Nuclear and the Chemical Industries

Jeff Siirola
Davidson School of Chemical Engineering
Purdue University

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Chemical and Related Industries
Make Stuff, not Things

- Commodity Chemicals (Polymers, Acids, Bases, Intermediates, etc.)
- Specialty (Fine) Chemicals (Dyes, Solvents, Electronic Chemicals, etc.)
- Agricultural Chemicals (Fertilizers, Pesticides, etc.)
- Pharmaceuticals
- Pulp and Paper
- Metals (Steel, Aluminum, Copper, etc.)
- Glass and Ceramics
- Fuels (Gasoline, Diesel, Jet Fuel, etc., by volume about 20 times larger than chemicals)

Chemical Plant Characteristics

- Operational Mode:
  - Batch (Recipes), up to 1M kg/yr
  - Continuous, 1M to 1^{+}B kg/yr (may run months or years between shutdowns)

- Energy Requirements:
  - Mostly Thermal
    - Condensing steam, up to 250C (Latent Heat)
    - Hot oil, 250-350C (Sensible Heat)
    - Fired furnace, 350-1000C (Mostly Radiation)
    - Direct contact (Blast Furnace, Gasifiers, etc.), up to 1500C
    - Electric arc furnace (Steel Recycling)
    - Water cooling
  - Some Power
    - Pumps, Compressors, Refrigeration Systems (Compressors), Agitators, Rotating/Moving Equipment (Centrifuges, Dryers, Conveyors, etc.): Motive Steam or Electricity
    - Electrochemistry (Chlorine, Caustic, Aluminum, etc.): Electricity

Chemical Plants were Historically Driven by Steam, Cooling Water, and Compressed Air

- Early chemical process industries predated electricity
- Chemical reaction rates are temperature-dependent
- Many separation technologies (distillation, crystallization, etc.) are also driven by phase changes and temperature differences
- Some vapor chemical reactions are favored by high pressures; steam turbines supplied the motive power for pumps and compressors
- Sensor and control information was encoded into pneumatically transmitted air pressures
- Control valves were actuated with compressed air (steam driven)

Modern Use of Electricity

- Electricity has replaced motive steam for most rotating equipment, conveyors, and smaller pumps and compressors
  - Motive steam expanding in turbines is still often used for largest equipment and in parallel with electrically-driven equipment for resilience and reliability
- Electrical signals have replaced pneumatic air pressures for information transmission and control calculations
  - Compressed air is still used for valve actuation
- Electricity is used for electrochemical reactions
- Electricity is used for lighting

Electricity is Relatively Expensive and its Use within the Chemical Industry is Still Minimized

- Thermally-driven separations (like distillation) remain favored over pressure-driven separations (exploiting membranes)
- Some work-driven operations (like compressors) are expensive; extraordinary design measures (like multiple effect distillation) are employed in processes with high refrigeration needs (like air separation plants) in order to minimize compressor work requirements
- Although common in laboratory settings, electrical process heating is rare (but is used, for example in electric arc furnaces)
- Many chemical plants co-generate their own electricity in steam boiler topping cycles, but in general thermal requirements far exceed electricity requirements
  - Some plants cogenerate as much electricity as possible given their thermal steam requirement and sell the excess, although most plants scale back cogeneration to just meet internal electrical needs

Approaches to Chemical Plant Carbon Emissions Mitigation

- Switch from steam coal to natural gas fuel
- Fluegas carbon capture and sequestration
- Switch to "carbon-neutral" biomass fuel
- Consider nuclear for process heat (and electricity)

- Electrify chemical processes
  - Employ only carbon-emission-free electrical energy (hydro, wind, PV, solar thermal, fossil with CCS, geothermal, nuclear, etc.)

Thermal Temperature Requirements

- Some seemed to think that the chemical industry needs its heat inputs at 800C
  - That is the temperature for thermal water splitting (which no one does) and for some endothermic cracking, reforming, and other reactions
  - Such a temperature requirement might limit nuclear reactor concepts to high temperature gas cooled technologies
- However, most chemical plant thermal energy is supplied by condensing steam at 250C (600psi) or lower
  - Steam at this temperature could be generated with a broader range of nuclear reactor technologies
  - The less common energy requirements at higher temperatures could be supplied by non-nuclear alternatives

Energy/Process Reliability

- Some expressed concern that a chemical plant would be a non-reliable nuclear thermal energy customer
  - The concern being that the chemical plant may shut down leaving the nuclear reactor without a thermal sink

