new technologies (not taken hostage by large invest)
• New supply chain models possible
Dynamics of innovation
Technologies evolve

Technological change follows evolutionary principles (J. Mokyr)

- **Knowledge**
  - Radically alters (mutation)
  - Transfers to new areas
  - Combines to new species

- **Products**
  - Emerge, compete, adapt, extinct

- **Technologies**
  - natural selection (market)
Behavioral aspects

People respond differently to new technologies (E. Rogers)

- easy to convince
- just being new

- difficult to convince
- must work properly
Key phases in development

During its development a technology follows five key phases (Gartner). The hype-cycle can be used to determine maturity and adoption level.
Incubation period

There is an incubation period in the S-curve adoption profile

Because often complementary technologies/developments are required to enhance commercial viability

From discovery to commercial success

Edison succeeded because of the better vacuum.
Micro reactor principles
The micro reactor is just a tube reactor

The design equals a conventional tube reactor with small diameter

The channel diameter is a key aspect
Impact of transfer distance

\[ \text{Mass flow} \quad (\text{mol/s}) = -D \cdot A \cdot \frac{\Delta C}{\Delta x} \]

\[ \text{Heat flow} \quad (\text{J/s}) = -\lambda \cdot A \cdot \frac{\Delta T}{\Delta x} \]

- \( D \) = Diffusion coefficient [m²/s]
- \( \lambda \) = Heat conductivity coefficient [W/mK]
- \( A \) = Transfer surface area [m²]
- \( \Delta C \) = Concentration difference [mol/m³]
- \( \Delta T \) = Temperature difference [K]
- \( \Delta x \) = Transfer distance [m]

High performance comes from short transfer distance (high A/V)
Impact of laminar flow

At such small diameters the flow mode goes to laminar

Laminar flow mode gives less control over time
What is your ‘product’, information or mass?

**Information, data**

- μL reactor volume
- Size is irrelevant

**Product, mass**

- 1-100 ltr reactor volume
- Size is relevant
Hurdles towards industrial application
Development of the micro reactor

Vast number of publications

Only a few industrial reactors

Supplier (labscale) shake out
Scaling up by numbering up is too expensive

How many channels are required on industrial scale?

Channel dimensions: 100 micron ID, 1 m length
Productivity 10,000 - 100,000 kg/m³h

<table>
<thead>
<tr>
<th>Capacity (kT/a)</th>
<th>Reactor volume (ltr)</th>
<th>Pressure drop (bar)</th>
<th>Number of channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-10</td>
<td>~2</td>
<td>(10^5 - 10^6)</td>
</tr>
<tr>
<td>10</td>
<td>10-100</td>
<td>~2</td>
<td>(10^6 - 10^7)</td>
</tr>
<tr>
<td>100</td>
<td>100-1000</td>
<td>~2</td>
<td>(10^7 - 10^8)</td>
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Small channel diameter micro reactors will be difficult to manufacture.
Impact of manufacturing

Construction materials

<table>
<thead>
<tr>
<th></th>
<th>polymer</th>
<th>glass</th>
<th>SiC</th>
<th>metal</th>
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<tbody>
<tr>
<td>Corrosion resistance</td>
<td>high</td>
<td>alkaline</td>
<td>high</td>
<td>Acid, halogen</td>
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<tr>
<td>Solvent resistance</td>
<td>low</td>
<td>high</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.3</td>
<td>1.4</td>
<td>140</td>
<td>14</td>
</tr>
<tr>
<td>High temperature resistance</td>
<td>low</td>
<td>high</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>High pressure resistance</td>
<td>low</td>
<td>medium</td>
<td>medium</td>
<td>high</td>
</tr>
<tr>
<td>Price of material</td>
<td>low</td>
<td>low</td>
<td>medium</td>
<td>medium</td>
</tr>
<tr>
<td>Ease of manufacturing</td>
<td>high</td>
<td>low</td>
<td>low</td>
<td>medium</td>
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Manufacturing technologies

Channel
- Machining
- Laser ablating
- Deep ion etching
- Etching
- Sandblasting
- Punching
- Spark erosion
- Extrusion
- Embossing

Parallelization
- Stacking
- Clamping
- Diffusion bonding
- Laser welding
- Brazing

Impact of manufacturing

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Glass
Silicon carbide
Metal
There’s a gap in manufacturing innovation.
How to move forward?

