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An Overview of Chemical Engineering

Chemical engineering is a compelling discipline. It has a rich intellectual history and has provided humankind with technologies that have transformed our lives. Introductory textbooks in chemical engineering, as well as numerous websites, detail our history and contributions to society. The appeal of chemical engineering lies in its balance of two diverse endeavors: to serve society and to advance fundamental science and engineering. Chemical engineering is the academic embodiment of F. Scott Fitzgerald's contention that ". . . the test of a first rate intelligence is the ability to hold two opposed ideas in the mind at the same time, and still retain the ability to function."[1]

A challenge for chemical engineering derives from its two ostensibly disparate goals: deepening the great intellectual concepts befitting academic engineering, yet enabling the practical "hands-on" skills for professional practice. Chemical engineering is eminently practical because the skills associated with it are integral to people who make products via chemical transformations. It remains one of the highest-paid engineering professions (often second only to petroleum engineering, a specialty within chemical engineering), and students seek training in chemical engineering to join great worldwide enterprises in chemicals, food, energy, electronics, pharmaceuticals, and biotechnology, for example. Academic chemical engineering therefore must enable the professional practice of its graduates, including practices and tools used in the workplace.

Chemical engineering is also a rich intellectual discipline that embraces enduring concepts from science and mathematics. For example, Josiah Willard Gibbs is considered one of the greatest scientists of the twentieth century: "Gibbs energy" is the foundation for undergraduate chemical engineering thermodynamics. The differential control volume constructed for calculus to express conservation of mass, energy, and momentum is an engineering science triumph of the twentieth century and a hallmark of undergraduate chemical engineering. Computational methods as analytical tools (such as non-linear mathematics, and digital data acquisition for process control and analysis) were developed by the twentieth-century intellectual and academic elite, and are now routinely employed in the university classroom and laboratory.

The practical and the theoretical are the yin and yang of chemical engineering, in constant balance. Most chemical engineering curricula achieve this balance by relying on research professors to teach analysis, with the design aspects taught via internships, "co-ops," lab research, and a capstone design course typically taken just before graduation

[1] *The Crack-Up*, by F. Scott Fitzgerald, www.esquire.com/lifestyle/a4310/the-crack-up. Originally published in the February, March, and April 1936 issues of *Esquire*.

and taught by licensed engineers. Yet within each course, and indeed within the definition of chemical engineering itself, this balance is manifest in many ways.

In this textbook we introduce chemical engineering to students as "the design and analysis of systems . . ." because this expression nicely frames the contrasting attributes of the chemical engineer. Design is often associated with the moniker "right brain activity," where creative and practical arts merge to conceive a plan for something new. The great twentieth-century engineer Theodore von Kármán stated, "Science discovers what is, engineers build what never has been."[2] Analysis, on the other hand, is convergent thinking that typically involves mathematics. This "left-brain activity" constitutes a considerable portion of the engineering practice because mathematical modeling is an essential tool in the "creation of what has never been." Chemical engineering is regarded as one of the most challenging majors because it requires creative and practical designs, as well as mathematical analysis in systems highly constrained by physical laws. But with challenge comes pride in achievement – as an introductory student you stand proudly on the bridge spanning these two complementary views.

We complete the phrase above: chemical engineering is "the design and analysis of systems governed by physical and chemical rate processes." At the start of the twentieth century, chemical engineering was born considering the "unit operations" associated with commodity chemical production, sometimes called industrial chemistry. The post-World War II generation of chemical engineers designed and still operate the refineries that fuel modern transportation. The notion of chemical plant design as parsed into "units" where each performs a specific operation (mixing, reactions, separations, etc.) is canon to chemical engineers and remains to the present day. The worldwide volume (or value) of chemicals produced has grown by a factor of 6 over the period 1980–2020, yet the number of BS chemical engineers entering the profession each year has remained roughly constant.[3] This is superb testimony to the increased production efficiency of the systems attributable to our discipline. It is worth noting that early chemical engineers embraced computational modeling and design which amplified the economic value and quantity of chemical goods produced. Emerging economies, where new manufacturing and chemicals production are often co-located, still seek the "unit operations" training in the contemporary chemical engineer. The practical engineer indeed has much to contribute here. Finally, it is interesting to note that the stunning success of the "unit operation" style of design and analysis of chemical plants in the mid twentieth century is a primary motivator for the application of chemical engineering to emerging technologies.

