Separations Opportunities and Challenges

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Agenda

• What drives separation processes
• Growth of membrane processes
• Separation opportunities
• Conclusions
Separation Task
Separation Task

Feed → Separation Device → Products

Energy or Mass Separating Agent
Separation Processes

• Equilibrium
  – Immiscible phases (G/L, G/S, L/L, L/S)
  – Heat commonly drives separation
  – Distillation, ad/absorption, liquid-liquid extraction

• Rate-governed
  – Transport under imposed chemical potential gradient (c, P, T, E)
  – Immiscible phase aided
  – Membrane filtration
Sherwood Plot
End of the Thermal Age?

- Conventional thermal separations = ~10% of total global energy consumption

Chemical potential difference driven rate based separations can be more energy efficient if ...
Membrane Separations

Materials are available that allow selective transport ...

Gas or Liquid Feed → Membrane → Permeate → Reject
Membrane Separations

Materials are available that allow selective transport ...
Membrane Separations

<table>
<thead>
<tr>
<th>Micrometers (Log Scale)</th>
<th>Angstrom Units (Log Scale)</th>
<th>Approx. Molecular Wt. (Saccharide Type-No Scale)</th>
<th>Relative Size of Common Materials</th>
<th>Process For Separation</th>
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<tbody>
<tr>
<td>Ionic Range</td>
<td>10</td>
<td>100</td>
<td>Aqueous Salts</td>
<td>REVERSE OSMOSIS</td>
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<tr>
<td>Molecular Range</td>
<td>100</td>
<td>200</td>
<td>Atomic Radius</td>
<td>ULTRA FilTRATION</td>
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<tr>
<td>Macro Molecular Range</td>
<td>1000</td>
<td>1000</td>
<td>Sugar</td>
<td>NANO FilTRATION</td>
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<tr>
<td>Micro Particle Range</td>
<td>10000</td>
<td>10000</td>
<td>Metal Ion</td>
<td>MICRO FilTRATION</td>
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<td>Macro Particle Range</td>
<td>100000</td>
<td>500000</td>
<td>Synthetic Dye</td>
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<td>Virus</td>
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<td>A. C. Fine Test Dust</td>
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<td>Tobacco Smoke</td>
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<td>Milled Flour</td>
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<td>Latex/Emulsion</td>
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<td>Colloidal Silica</td>
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<td>Blue Indigo Dye</td>
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<td>Red Blood Cells</td>
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<td>Pollen</td>
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<td>Human Hair</td>
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<td>Mist</td>
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Note: 1 Micron (1x10^-6 Meters) = 4x10^-8 inches (0.000004 inches)
1 Angstrom Unit = 10^-10 Meters = 10^-6 Micrometers (Microns)

Success Story – Desalination

Ashkelon SWRO Plant 100 million m$^3$/y (2005)

http://www.water-technology.net/projects/israel/
Hadera (127, 2009), Sorek (150, 2013)
Success Story – Desalination

![Graph showing energy input vs. cost for MSF, MED, and RO desalination methods. The graph indicates the desired direction towards lower energy input while maintaining or lowering cost. The minimum energy input is approximately 0.9 kWh/m³.](http://www.desware.net/desa4.aspx)
Membrane Separation Figures of Merit

**Permeability** = $Q_A$

**Selectivity** = $\alpha_{AB} = \frac{Q_A}{Q_B}$

As $Q_A$ and $\alpha_{AB}$ increase, process performance improves.

As $Q_A \uparrow$
Membrane area ↓, Capital costs ↓

As $\alpha_{AB} \uparrow$
Product recovery ↑, Energy ↓
Permeation Upper Bound

![Graph showing permeation upper bound](image-url)
Bioethanol Production – VP or PV

• Organic/water

Fermented mash

Originally from http://www.vaperma.com/
Bioethanol Production – Contactor

- Reactive extraction of acetic acid inhibitor
Acid Recovery From Aqueous Solutions

D. Painer et al. /http://www3.aiche.org/proceedings/content/Annual-2013/extended-abstracts/P318747.pdf
Acid Recovery From Aqueous Solutions

**Extraction**

Aqueous Feed
Acetic Acid < 60 g/l
Formic Acid < 30 g/l

**Distillation**

Laden Solvent

Crude Distillate
Acetic Acid < 600 g/l
Formic Acid < 300 g/l

Solvent (e.g. Cyanex 923) regenerated

Raffinate
Acetic Acid < 1 g/l
Formic Acid < 1 g/l

D. Painer et al. /http://www3.aiche.org/proceedings/content/Annual-2013/extended-abstracts/P318747.pdf
Acid Recovery From Aqueous Solutions

Diagram:

- **Reaction**
  - Formic Acid
  - Acetic Acid
  - Water
  - Methanol

- **Amberlyst® 15**

- **Pervaporation**
  - Methanol
  - Water

- **Distillation**
  - Methyl Formate
  - Methyl Acetate

D. Painer et al. /http://www3.aiche.org/proceedings/content/Annual-2013/extended-abstracts/P318747.pdf
Acid Recovery From Aqueous Solutions
Acid Recovery From Aqueous Solutions

Sugar cane juice/cheese whey or other renewable and cheap carbohydrates/ nutrients

Continuous fermentor

Cell recycle

Microfiltration membrane

Low pressure pump

Pure Lactic acid

Nanofiltration

High pressure pump

Recycle of unconverted carbon, nutrients module (cross flow)
Acid Recovery From Aqueous Solutions

- Acetic acid separation and sugar concentration by RO
Acid Recovery From Aqueous Solutions

- Two stage acetic acid production
Acid Recovery From Aqueous Solutions

- Lactic acid recovery from lactate
Biogas Production

- Gas purification

(a) Single stage without recycling.

(b) Single stage with recycling.

(c) In the process two compressors are required, and the retentate of the second stage is mixed with the retentate of the first stage.

(d) In the process the feed gas is used as a sweep gas on the permeate side of the second stage. Here only one compressor is required.
Biogas Production

- Anaerobic membrane bioreactor (AnMBR)
Biogas Production

- Anaerobic membrane bioreactor (AnMBR)
Biogas Production

• GE Water configuration
Spectrum of Membrane Applications

- **Substrate**
  - Sugar cane
  - Sugar cane
  - Grass
  - Corn
  - Grass
  - Sugar cane / Corn
  - Canola oil
  - Wood
  - Papaya

- **Membrane Process(es)**
  - Ultrafiltration
  - Microfiltration
  - Electrodialysis
  - Ultrafiltration / Pervaporation
  - Ultrafiltration
  - Ultrafiltration / Nanofiltration

- **Products**
  - Sugars
  - Nutrients
  - Lactic acid
  - Proteins
  - Carbonic acids
  - Amino acids
  - Bio-ethanol
  - Biodiesel
  - Lignin
  - Fab antibody

- **Applications**
  - Foods
  - Bio-chemicals
  - Fuels, Energy
  - Biomaterials
  - Pharmaceuticals
Conclusions

• Separations are critical to chemical industry

• Membranes can improve sustainability of industrial petrochemical, chemical, and pharmaceutical separation processes

• Integration of separations within biorefinery offers unique opportunities for process intensification
  – Product concentration/preparation
  – Feed preparation/impurity removal
  – Water purification/recovery
  – Multi-stage fermentation