- We developed metrics for economic evaluation
- We evaluated manufacturing technologies
- We set up a database of capable MR suppliers
Solving the contradiction

100 µm

1-4 mm

• high performance
  • too difficult, too expensive

• bad performance
  • Easy to manufacture, lower cost
Design for secondary flow

Primary flow

Dean vortices (secondary flow)

A-A

stabile

Increasing
• curvature
• velocity

instabile / chaotic in time and position
µm thick fluid layers are created
Secondary flow

Applied in T-mixers

Experiment

CFD

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N.Kockmann, IMTEK Freiburg
Secondary flow

Applied in the reaction channel by influencing shape and geometry

Re = 103

Re = 310

Re = 828
Works also for biphasic systems

Design strategy for industrial micro reactors

- Maximize channel volume (diameter, length)
- Maximize channel performance (shape, geometry)
- Keep geometry equal
- Number up to N channels per module (manifold)
- Use P modules in parallel to obtain volume

Manufacturability
Performance

We need a manufacturing technology that provides design freedom at low cost
Additive manufacturing
Selective Laser Melting (metal)

SLM produces homogenous metal objects directly from 3D CAD data by selectively melting fine layers of metal powder with a laser beam.

Max build envelop: 60x40x50 cm³
Min feature size: 40-200 micron
Min layer thickness: 30 micron
Accuracy: 20-50 micron
Surface finish: 4-10 micron RA
Density: 99.9%

Aluminium, Cobalt-chromium alloy, Nickel based alloys, Stainless steel, Titanium, Tantalum, Tungsten
Video

https://www.youtube.com/watch?v=fa7aYCylNWM
SLM freedom of design
SLM economic evaluation

316L stainless steel

Forecast metal AM costs [EUR/cm³]

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<tr>
<th></th>
<th>2013</th>
<th>2018</th>
<th>2023</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct</td>
<td>3.1</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Indirect</td>
<td>1.1</td>
<td>0.59</td>
<td>0.75</td>
</tr>
</tbody>
</table>

PREREQUISITES

<table>
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<th></th>
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<th>2018</th>
<th>2023</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build speed (cm³/h)</td>
<td>10</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>Machine costs (EUR)</td>
<td>500,000</td>
<td>700,000</td>
<td>800,000</td>
</tr>
<tr>
<td>Share of monitoring</td>
<td>5%</td>
<td>2%</td>
<td>0%</td>
</tr>
<tr>
<td>Machine utilization</td>
<td>86%</td>
<td>84%</td>
<td>81%</td>
</tr>
<tr>
<td>Powder price (EUR/kg)</td>
<td>89</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>Post-processing effort</td>
<td>1.52 h/kg</td>
<td>1.05 h/kg</td>
<td>0.96 h/kg</td>
</tr>
</tbody>
</table>

Source: EPSRC; DMRC; expert interviews; Roland Berger

http://www.emdt.co.uk/print/3529
SLM provides significant benefits

SS, Ta

Corrosion resistance: high, high, high, high
Solvent resistance: low, high, high, high
Thermal conductivity (W/mK): 0.3, 1.4, 140, 14 - 55
High temperature resistance: low, high, high, high
High pressure resistance: low, medium, medium, high

Construction materials

combined

Manufacturing technologies

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design freedom

competitive cost level

Summary

- Micro reactor technology provides interesting capabilities for chemical production

- The numbering up principle fails to deliver commercial viable industrial micro reactors (10-100 micron diameter)

- Larger diameter channels (1-4 mm) can deliver high performance if we create secondary flow

- The feasibility of industrial micro reactors has been boosted by 3D metal printing (SLM)
Thank you for your attention

Questions?