Recent and Future Trends in Research and Education in Chemical Engineering

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125th Anniversary Chemical Engineering
IMIQ-Academia Mexicana de Ingenieria
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Outline

1. Brief account historical evolution

2. Recent trends towards science and diversification

3. Current challenges industry-academia disconnect

4. Future trends: expanding scope, sustainability/energy
Chemical Engineering curriculum

George Davis, Manchester 1887
Lewis Norton, MIT 1888

Unit Operations

Chemical Engineering Principles

Arthur D. Little, MIT, 1916
William Walker, MIT 1924
Olaf Hougen, Wisconsin 1947

J.W. Gibbs, 1878
H. Helmholtz, 1847
L. Boltzmann, 1866
K.G. Denbigh, Southampton, London, Imperial, 1955
Transport Phenomena

Bird, Stewart, Lightfoot, Wisconsin, 1960

Applied Mathematics/Reaction Engineering
R. Aris, 1962; N. Amundson, 1972; Minnesota

Fluid Mechanics
G. Batchelor, Cambridge, 1967

Mass Transfer
P.V. Danckwerts, Cambridge 1965

Catalysis
Michel Boudard, Stanford 1968

Polymers
P. Flory, 1969; Dupont, Cornell, Carnegie Mellon
Process Systems Engineering

Dale Rudd, Wisconsin 1968  Roger Sargent, Imperial College 1964

Bioengineering

Robert Langer, MIT 1977  Jay Bailey, Caltech 1986

Nanotechnology

Study and development of polymers to deliver drugs, particularly genetically engineered proteins, DNA and RNAi, continuously at controlled rates for prolonged periods of time

US5797898 (1998)
Microchip drug delivery devices with John T. Santini, Jr., Michael J. Cima

US5759830 (1998)
Three-dimensional fibrous scaffold containing attached cells for producing vascularized tissue in vivo, with Joseph P. Vacanti

Other Selected Patents:
US4891225 (1990) Bioerodible polyanhydrides for controlled drug delivery, Massachusetts Institute of Technology, with Howard Rosen
US4391797 (1983) Systems for the controlled release of macromolecules, The Children's Hospital Medical Center, with Moses J. Folkman
Diversification Chemical Engineering Research

B.S. Job placement (AIChE, 2007)

Industry Hiring Trends for Chemical Engineers

- Chemicals 22%
- Fuels 20%
- Food & Consumer Products 9%
- Biotechnology 9%
- Design & Construction 7%
- Other Industry 7%
- Research & Testing 6%
- Electronics 4%
- Materials 4%
- Environmental Engineering 4%
- Business Services 4%
- Pulp & Paper 2%
- Public Utilities 1%
- Aerospace 1%

Chemicals Fuels ~45%
Bioengineering area:
- Perceived as “hot” area: most new faculty in bio area
- Many new Biomedical Engineering Depts
  Job market biomedical engineers?

Many U.S. departments (~50%) were renamed as:
Chemical and Biomolecular Engineering
(e.g. Cornell, U. Penn., Illinois, Georgia Tech)
Chemical and Biological Engineering
(e.g. Colorado, Northwestern, Notre Dame, Wisconsin)

Nanotechnology is other “hot” area
Trends in Chemical Engineering Education
(Last decade)

- **Increasing emphasis on Science in Chemical Eng. Departments**
  - Many professors are not chemical engineers and do not regard AIChE as their primary organization
  - Has increased multidisciplinary approach
  - Decreased emphasis on chemical engineering fundamentals

- Process Design courses largely outsourced to retired industry people
- Process Control no longer required at many U.S. universities
Other examples trends in Chemical Engineering

- Netherlands has now only two chemical engineering departments: *Delft, Eindhoven; no Chaired Process Systems Eng. Professors*

- Houston, the capital city of Oil & Gas and Chemical Industry in US has only ONE Process Systems Engineering Professor *U. Houston: Michael Nikolaou; Rice University: NONE*