Should growth in large-scale manufacturing return to the USA, no doubt unit operations as deployed by the chemical engineering professional will wax. In the last 20 years or so, however, nations such as the USA have built few new chemical plants, and even fewer new refineries. Specialty chemical, small-scale manufacturing, electronic and "niche" industries, medical diagnostics, health and personal-care products require chemical engineers who will optimize "physical and chemical rates" in devices and situations not previously explored by chemical engineers. It is tempting to conclude that academic chemical engineering, with its emphasis on molecular engineering and science fundamentals with mathematical modeling, is the most valuable skill set for the

[2] www.quotesby.net/Theodore-von-Karman; www.nationalmedals.org/laureates/theodore-von-karman.
[3] Worldwide chemical production is posted at several websites, including www.americanchemistry.com/Jobs/EconomicStatistics/Industry-Profile/Global-Business-of-Chemistry. We have used data from UNEP (2013) (ISBN: 978-92-807-3320, © United Nations Environment Programme). The number of BS graduates per year is typically reported in *Chemical and Engineering News*'s Annual Reports on Professional Training.

twenty-first-century chemical engineer, with "unit operations design" a vestige of history. Von Kármán would be annoyed at this sweeping generalization and correctly argue, we believe, that the natural sciences have moved considerably closer to the historical values of engineering ("to create what never has been . . .") while engineers have moved closer to science ("to discover what is . . .") to innovate in a marketplace suited for nine billion individuals. Chemical engineering is quite functional *and yet* employs both the right and left brain, much to the delight and sometimes frustration of all who participate.

The physical and chemical rate processes that dominate chemical engineering practice have endured for many decades, starting with production rates that tie to economic productivity. How fast can a product be made? What economic rates of return are necessary to justify the interest rate paid to build the manufacturing plant? The chemical engineer looks at the "conservation of assets" and envisions the accumulation of assets for the company, which in turn creates jobs and economic opportunity for others. The movement of fluid from one place to another involves momentum transfer rates, which transcend pumping macroscopic fluids to the motion of complex fluids composed of highly interacting molecules that move through complex geometries in devices with small length scales. How long must you wait before your fuel-cell-powered car will move in winter? Heat-transfer rates often couple strongly with fluid flow, as well as with molecular constitution and structure. Rates of mass transfer mostly concern the relative movement of atoms and molecules, often between different phases, when driven by some external "driving force." Thus mass transfer dominates the design of anything that reacts and separates chemicals, from fuel cells to artificial kidneys to distillation columns. All chemical engineering programs now focus more heavily on rate processes from the point of view of the molecules, yet to some extent must be familiar with empirical (industrial) design correlations for the coupling of mass, momentum, and heat transfer in bulk manufacture.

Finally, the control of chemical rates through the use of elegantly designed apparatuses is where the chemical engineer shines. The twentieth century brought the sub-discipline of "chemical reaction engineering" to extraordinary heights, where chemical rates in conjunction with all the other rates described above are brought to bear to design new equipment and products. The "chemical engineering student as chemist" seeks to extract an understanding of chemical rate phenomena within the sub-disciplines of chemistry. Chemical engineering programs are faced with the application of twentieth-century knowledge of rate processes for traditional roles but must employ twenty-first-century concepts and tools for the next new industries. John Prausnitz (Professor of Chemical Engineering, University of California at Berkeley) captured this theme eloquently when he said that we are now teaching chemical engineering as "the future practical." [4]

1.1 ACHIEVEMENTS OF CHEMICAL ENGINEERING

Chemical engineers have a rich history of transforming society. The design and analysis skills mentioned are manifested in the following list of significant achievements by chemical engineers, as published by the American Institute of Chemical Engineers (AIChE) in 2008.[5]

[4] www.annualreviews.org/userimages/ContentEditor/1315331682902/JohnPrausnitzInterviewTranscript.pdf.
[5] *Chemical Engineering Progress*, November 2008, pages 7–25.