- In contrast, the chemical industry has concerns that nuclear is not a reliable process heat source
  - While it is true that individual processes may shut down from time to time, chemical plants consist of dozens to hundreds of individual processes and overall chemical plantsites have run 24/7/365 for decades or longer
  - If a nuclear plant supplying electricity shuts down (which it does often), there is an electrical grid infrastructure to back it up
  - However, if a nuclear plant supplying process heat shuts down, it is not clear how the chemical plant thermal requirement could be backed up; a large amount of local fossil-fueled thermal capacity on hot-standby does not appear practical; however, the loss of heat (and the resulting reaction and separation failures and the solidification of molten materials within processing equipment) could be catastrophic

Nuclear Reliability Solutions

- Dow Nuclear Energy Design (1970s)
  - Twin 650 Mw(e) light water reactors each also providing 2M lb/hr process steam
    - Project ultimately cancelled and replaced by 12-unit natural gas fired cogeneration
- Modern Nuclear Steam Reliability Proposal
  - Multiple Small Modular Reactors
    - One more reactor than that needed for plant steam and electrical requirement
    - Excess energy used to generate electricity delivered to the grid
    - Electrical grid used as a resource to withdraw from in event of the scheduled or unplanned loss of any one modular reactor (or sink for excess nuclear energy)
    - Most any small modular reactor concept possible

Chemical Plant Nuclear Reactor Siting

- On the site of an existing process steam powerhouse
  - PROS: Existing steam and electricity distribution infrastructure
  - CONS: Within a highly-populated plantsite

- Separate but adjacent to the chemical plant site
  - PROS: Better facility isolation and more limited personnel in the immediate area
  - CONS: Longer than typical steam transmission piping

- At an existing nuclear power plant site (not a nuclear process heat solution)
  - PROS: Conventional siting considerations and constraints
    Conventional reactor technology (not necessarily small modular)
  - CONS: Electrical energy transfer only

Totally Electrical Chemical Processing

- An approach to decarbonize chemical production by using mostly carbon-emission-free electricity
  - Yes, you can run a chemical plant with a windmill (lots of them)
  - Or, conventional nuclear and electrical grid technology

- It has not been economical in the past
  - On an energy basis, electricity is generally more expensive that thermal energy
    - Electricity is conventionally generated from thermal energy at about 35% Carnot efficiency (and less if carbon capture and sequestration is required)
    - Compressors in particular are very expensive to buy and to operate and are generally avoided
    - This is why refrigeration and high pressure vapor processes are so expensive
  - Most chemical processes today remain thermal energy dominated

- But it may be competitive in the future
  - If Carbon Taxes approximating the cost of fluegas CCS or direct air capture are imposed and could thereby be avoided

Some Possibilities

Use of Electricity to Generate Thermal Energy

- Almost Trivial
  - Replace heat transfer through a reactor or tube wall because of condensing steam by heat transfer through a wall wrapped with an electrical resistance element
- Nearly as Trivial
  - Replace a fired heater by electrical element or induction heating
    - Also eliminates the requirement for processing hot exiting furnace fluegas

More Possibilities

Use of Electricity to Transfer Thermal Energy

- Heat-Pumped Distillation
  - Refrigeration cycle between the distillation column condenser and its reboiler
    - Substituting turbomachinery and electrical work for both heating and cooling thermal utilities
    - Consider distillations with greater reboiler-condenser temperature differences than previously practical

- Heat-Pumped Temperature Swing Adsorption
  - Refrigeration cycle between beds adsorbing at low temperature and beds desorbing at higher temperature, again substituting mechanical for thermal energy

- Other Heat-Pumped Heat Integration (Sources Cooler than Sinks)
  - Involves working fluid or process vapor compression

Still More Possibilities
Greater Use of Work-Driven Pressurized Unit Operations

- Membrane-based Separations
  - For vapor as well as liquid systems
- Pressure- (or Vacuum-) Swing Adsorption
- Higher Pressure Vapor Reaction Conditions

And More

Electrocatalysis and Electromagnetic Energy

- Electrocatalysis for high effective gas pressures and intensified reaction kinetics
- Microwave energy tuned to specific molecular vibrations for improved reaction selectivity
- Organic electrochemistry (minimally practiced today)
- Possible electrically-driven chemical processing technologies yet to be developed

Summary

- Nuclear thermal energy has been considered for the chemical industries which are currently dominated by thermal energy
- Most (but not all) chemical thermal requirements are below 250C (currently met by condensing steam), well within the capabilities of most nuclear reactor concepts
- Nuclear thermal energy delivery reliability can be achieved with multiple (and redundant) small modular reactors
- Practical steam transmission distance limits reactor siting to on or adjacent to the chemical plantsite
- However, to meet environmental goals exploiting carbon-emission-free electricity, chemical plants could be redesigned to substitute work-based operations for currently thermally-driven operations (as well as the conversion of electricity to heat)
- Conventional nuclear electricity might prove more applicable to an appropriately modified chemical industry than on-site nuclear thermal energy might be