CORNING

Efficient Processing with Corning® Advanced-Flow™ Glass Technology

Jay Sutherland
June 24, 2009
Corning Incorporated

**Founded:**
1851

**Headquarters:**
Corning, New York

**Employees:**
Approximately 25,000 worldwide

**2008 Sales:**
$5.9 Billion

**Fortune 500 Rank (2008):**
417

- Corning is the world leader in specialty glass and ceramics.
- We create and make keystone components that enable high-technology systems for consumer electronics, mobile emissions control, telecommunications and life sciences.
- We succeed through sustained investment in R&D, more than 150 years of materials science and process engineering knowledge, and a distinctive collaborative culture.
A Culture of Innovation

Glass envelope for Thomas Edison’s light bulb
1879

Dow Corning silicones
1915

Glass ceramics
1934

Processes for mass producing the television bulb
1947

Ceramic substrates for automotive catalytic converters
1952

Heat-resistant Pyrex® glass
1960

First low-loss optical fiber
1970

Fusion draw process
1972

AMLCD glass for TVs, notebook computers & monitors
1984

High-throughput label-free screening platform for drug discovery
2006
Doing chemical reactions in big tanks is like trying to bake big cakes… **hard**

- Oven hard to build an oven for this!
- Heat transfer poor… cake will burn on outside and be raw inside
- Must fit cake recipe to equipment
  (in fact, they had to make an ice cream cake!)

- Ovens work well for these
- Better heat transfer means perfectly baked cake
- Predictable scale-up by simply adding more pans
- Easy to make ovens and pans for any kind of cupcake!
Solution: Don’t do batch reactions!

- Mixing is poor
- Hard to get heat in and out
- Scale-up is hard
- Must fit chemistry to equipment

*Conventional batch chemical reactors*

- Easier and safer to operate
- Better heat & mixing control
- Predictable scale-up by adding modules
- Equipment adapts to chemistry

*continuous reactors*
This is an even better analogy!

Edge Brownie Pan
A baker’s dream: deliciously chewy edges for every piece!

If you love the crunchy, caramelized, toasty edges of a brownie, this pan is for you. No more gooey centers—every serving has two edges, thanks to the patented interior sidewalls on this pan.
Revolution
Evolution in processing

Alchemy
Glass Fluidic Modules
Corning® Advanced-Flow™ Glass Reactor
Today’s Industrial Manufacturing
Reactor components

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

PRODUCTION BANKS
(Reactors in Parallel)

FLUIDIC MODULES

REACTORS
Fluidic modules for many applications

- Gas phase
- Aqueous phase
- Organic phase
- Solid phase suspensions
Multiple ports add even more flexibility
Heat exchange & mixing are integrated in the fluidic module

Heat exchange layer
Reaction layer
Heat exchange layer

Reactants
Product
Designs optimize heat and mass transfer

**Heat transfer**
- 700 microns

**Mixing**
- 300 microns

**Pressure drop**
- 1 millimeter

**Dimensions**
- Reactants: 4 mm
Benefits of process intensification

**Reactor Characteristics**
- Continuous processing
- Reduced process hold up
- Residence time control
- Efficient mixing
- High surface-to-volume ratio
- Improved process control
- Worry-free scale-up by “numbering-up”
- Work above solvent boiling point
- Easy to clean
- Equipment fits the chemistry

**Safety**
- Enhanced safety; new reactions possible
- No scale-up issues
- No unstable intermediate accumulation
- Elimination of batch critical operations

**Chemistry Benefits**
- Improved yield, selectivity & product purity
- Increased reaction rates
- Expanded temperature range
- New process windows

**Economic**
- Less capital risk
- Lower manufacturing and operating cost
- Less raw material, solvent, waste, energy
- Less work-up
- Constant quality
- Shorter time to market
- Improved production management (on demand)
Multi-phase chemistry: Liquid/Liquid

### Miscible liquids

![Image of miscible liquids](image1)

### Non-miscible liquids

![Image of non-miscible liquids](image2)

<table>
<thead>
<tr>
<th>Source of the data</th>
<th>Biphasic bubble system</th>
<th>Biphasic bubble system</th>
<th>Biphasic bubble system</th>
<th>Corning (NIM) One phase system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical size (µm)</td>
<td>50</td>
<td>500</td>
<td>1000</td>
<td>700-4000</td>
</tr>
<tr>
<td>Flow rates mL/h</td>
<td>0.1</td>
<td>2</td>
<td>6</td>
<td>4000-8000</td>
</tr>
<tr>
<td>Mixing time (ms)</td>
<td>10 - 60</td>
<td>400-1500</td>
<td>3000-10000</td>
<td>10 - 20</td>
</tr>
<tr>
<td>Shear rate (s-1)</td>
<td>4000</td>
<td>80</td>
<td>15</td>
<td>30000-65000</td>
</tr>
</tbody>
</table>