Energy. Chemical engineers created equipment and processes on a massive scale to crack hydrocarbon molecules from crude oil and transform them into fuels. The ability to synthesize high-octane fuel was a crucial factor in the Battle of Britain and World War II. In the latter twentieth century, chemical engineers transformed natural gas to premium blend gasolines. Catalytic cracking also creates the molecular building blocks used to assemble complex chemicals.

Carbon-free energy. Chemical engineers developed massive-scale separation processes to prepare isotopically enriched uranium, thereby launching the nuclear power industry (and other industries associated with more destructive ends). Electrochemical engineers brought analytical rigor to the design and operation of batteries and fuel cells, creating new industries for vehicular transport and portable power.

Environmental technologies. The twentieth century witnessed the discovery by chemical engineers of the hollow-fiber membrane, the basis for reverse-osmosis water purification. Polymer replacements for asbestos, anaerobic wastewater treatment, and removal of toxic and/or dangerous solvents in the chemical industry were all contributions by chemical engineers. Chemical engineers also work to design processes with minimal offensive by-products and devise strategies to remediate polluted sites.

Air pollution. The modeling of air pollution in cities based on principles of chemical reactor engineering provided sound strategies for policymakers to create laws aimed at reducing urban pollution. Chemical engineers developed the three-way automobile catalyst to remove CO, NO_x, and hydrocarbons from the exhausts of cars, thereby reducing their emissions. The solid-state electrochemical oxygen sensor, developed by chemical engineers, affords computer control of automobile combustion, further reducing emissions and greatly improving automobile mileage.

Polymers. Beginning with Bakelite, the first hard, moldable plastic, chemical engineers developed the plastics – such as PVC, nylon, polystyrene, and polyethylene – that are the predominant materials for consumer products. Plastics have replaced wood, metal, and glass in many applications because of superior strength:weight ratio, chemical resistance, and mechanical properties. Chemical engineers built the reactors that produce polymers and designed the processing tools to prepare fibers, films, and macroscopic pieces for a panoply of industries.

Synthetic rubber. Elastic materials, such as automobile tires and drive belts, are an integral part of everyday life. Beginning with rayon in 1933, chemical engineers have brought stretchable polymers to the consumer in a host of technologies. The annual production of rubber typically exceeds a million tons. Remarkably, this industry was developed in only two years, just in time to replace shortages of natural rubber during World War II.

Manufacturing at scale. Chemical engineers have brought their fundamental skills in thermodynamics, kinetics and reactor design, and transport phenomena to many industries, affording mass production of many products. Borosilicate glass, isopropyl alcohol, fertilizers, dyes, laundry detergents, zeolite adsorbents, and diapers are just a few of the many products AIChE has identified as being the result of scale-up by chemical engineers.

Medicine. In 1918 an influenza epidemic killed 20 million people worldwide, half a million in the United States alone. Venereal diseases were incurable. Until the 1950s polio crippled millions. Discovering medicines was only part of the solution. After it was observed that a mold inhibited bacterial growth in a Petri dish, chemical engineering developed the technology to ultimately produce millions of pounds per year of penicillin. Chemical engineering made possible the mass production of medicines and their subsequent availability to people worldwide. Chemical engineering principles have been used to model the processes of the human body as well as to develop artificial organs, such as the kidney, heart, and lungs. Sunscreens, medical oxygen, wafer-delivered chemotherapy, and contact lenses are a few examples of products and processes developed by chemical engineers for health care.

Food and agriculture. Beginning with peanut butter in 1922, chemical engineers have developed food and agricultural processes that provide food for more people than ever before in recorded history. Freeze-drying was enabled by chemical engineers, allowing for juices to be stored and delivered worldwide. Insecticides and pesticides were developed that greatly improved crop yields. While "industrial farming" is coming under criticism in the twenty-first century, no one is advocating a return to the low-yield, low-quality crop harvests of the early 1900s.

