Continuous biobutanol production: Comparison between two-stage reactor and one-stage coupled with repeated batch reactor

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Introduction: n-Butanol Chemical

- **Petroleum production routes**
  - Oxo synthesis (propylene hydroformylation)
  - Crotonaldehyde hydrogenation: hydrogenation starting from acetaldehyde or ethanol

- **Production** 1.4 billion Litres/yr, 63% USA, $0.64-0.85 /kg butanol

- **Starting compound for wide range of substances**
  - Butyl acetate: lacquers coating industry
  - Butyl acrylate: plastics, textiles, latex
  - Extraction solvent: perfumes, oils, antibiotics, vitamins

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Energy Density (MJ/L)</th>
<th>Specific Energy (MJ/Kg air)</th>
<th>Heat of Vap. (MJ/Kg)</th>
<th>MON (motor octane no.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petrol/Gasoline</td>
<td>32</td>
<td>2,9</td>
<td>0,36</td>
<td>81-89</td>
</tr>
<tr>
<td><strong>Butanol</strong></td>
<td><strong>29.2</strong></td>
<td><strong>3.2</strong></td>
<td><strong>0.42</strong></td>
<td><strong>78</strong></td>
</tr>
<tr>
<td>Ethanol</td>
<td>19.6</td>
<td>3.0</td>
<td>0.92</td>
<td>102</td>
</tr>
</tbody>
</table>
Introduction: Biological Production

- **Clostridium acetobutylicum, C. beijerinckii, C. saccharobutylicum and C. saccharoperbutylacetonicum**

- **C. acetobutylicum ATCC 824**
  - Weismann strain
  - Anaerobic, spore forming
  - Complex growth
    - Acidogenic
    - Solventogenic
  - ABE (3:6:1)

- **Process challenges**
  - Product titers: 15-20 g/L
  - Toxicity: 1% (w/v), 50% cell death
  - Productivity: <0.5 g/L/h
  - Yields: 0.3 g/g glucose
**Current Process Intensifications**

- **Feedstocks**
  - Agricultural waste: straw, corn stover
  - Non food energy: miscanthus, switchgrass
  - Industrial waste: sawdust, paper pulp
  - Municipal solid waste, food waste

- **Metabolic Engineering**
  - *E. coli*
  - *S. cerevisiae*
  - *P. putida* (TU Dortmund, Laboratory of Chemical Biotechnology)
  - All the titres < 2 g/L

- **Process Development**
  - Continuous fermentation
  - Cell immobilization
  - Fermentation with in-situ product removal

- **Downstream Process**
  - Gas stripping
  - Pervaporation
  - Liquid-liquid extraction (Ionic liquids, TU Dortmund, Laboratory of Fluid Separation)

This project: Fermentation process development with high productivity and increased catalyst rate
Process Optimization in Two-stage Reactor System

Stage 1: Always operated continuous
- Acids production
- High pH
- High dilution rate

Stage 2: either continuous or fed-batch alternating 2 or more reactor
- Solvents production
- Low pH
- Low dilution rate
Results: Only 2nd Stages (overall process)

- More stable process due to two separate reactor stages
- ABE = 14.6 g/L, BuOH= 9.44 g/L
- 96% glucose usage
- Productivity = 0.58 g_{ABE}/(L*h )
- Specific Productivity = 0.26 g_{ABE}/g_{biomass}/h )

- ABE = 19.22 g/L, BuOH = 11-12 g/L
- 100% glucose usage
- Productivity = 1.47 g_{ABE}/(L*h )
- Specific Productivity = 0.78 g_{ABE}/g_{biomass}/h )
- Process superior to two stage continuous process
Conclusions and Way Forward

- Operating 2nd stage as fed-batch coupled with 1st stage as continuous is a new process concept
- The reported cell activities are the best reported to date
- Reduced reactor volume for 2nd stage, hence reduced reactor costs
- Cell immobilization will improve the overall volumetric productivity
- Product toxicity in the 2nd reactor could be reduced with integrated product removal like gas striping
- Gas stripping has already been tested and it shows great potential
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