(1) Laboratoire de Génie Chimique – Toulouse – France
(2) Institut National Polytechnique de Toulouse – France
Multi-phase: Gas/Liquid

![Graph showing specific surface area vs. gas flow rate for different liquid flow rates. The graph includes data points for 100 ml/min, 75 ml/min, and 50 ml/min, represented by red, blue, and green markers, respectively. The x-axis represents gas flow rate (ml/min), and the y-axis represents specific surface area (m²/m³).]
Multi-Phase: Liquid/Solid

Many solid types are compatible with our reactors:

- Slurries
- Particles in feed
- Fine precipitates

<table>
<thead>
<tr>
<th>SiC nominal size (µm)</th>
<th>Concentration (g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>&gt;300</td>
</tr>
<tr>
<td>37</td>
<td>&gt;300</td>
</tr>
<tr>
<td>105</td>
<td>&gt;25 g/L</td>
</tr>
</tbody>
</table>

High mixing capability fluidic module
Processing of high viscosity fluids

- Fluid with viscosities up to ~500 cP
- Viscosities at operating temperature up to ~100 cP

Pressure drop <10 bars (6 kg/h)
Multi-port injection: Provides better temperature management along the flow path

\[ \rho C_p \frac{dT}{d\tau} = kA(-\Delta H) - U \frac{S}{V} (T - T_c) \]

Heat generation

Heat removal

Heat removal

Corning Advanced-Flow Reactor Technology
Specific examples

- **Increase product quality**
  - Esterification from RCOCl
  - **Nitration (HNO₃ / H₂SO₄)**
  - Hydrosilation

- **Increase yield and/or consume less solvent, energy etc.**
  - **Nitration (HNO₃)**
  - Condensation
  - Metalorganic reactions

- **Remove or reduce time consuming operations**
  - Oxidation (NaClO)
  - Condensation
  - Metalorganic reactions

- **Improve safety**
  - Oxidation (NaClO)
  - Coupling (H₂SO₄)
  - **Nitration (HNO₃)**

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Outputs: Process Results
Yield Selectivity Cost Safety...

Inputs: Process Parameters
Pressure Temperature Concentration

Process optimization depends on the output target

X
X
X
X
X
Broad range of applications

- **Reactions which have already benefited from Corning reactors**
  - Nitration
  - Metal Organic
  - Oxidation
  - Reduction
  - Coupling, substitutions
  - Rearrangements
  - Amidation
  - Bromination
  - Alkylation
  - Hydrogenation etc.

- **Mono- or multi-step processes including pre-mixing, quenching etc.**

- **In mono- or multi-phase reactions**
  - Miscible liquid feeds
  - Non miscible feeds – emulsions
  - Liquid and gas feeds
  - Precipitation of sub-product or products

**Under Development**
- Fluoride-containing systems
- Hot alkaline conditions
- Solid starting materials
- Immobilized heterogeneous catalysts
- Microwaves, Ultrasound, UV light
Batch vs. Corning Reactors (CR) – Reaction time

Reaction time (s)

Nitration (sulfonitric)
Oxidation (bleach)
Hydrosilation
Metal Organic

Application 1
First trials

Reaction time (min)

1 10 100 1000 10000

Batch

CR
Batch vs. Corning Reactors – Yield and Purity

Yield (%)

Nitration (nitric)
Nitration (sulfonitric)
Metal Organic

Purity (%)

Nitration (nitric)
Nitration (sulfonitric)
Hydrosilation
Batch vs. Corning Reactors – Temperature and Solvent

Temperature (°C)

Solvent ratio (wt %)

CR

Batch

Metal Organic 1
Metal Organic 2
Coupling
Rearrangement 1
Rearrangement 2

Nitration (nitric)
## Batch vs. Corning Reactors – Safety

<table>
<thead>
<tr>
<th>END-USER CASE</th>
<th>CONVENTIONAL TECHNOLOGIES</th>
<th>Corning Reactors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidation with bleach</td>
<td>Scale-up issues</td>
<td>Safe operation</td>
</tr>
<tr>
<td></td>
<td>Hazardous reaction</td>
<td></td>
</tr>
<tr>
<td>Coupling in presence of sulfuric acid</td>
<td>First production batch at 60°C damped into a quench solution</td>
<td>Operation under full control at 90°C</td>
</tr>
<tr>
<td>Autocatalytic nitration</td>
<td>Accumulation risks</td>
<td>Safe operation</td>
</tr>
<tr>
<td></td>
<td>No scale-up possible</td>
<td></td>
</tr>
<tr>
<td>Nitration reaction</td>
<td>Dedicated equipment</td>
<td>Safe operation</td>
</tr>
</tbody>
</table>