Electronic materials. A chemical engineer, Andrew Groves, founded Intel. Intel co-founder Gordon Moore's prediction about transistor density in integrated circuits was made in part by applying the principles of chemical engineering to each of the processing steps in circuit manufacture, from preparing high-quality silicon to plasma etching and deposition of nanometer-thin layers to packaging in ceramics and polymers. Whenever electronic device manufacture requires chemistry (photolithography, etching, heat-shrink tubing, or organic LEDs, for example), or when the length scale of a device approaches the molecular regime (e.g. oxide gate barriers, nanowires) then the toolkit of the chemical engineer is indispensable.

The contributions of chemical engineers influenced the evolution of modern society. Most of the top-ten achievements listed above were achieved during the heyday of engineering – when it seemed that society's needs could be met by technology, with engineers as the purveyors of technology. Around the mid 1950s, however, technology came to be perceived as dangerous. People began to feel that society and the environment were dominated by technology, even victimized by technology. This perception remains today. The chemical engineering curriculum attempts to sensitize students to these issues by encouraging studies in humanities, social sciences, and ethics.

1.2 OPPORTUNITIES FOR CHEMICAL ENGINEERING

And what of the future? What will the chemical engineer bring to the twenty-first century? Contemporary chemical engineers are increasingly involved in services, compared to the historical emphasis on manufacturing. This trend will probably continue as chemical engineers are enlisted to remedy environmental contamination and modify existing processes to meet modern business and manufacturing agendas. We anticipate that a few frontier areas will emerge as new opportunities for chemical engineers, including:

Decarbonizing the atmosphere. Chemical engineers will play an increasingly large role in mitigating climate change as climate science becomes carbon policy. Direct air-capture of CO_2, pre- and post-combustion carbon capture, bioenergy carbon capture, and carbon utilization are ideally addressed with the toolkit of chemical engineering. Low- or zero-carbon energy generation and storage has already emerged within the chemical engineering academic and industrial enterprises, including fuel cells, batteries, capacitors, flow systems, and materials for high-power electrical controls.

Innovation at the nanometer scale. Personalized health care, home maintenance, consumer electronics, and manufacturing efficiency all portend the creation of devices and products that comprise extremely small components. Microfluidic devices will become (and indeed already are) miniature chemical plants, with fluid hydraulics, reaction, separations, and chemical analysis all happening at sub-millimeter length scales. These technologies require engineering design and analysis in the presence of chemical reactions and separations, at surfaces, and in structures that are of nanometer lengths.

Production of novel materials. Chemical engineers will design processes to produce ceramic parts for engines, high-T_c superconductors, polymer composites for structural components, and specialty chemicals produced in small amounts to exacting specifications. Chemical processes will shift from the traditional area of petrochemicals to inorganic compounds, from liquids to solids, and from large scale to small scale.

Biotechnology. Chemical engineers will improve methods of isolating bioproducts, design processes for chemical production from biomass, and capitalize on advances in genetic engineering to produce drugs, foods, and materials. Whereas chemical engineering has traditionally sought new reaction paths to produce established chemical commodities, biotechnology will seek ways to produce new chemicals, such as secondary metabolites and so-called customized proteins. With the emergence of point-of-care and personal-care medical technologies, the systems and rates associated with control of cellular processes ("applied molecular biology") have become important for the chemical engineer to master. "Synthetic biology" and "cellular engineering" are new fields that seek to modify plant, animal, and viral life forms for great societal benefit, though not without considerable ethical debate. For this reason many chemical engineering programs require a course in modern molecular biology and biochemistry.

Product design. The creation of new products and generation of economic growth are not limited to process design. Chemical engineers with knowledge and field experience in the complex process of transforming chemicals can also contribute to transforming technical innovations into commercially successful products. The "Post-It Note" paper products used everywhere to secure notes to various surfaces over and over again is an example of transforming a chemical process – the preparation of a pressure-sensitive adhesive – into a hugely successful commercial product. We see product design as an enormous opportunity for chemical engineers in the twenty-first century.

Solid wastes. Chemical engineers will invent methods to treat landfills as well as to remedy contaminated sites. Chemical engineers will also design alternatives for waste, such as incineration, biological decomposition, and recycling. Whereas the reactants entering traditional chemical processes are well characterized and invariable from day to day, processing wastes requires designs that accept reactants with ill-defined compositions that may change daily.