- Many faculty members in US *do not publish anymore in chemical engineering journals*
Move from Engineering to Science

Impact factors ~2.2

Impact factors ~30
### AIChE J: Top Accepted Articles by Country of Origin

October 30, 2012

<table>
<thead>
<tr>
<th>Country</th>
<th>Total</th>
<th>% of Submissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>73</td>
<td>13.32%</td>
</tr>
<tr>
<td>China</td>
<td>157</td>
<td>28.65%</td>
</tr>
<tr>
<td>Canada</td>
<td>32</td>
<td>5.84%</td>
</tr>
<tr>
<td>France</td>
<td>16</td>
<td>2.92%</td>
</tr>
<tr>
<td>Spain</td>
<td>16</td>
<td>2.92%</td>
</tr>
<tr>
<td>Germany</td>
<td>10</td>
<td>1.82%</td>
</tr>
<tr>
<td>India</td>
<td>51</td>
<td>9.31%</td>
</tr>
<tr>
<td>Netherlands</td>
<td>9</td>
<td>1.64%</td>
</tr>
<tr>
<td>Japan</td>
<td>17</td>
<td>3.10%</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>17</td>
<td>3.10%</td>
</tr>
<tr>
<td>Australia</td>
<td>12</td>
<td>2.19%</td>
</tr>
<tr>
<td>Taiwan</td>
<td>10</td>
<td>1.82%</td>
</tr>
<tr>
<td>Sweden</td>
<td>5</td>
<td>0.91%</td>
</tr>
<tr>
<td>Belgium</td>
<td>3</td>
<td>0.55%</td>
</tr>
<tr>
<td>Korea, Republic of</td>
<td>6</td>
<td>1.09%</td>
</tr>
<tr>
<td>South Africa</td>
<td>3</td>
<td>0.55%</td>
</tr>
</tbody>
</table>

**Articles Accepted Dec. 15, 2011 through Oct. 23, 2012**

*US/Canada: 20%*  
*Europe: 18%*  
*China: 30%*  
*India: 10%*  
*Japan, Taiwan, Korea: 7%*
## The Industry Connection

### Revenues of major U.S. companies (billions)

<table>
<thead>
<tr>
<th>Company</th>
<th>2006</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>ExxonMobil</td>
<td>$365.5</td>
<td>$452.93</td>
</tr>
<tr>
<td>ChevronTexaco</td>
<td>204.9</td>
<td>241.9</td>
</tr>
<tr>
<td>Dow</td>
<td>49.1</td>
<td>56.8</td>
</tr>
<tr>
<td>DuPont</td>
<td>27.4</td>
<td>38.72</td>
</tr>
<tr>
<td>Procter &amp; Gamble</td>
<td>68.2</td>
<td>82.55</td>
</tr>
<tr>
<td>Johnson &amp; Johnson</td>
<td>53.3</td>
<td>67.22</td>
</tr>
<tr>
<td>Merck</td>
<td>22.3</td>
<td>48.05</td>
</tr>
<tr>
<td>Bristol-Myers Squibb</td>
<td>17.9</td>
<td>21.24</td>
</tr>
<tr>
<td>Amgen</td>
<td>13.8</td>
<td>23.6</td>
</tr>
<tr>
<td>Genentech</td>
<td>7.6</td>
<td>17.3</td>
</tr>
</tbody>
</table>

One trillion dollar industry !!
## Industrial Survey on Importance of Skills

*John Chen (2013)*

<table>
<thead>
<tr>
<th>Skill</th>
<th>Average Relative Importance 1-5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UO:</strong> unit operations, transport phenomena, thermodynamics, separation processes *</td>
<td>4.6</td>
</tr>
<tr>
<td><strong>RE:</strong> reaction engineering, catalysis, kinetics.</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>AM:</strong> analysis, modeling, simulation, process control *</td>
<td>4.0</td>
</tr>
</tbody>
</table>

