Advanced Flow Reactors
Teaming up Chemistry and Chemical Engineer
“Greener” Processes and Improved Economics

Frank Schmidt
Sales Director
Evolution (Revolution) in Chemical Processing
Batch process scale up

<table>
<thead>
<tr>
<th>Time</th>
<th>Cost</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab scale</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kilo Lab</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pilot Plant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturing plant</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Process development benefits
Example: Fine Chemicals and Pharma API production

Batch Technology

Discovery  Development  Production  Distribution

Laboratory  Pilot Plant  Scale – up  Technology transfer  large scale production

15 - 60 months, XX MM$

Key activity

Development of second generation process
Transfer to manufacturing
Regular production

Risk on the manufacturing site

Final process parameter definition on large scale production

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Fine and Pharma Industries

Advanced Flow Reactor Technology

8 - 15 months, X MM$

Laboratory → Pilot Plant → Scale-up → Technology transfer → large scale production

One tool engineered to fit all needs

Key activities
- Development of second generation process
- Transfer to manufacturing
- Regular production

Risks at the manufacturing site
- Scale up failure, no scale up
- Limited scale up, management of numerous batch no limitation
- Complex transfer to regular production no issues
- Final process parameter definition for large scale production simple

Simple and fast PAR, Pilot Production Banks
Fluidic modules: concept and library

- Heat transfer
- Reactants
- 700 microns
- Mixing
- 300 microns
- Pressure drop
- 1 millimeter
- 4 mm

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The Impact of Dimensions

\[ \frac{\Delta P}{L} = 128 \cdot \frac{\eta Q}{\pi \cdot d^4} \]

Laminar flow

Pressure drop
Simple tube (bar)

Heat transfer
U \times (S/V) (kW/m^3.K)

Mixing Quality
Villermaux (%)

20 bar

450 \, \mu m

6 mm
## Corning Fluidic module heat exchange performance

<table>
<thead>
<tr>
<th>Apparatus</th>
<th>Specific area, m²/m³</th>
<th>Volumetric heat transfer coefficient (MW/m³K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jacketed batch</td>
<td>2.5</td>
<td>10⁻³</td>
</tr>
<tr>
<td>Batch with external heat exchanger</td>
<td>10</td>
<td>10⁻²</td>
</tr>
<tr>
<td>Shell and tubes (metallic; water/water; 1 m/s)</td>
<td>400</td>
<td>0.2</td>
</tr>
<tr>
<td>Plate (metallic, 4 mm spaced; water/water, 1 m/s)</td>
<td>800</td>
<td>1.25</td>
</tr>
<tr>
<td>Corning glass fluidic modules</td>
<td>2500</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Fluidic modules: concept and library
AFR evaluation tool: *flexible with capability all the way to pilot scale*
Engineered reactor components

- Interfaces
- Frames
- Standard Fittings
- Connectors
- Tubing
- Sensing
- O-ring seals
- Fluidic Modules
- Labelling
- Add-on (insulation…)
- Instrumentation (Pressure relief valve…)

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Glass Fluidic Modules are the building blocks
Numbering up: system distribution

Individual feed of each reactor

Mix system

Passive distribution
Numbering up: system distribution

- stability
- robustness
- versatility
Scaling the technology to industrial production in 2 ways:

- **Scale-out** = increase the total fluidic channel path length/fluidic module
- **Scale-up** = increase the number of fluidic modules

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**Gen I**
- Process
- Development and Pilot Production Capable

**Gen II**
- Scale-out

**Gen III**
- Scale-out

**Stacking scale-out**

**Scale-up**: simple numbering up to full production
AFR: wide range of throughput (*) for production of Fine, Pharma and Specialty chemicals

<table>
<thead>
<tr>
<th>Gen I</th>
<th>Gen II</th>
<th>Gen III (Under development)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T -60°C - 230°C</td>
<td>P up to 18 bar</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>g/min</th>
<th>kg/h</th>
<th>Tons / 5600h</th>
<th>Tons / 8000h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gen I</td>
<td>15</td>
<td>1</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>10</td>
<td>56</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>25</td>
<td>140</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>660</td>
<td>40</td>
<td>220</td>
<td>320</td>
</tr>
<tr>
<td></td>
<td>1600</td>
<td>100</td>
<td>560</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>3200</td>
<td>200</td>
<td>1120</td>
<td>1600</td>
</tr>
</tbody>
</table>

(*) per single reactor
Broad range of applications

• Reactions which have already benefited from Corning Advanced-Flow Reactor
  – Alkylation
  – Amidation
  – Bromination
  – Condensation
  – Chlorination
  – Metal Organic
  – Hydrogenation
  – Oxidation
  – Nitration
  – Sulfonation

• In mono or multi phase environments
  – Miscible liquid feeds
  – Non miscible feeds – emulsions
  – Liquid and gas feeds
  – Suspensions
Case 1: **Plant Footprint** Comparison – Batch vs. Continuous Selective Nitration

**NITRATION PLANT – BATCH 400 ton/yr**

- Length: 42.80 m
- Width: 22.80 m
- Height: 14.80 m

**NITRATION PLANT – CONTINUOUS 400 ton/yr**

- Length: 30.80 m
- Width: 22.80 m
Case 1: **Capex and Opex** Comparison – Batch vs. Continuous Selective Nitration

NITRATION PLANT – 400 tons/year

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**Capex comparison batch versus continuous**

**Opex comparison batch versus continuous**
Case 2: **Plant Footprint** Comparison – Batch vs. Continuous Selective Hydrogenation
Case 2: **Capex and Opex** Comparison – Batch vs. Continuous Selective Hydrogenation

**HYDROGENATION PLANT – 400 tons/year**
Case 3: **Plant Footprint** Comparison – Batch vs. Continuous Organo-Metallic

Organo Metallic: 100 tons/year
Case 3: **Capex and Opex** Comparison – Batch vs. Continuous Organo-Metallic

**Organo Metallic: 100 tons/year**

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**Opex comparison batch versus continuous**

**Capex comparison batch versus continuous**
Advanced Flow Reactors: Greener and More Economical