Pollution control. Chemical engineers will continue to reduce pollution at its sources – for example, by recycling intermediate outputs, redesigning chemical reactors, and re-engineering entire processes. Gone are the days when a public waterway was designated "for industrial use." Wastewater today sometimes exceeds the purity of the public waterway it enters. Chemical engineers will design processes that not only meet current regulations but also anticipate regulations. Chemical engineers will aspire to the ultimate goal of "zero emissions."

Energy. Chemical engineers will continue to improve the efficiency of present energy sources as well as develop new sources and energy storage systems.

Process control. Chemical engineers will develop and implement better sensors for temperature, pressure, and chemical composition. Processes will be designed to integrate artificial intelligence for process control, monitoring, and safety.

This is it, the beginning of your journey through one of the greatest disciplines on your campus.

REFERENCE

UNEP 2013. *Global Chemicals Outlook: Towards Sound Management of Chemicals*, ed. E. Kemf, United Nations Environment Programme, Geneva.

2

Chemical Process Design

In the first chapter we learned that chemical engineers create processes based on physical and chemical changes. In this chapter we develop designs for seven chemical processes. The step-by-step examples will also introduce strategies for design and conventions for depicting a chemical process.

2.1 DESIGNING A CHEMICAL PROCESS

2.1.1 Design Evolution by Successive Problem Solving

Context: A process to synthesize ammonia.

Concepts: Unit operations, process flowsheets, continuous operation, and separation based on boiling points.

Defining Question: How does one design a chemical process? How does one start?

Let's design a chemical process based on the chemical change of N_2 and H_2 into ammonia, NH_3, used primarily as a fertilizer. When crop fertilizing was introduced in the mid 1800s, nitrogen fertilizer – mostly ammonia and urea – was mined as seabird guano in coastal rookeries and bat guano in caves. Clearly, guano was not a sustainable source – the nitrogen-rich deposits from centuries of droppings were soon exhausted. Sustainable production of nitrogen fertilizer was realized by chemist Fritz Haber's 1905 invention of a synthetic route to ammonia by the chemical reaction

$$N_2 + 3H_2 \rightarrow 2NH_3. \qquad \text{rxn (2.1)}$$

This reaction is the basis of an efficient chemical process; the worldwide production of ammonia was almost 310 *billion* pounds in 2016, perennially in the top ten largest chemical productions.

Reaction 2.1 is the key to the ammonia synthesis. So we start with reaction 2.1. The device that conducts this reaction, the *reactor*, is the core of the process. The details of this reactor are key to the viability of the process, but these are not important now. We assume a viable reactor is available and devise a process to deliver the reactants and purify the product.

We need a means of describing our design. We could describe the process with words, such as "a mixture of N_2 and H_2 is piped into the reactor." This would be cumbersome. A chemical process exemplifies the adage "a picture is worth a thousand words." A chemical process is represented by a diagram known as a process *flowsheet*, a key tool in chemical engineering design.

Cambridge University Press
978-1-108-42147-8 — Chemical Engineering Design and Analysis
2nd Edition
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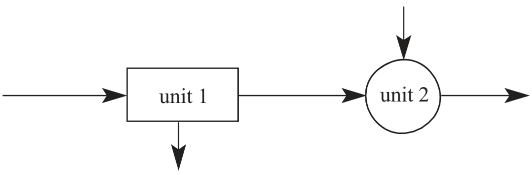
More Information

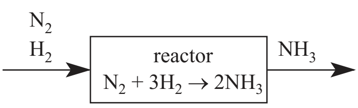
2.1 Designing a Chemical Process

A process flowsheet comprises *units*, represented by simple shapes, such as rectangles or circles:

The pipes that conduct material between units are called *streams*. The streams are represented by arrows:

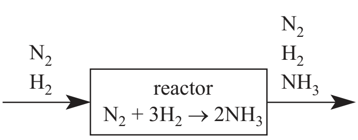


The specifics of a stream, such as its composition, are typically written above the stream. For example, the ammonia reactor can be represented as



The ammonia reactor is a *continuous* process; material constantly moves through the unit. A *batch* process, in contrast, is characterized by chemical or physical change without material moving in or out, except at the beginning and end of a cycle. A chemical reaction you conduct in a flask in your introductory chemistry laboratory is a batch process. Continuous processes are rarely encountered in undergraduate chemical laboratories, yet they dominate in the chemical industry.