*Main perceived gaps between importance and proficiency by new hires*

- **Industrial Survey on Importance of Skills**
  - Manufacturing: 49%
  - Engineering: 49%
  - R&D: 29%

93 respondents (ChemE recruiters and leaders)
Academic Disconnect: Trends Faculty Composition

**Unit Operations**
Faculty Strength in UO

**Reaction Engineering**
Faculty Strength in RE

**Advanced Modeling**
Faculty Strength in AM

Evolution over Time
Academic Disconnect: Trends Faculty Composition

**Bioengineering**

Faculty Strength in Bio

Evolution over Time  --->

<table>
<thead>
<tr>
<th>Rank</th>
<th>Emeritus</th>
<th>Professor</th>
<th>Associate Prof.</th>
<th>Assitant Prof.</th>
</tr>
</thead>
<tbody>
<tr>
<td>% in Each Rank</td>
<td>0%</td>
<td>5%</td>
<td>10%</td>
<td>15%</td>
</tr>
</tbody>
</table>

**Nanotechnology**

Faculty Strength in Nano

Evolution over Time  --->

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<td>15%</td>
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</tbody>
</table>

**Materials**

Faculty Strength in Mat

Evolution over Time  --->

<table>
<thead>
<tr>
<th>Rank</th>
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</table>
Dow concerned about big-push to Bio

Dow requires critical scientific & engineering skills ➔ 75-100 PhD/year
- Chemistry, Materials Science, Chemical Engineering, Mechanical Engineering

US Chemical Engineering & Chemistry Departments are chasing biotechnologies
- 31% of the Chemical Engineering Departments in the US added “bio” to their names in 20yrs
- “Bio-Tsunami”: Funding ➔ New Faculty ➔ Research ➔ Teaching ➔ Students ➔ Workforce

<table>
<thead>
<tr>
<th>Number of Published Articles</th>
<th>Percentage of Faculty with “bio” Related Research Interests:</th>
</tr>
</thead>
<tbody>
<tr>
<td>3K Biodiesel + Cellulosic Ethanol + Bioengineering</td>
<td>Caltech 23%</td>
</tr>
<tr>
<td>2K Reactor Design + Transp. Phenomena + Fluid Dynamics</td>
<td>UC Santa Barbara 28%</td>
</tr>
<tr>
<td>1K</td>
<td>Northwestern 35%</td>
</tr>
<tr>
<td>0K</td>
<td>Georgia Tech 42%</td>
</tr>
<tr>
<td></td>
<td>Berkeley 44%</td>
</tr>
<tr>
<td></td>
<td>UT Austin 45%</td>
</tr>
<tr>
<td></td>
<td>U Illinois 58%</td>
</tr>
</tbody>
</table>

Top Strategic Universities

Dow Research & Development
Dow Intends to Influence the Scientific Funding Environment

AS THE BIGGEST US EMPLOYER IN THE CHEMICAL INDUSTRY DOW HAS TO:

• Partner with strategic universities to:
  • Work on problems relevant to Dow
  • Develop talent with the skills needed
  • Influence the “Influencers”

Commit to Long Term Funding
$25 million/year for next 10 yr in US
$10 million/year for next 10 yr outside US
Example Process Innovation

Methyl Acetate Flowsheet

Single Reactive Dist. Col.

Siirola (1988)
Future Trends: Expanding the Scope of Chemical Engineering
Multiscale Product and Process Design: from “Bulk” to “Molecular” Processing

George Stephanopoulos (2004)

Macro-Processing:
Batch or Continuous Chemical Plants

Micro-Processing:
Plant-on-a-Chip

Molecular-Processing:
The Cell

Metabolites
DNA → RNA → Protein

Carnegie Mellon
New emphasis: energy and sustainability

Growing World Energy Demand
Most Energy Growth in Developing Nations

Energy and sustainability likely to swing pendulum against bio and nano areas in Chemical Engineering
Water scarcity