### Reactor Volume (L)

**Figure:**
- Global Heat Transfer Coefficient kW/(m³.K)
- CR Batch
- CR External HE
- CR Jacketed Batch

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Advanced-Flow Reactor Technology 25
## Typical values for Generation 1 Fluidic Modules

<table>
<thead>
<tr>
<th></th>
<th>Reaction channel</th>
<th>Heat exchange channels</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total flow rate</strong></td>
<td>20 – 300 mL/min</td>
<td>3 – 7 L/min</td>
</tr>
<tr>
<td><strong>min-max</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Working temperature</strong></td>
<td>-60°C up to 230°C</td>
<td>-60°C up to 230°C</td>
</tr>
<tr>
<td><strong>Working pressure</strong></td>
<td>up to 18 bar</td>
<td>up to 6 bar</td>
</tr>
<tr>
<td><strong>Internal volume</strong></td>
<td>20 – 50 mL</td>
<td>40 – 100 mL</td>
</tr>
<tr>
<td><strong>Residence time</strong></td>
<td>10 – 60 s @ 30 mL/min</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Mixing (Villermaux)</strong></td>
<td>90% @ 30 mL/min</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Pressure drop</strong></td>
<td>0.4 – 3.0 bar @ 100mL/min 1 cPo</td>
<td>1.4 bar @ 3L/min 7cPo</td>
</tr>
<tr>
<td>(calculated)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Evaluation kit
Full Product Synthesis Unit - eg. 3-step Nitration process

1. Sulfonitric mixture production

2. Nitration

3. Quench

PRODUCT OUTPUT
Designs for high throughput

- Need for higher throughput reactors:
  - Increase productivity (tons/year) for a given number of reactors
  - Reduce number of reactors needed to fit production requirements

- Main challenges to higher throughput:
  - Residence time
  - Pressure drop
  - Heat Transfer

- Solution: larger glass fluidic modules with comparable residence time, pressure drop and heat exchange performance
How the technology scales for production

<table>
<thead>
<tr>
<th>Typical tonnage (In isolated product)</th>
<th>Number of reactors at 13 kg/h processed per reactor in 1X</th>
<th>Feed concentration in wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>10 kg / day</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>100 kg / week</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>5 mT / month</td>
<td>19 -10-5</td>
<td>12-6</td>
</tr>
<tr>
<td>100 mT / year</td>
<td>16 - 8</td>
<td>19-10-5</td>
</tr>
<tr>
<td>50 mT / 3 month</td>
<td>32-16</td>
<td>19-10</td>
</tr>
<tr>
<td>400 mT / year</td>
<td>32</td>
<td>19</td>
</tr>
<tr>
<td>1,000 mT /year</td>
<td>48</td>
<td>24-12</td>
</tr>
<tr>
<td>10,000 mT /year</td>
<td>119</td>
<td>48</td>
</tr>
</tbody>
</table>
Full production banks

Two production banks, containing 4 reactor lines each, enable a multistep production capacity of up to 1,000 metric tons per year.

<table>
<thead>
<tr>
<th></th>
<th>Processed in metric TONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>per Month</td>
</tr>
<tr>
<td>Reaction step</td>
<td>40</td>
</tr>
<tr>
<td>Reaction + downstream</td>
<td>80</td>
</tr>
</tbody>
</table>
Fully engineered solution available with complete automation

• Multipurpose reactors or single chemistry reactors can be built into this turnkey system
• 50t/y up to 1,500t/y (depending on dilution)
• ATEX EEx Zone II
• 3 liquid feeds
• 1 gas feed
• Temperature from -60°C to +250°C
Making News

News Releases

Corning and DSM Announce Successful Pilot Operation of Industrial-Scale Microreactor for cGMP Pharmaceutical Production

CORNING, N.Y., October 01, 2008 – Corning Incorporated (NYSE: GLW) and DSM Pharma Chemicals announced publication of a joint paper at CPhI Worldwide 2008 in Frankfurt, Germany this week describing a successful unit, putting an end to the reactors’ usefulness in academia, in small-scale production—a notion that seems to be moving

Microreactors Hit the Major Leagues

Suppliers of microreactor technology aim BEYOND SPECIALTY NICHES at industrial markets

WITH THE BACKING of large companies, microreactor technology—that darling of academic papers, R&D labs, and small-scale production—finally seems to be moving toward major industrial applications. Chemicals, adds that the intercompany team was able to achieve pilot production for a challenging reaction in a “remarkably” short period of time. “The combination of Corning’s microreactor technology and DSM’s chemical expertise allowed us to
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