The ammonia reactor above is idealized. Reactants are rarely converted entirely into products. There is almost always some residual reactant in the effluent stream. A realistic description includes N_2 and H_2 in the reactor effluent, as shown below.



The customer for our NH_3 would probably not be satisfied with N_2 and H_2 in the product. And we would be wasting reactants. We need to purify the NH_3. How might this be done? To separate substances, we need a physical or chemical basis. The most common basis for separations is *states of matter*, or *phase*. A gas phase is easily separated from a liquid phase. N_2, H_2, and NH_3 are gases at room temperature and pressure. Let's explore the possibility of condensing one or more of the compounds without condensing the others. A handbook of chemical data gives the information listed in Table 2.1.

Table 2.1 Boiling points for the ammonia process.

Compound	Boiling point at 1 atm (°C)
NH_3	−33
H_2	−253
N_2	−196

Cambridge University Press
978-1-108-42147-8 — Chemical Engineering Design and Analysis
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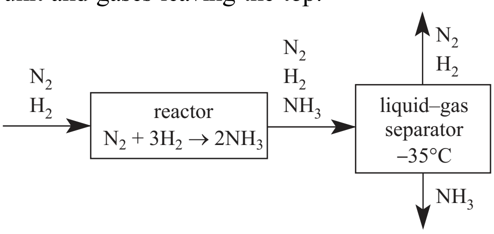
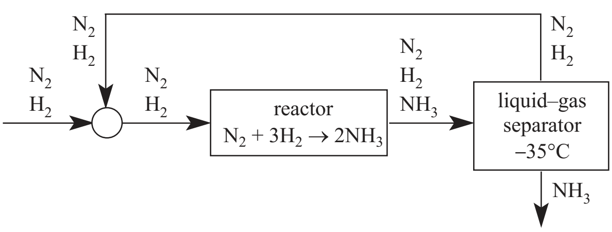
These data show that if we cool the gaseous mixture below −33°C, NH_3 will condense. We can thus separate liquid NH_3 from gaseous H_2 and N_2. We add to our flowsheet a unit to condense NH_3 and then separate NH_3 liquid from the $N_2 + H_2$ gas mixture. We will call this unit a "*liquid–gas separator*." It is conventional to show liquids leaving the bottom of a unit and gases leaving the top.



We have assumed the separation of NH_3 from N_2 and H_2 is perfect, which is idealistic. In Chapter 4 we will consider realistic separators and methods to design for specific product purity. We have also ignored the removal of heat from the liquid–gas separator.

What shall we do with the N_2 and H_2 exiting the liquid–gas separator? Both are environmentally benign and could be discharged to the air. But this is wasteful. *Recycling* the reactants to the reactor is more efficient, as shown below.



This flowsheet contains a new feature, a *combiner*, which is represented by a circle with two or more streams entering and one stream leaving. A combiner merely combines streams; no mixing is implied. But in this case no mixing is needed because the two streams combined have the same composition.

A process based on this rudimentary design will produce ammonia. One would purchase N_2 and H_2 and sell NH_3. But gases such as N_2 and H_2 are expensive. Furthermore, gases are bulky and must be compressed for efficient transport. H_2 has the added problem of explosion risk. Let's augment the process for producing the reactants N_2 and H_2. If our potential supplier can produce N_2 and H_2, perhaps we can, too. Consider first a source for N_2. Air is an obvious choice. Air is about 79% nitrogen and 21% oxygen and air costs nothing. A subtle benefit is that air contains nitrogen in the chemical form we desire. Thus we need only a separator and not a reactor. (As a rule, reactors are more expensive to build and operate.) It seems reasonable to consider separating nitrogen from air. (Nitrogen gas is another high-production chemical commodity. The US production is typically 90 *billion* pounds per year.) Again we first consider separation based on phase: liquid vs. gas. We add the boiling point of oxygen to our table.

Table 2.2 More boiling points for the ammonia process.

Compound	Boiling point at 1 atm (°C)
NH_3	−33
H_2	−253
N_2	−196
O_2	−183