Definitions and indicators
- **Little or no water scarcity.** Abundant water resources relative to use, with less than 25% of water from rivers withdrawn for human purposes.
- **Physical water scarcity** (water resources development is approaching or has exceeded sustainable limits). More than 75% of river flows are withdrawn for agriculture, industry, and domestic purposes (accounting for recycling of return flows). This definition—relating water availability to water demand—implies that dry areas are not necessarily water scarce.
- **Approaching physical water scarcity.** More than 60% of river flows are withdrawn. These basins will experience physical water scarcity in the near future.
- **Economic water scarcity (human, institutional, and financial capital limit access to water even though water in nature is available locally to meet human demands).** Water resources are abundant relative to water use, with less than 25% of water from rivers withdrawn for human purposes, but malnutrition exists.

Source: International Water Management Institute analysis done for the Comprehensive Assessment of Water Management in Agriculture using the Watersim model; chapter 2.

Two-thirds of the world population will face water stress by year 2025
Renewables: Carbon footprint various Energy Options

Adisa Azapagic (2012)
Biorefinery Supply Chain

**Bioethanol, FT-diesel and hydrogen from switchgrass**
**Biodiesel from cooking oil or algae oil**

Martin, Grossmann (2012)
Manufacture Solar Grade Silicon

Multi-scale models to integrate population balances (particulate systems), computational fluid mechanics, reactor design and process control

Ydstie (2008)

MARKET:

Multiscale Model for Distributed Parameters

Figure 1 - Evolution of global PV cumulative installed capacity 2000-2012 (MW)

Particles are well-mixed
Integrate over time for particle size distribution

Gas and powder are plug flow
Integrate over height for granular yield

Control fluidization regime
Simulate once to obtain model input

MARKET:
Depletion of fossil fuels?

**Oil Reserves**

- **Year 2000**
  - Total: **1105 thousand million barrels**

- **Year 2010**
  - Total: **1383 thousand million barrels**
  - **25% increase!**

- Discovery of New Large Oil and Gas Reserves
- New technologies for Offshore oil exploration and production

*Statistical Review of World Energy (June, 2011)*
Depletion of fossil fuels?

Shale Gas Reserves in World

units = trillion cubic feet

Larger circles = technical reserves
Smaller circles = potential reserves

Shale Gas in US

Marcellus Shale Gas

Large amount “wet gas”

Horizontal drilling
Hydraulic fracking
Optimal Drilling Strategy: Shale Gas

MINLP Optimization Model

Cafaro, Grossmann (2013)

9 well-pads
20 wells per pad
3 potential plants
10 years
40 periods

Well pads

Quarters

Methane Production

Ethane Production
Catalysis and Process Engineering Challenges
C$_1$ Chemistry

*Enrique Iglesia (2013)*
Energy Supply Chain Model

Hybrid Coal, Biomass, and Natural Gas to Liquids Systems

Biomass availabilities from database

Coal availabilities from database

Transportation fuel demand

Water supply

Carbon dioxide sequestration capacities

Energy Supply Chain Optimization Model

Grid points of candidate facility locations

Biomass availabilities from database

Natural gas availabilities from database

CBGTL plant parameters

Transportation infrastructure
Remarks

1. Need to keep core Chemical Engineering Knowledge
   Need to emphasize fundamentals: basis life-long learning

2. Need to modernize curriculum and add flexibility
   - Increase exposure molecular level
   - Increase exposure to energy (alternative/renewable) and sustainability issues
   - Expose students to new process technology
   - Introduce product design as complement of process design
   - Emphasize process operations, enterprise planning
   - Increase link to other industrial sectors (pharma, electronics)

3. Need to recognize that “bio-area”, while important, will not be dominant force in Chemical Engineering, emphasis should be on bioprocessing

4. Environmental Engineering increasingly important and requires chemical engineering (water use efficiency, pollution control, etc.)

5. Need closer interaction with industry; otherwise risk being irrelevant

6. Need to provide excitement to recruit the very best young people to join Chemical Engineering