INTRODUCTION TO CHEMICAL ENGINEERING

For Chemical Engineers and Students

UCHE NNAJI

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WILEY

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Preface

This book offers a comprehensive overview of the evolution, essence, concept, principles, functions and applications of chemical engineering. It systematically describes the link between the foundational science of chemistry, biology and processes, to the engineering that delivers the required hardware functionality and products.

It further explains the distinct chemical engineering knowledge, which, although it originally stems from the synthesis of mechanical engineering and industrial chemistry, has given rise to a general-purpose technology and the broadest engineering field. The discipline is wide-ranging in scope and flexibility; it focuses at the molecular level—in terms of chemical, biological, and physical transformations that occur at this level, while at the same time focusing at the process and systems level—in terms of the process design and systems engineering that deliver the required product. Hence, the text in clear terms traces these broad facets of the field, the various industry segments served and the discipline's contribution to global industrialization and well-being of humankind. Today, chemical engineering has evolved to such a unique knowledge area, which establishes the fact that the combination of a mechanical engineer and a chemist is not an alternative to a chemical engineer in an industrial setting.

The various features of a typical chemical engineering plant are described in this text. Moreover, it explains the education and training of chemical engineers and how the subjects studied in the class are integrated into the real-world of work. It likewise discusses career diversities in modern chemical engineering; and attempt is made to rate the level of chemical engineering knowledge being applied in the respective career options.

It further details the real activity model of the core chemical engineering knowledge base—process plant and equipment design, with a practical equipment design case study. Also, it shares the origin of chemical engineering information technology (the computer tools) and their applications. The book presents options in chemical engineering graduate programs, the requirements and how the options can provide graduates with advanced chemical engineering, process technology, production and managerial skills for exciting and challenging careers.

The current focus of the discipline is sustainable systems development through the integration of process safety, process systems engineering, process intensification, product design, life cycle analysis, cutting edge innovations in catalysis, materials, nanotechnology, molecular biology and advanced process economy. Thus, this book presents the global sustainability model and the unique role the frontiers of chemical engineering play toward ensuring sustainable solutions.

This book is expected to enhance students' understanding and performance in the field and the development of the profession worldwide. Students, fresh chemical engineering graduates, new hires and professionals will find this text very useful. The information the trainee engineer needs to excel and cross the critical but complex stage of transitioning from the university to the real-world engineering practice are explained.

Several figures and tables help maximize reader insights into the concept of the discipline.

Foreword

The products in the world we use every day require the skill of a chemical/process engineer, who is trained to ensure the safe and profitable production of the chemicals and materials required to create the products such as food, medicine, fuels, plastics, clean water, clothing and entertainment system. Chemical/process engineers are very much at the forefront of improving the quality of lives of people in a safe environmental manner. Chemical engineering is a fascinating and challenging profession with a wide range of career opportunities. Chemical engineers combine a detailed knowledge of chemistry with understanding principles in order to design, construct and operate chemical process plants in an efficient, safe, sustainable and profitable manner.

U. Nnaji provides a comprehensive overview of chemical engineering linking the topics described in a concise and elucidated manner for students, graduates entering the employment market and professionals as a refresher in the subject. He further introduces the pertinent topics of process safety and sustainability with an in-depth knowledge of these subjects, and the application of process simulation in achieving reliable and monitoring operation of the process plants. This book would be most useful to students in this field, graduates and professionals as a refresher in the topics highlighted.

I highly recommend this book to these groups of individuals worldwide.

Kayode Coker

Acknowledgements

Let me start by thanking Dr. A. Kayode Coker, one of the world's foremost chemical engineering author, for reading the manuscript and suggesting additional areas to cover in the book. Thank you so much.

This work is a result of two decades industrial experience and over a decade of thoughtful investigation on the subject during weekends and after work periods. Consequently, I encountered several individuals who either supported, encouraged and or proffered useful advice and suggestions. A few notable ones are Lee Webster, Contract Specialist, Onesubsea, Schlumberger; Stephen Lockett, SSA Geomarket PSD, Cameron, Schlumberger; Donald Ibegbu, NCD Manager, Schlumberger; Richard J. Emptage, Technical Director, Integrated Solutions, Early Engineering Engagement; and Rasheed Adebayo, Asset Manager, all Onesubsea, Schlumberger. Many thanks to Omongbai Ashion, Schlumberger Segment Sales Representative who was instrumental in keeping me on my toes during the final proofs of the work.

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I am grateful to Phillip Carmical for his useful feedback and role in directing the publication of this book.

To my beautiful wife and kids – thanks for being there for me.

The book contains images of processes and equipment from many sources for which I am grateful.

Finally, and above all, I want to thank my maker for the inspiration to write this book.

1
Introduction

1.1 Definition of Chemical Engineering

Chemical engineering is a branch of engineering concerned with the conceptual, front-end and detailed design, construction, and operation of technologies and plants that perform chemical reactions to solve practical problems or make useful products or provide chemical and environmental solutions for many societal needs. It deals mainly with industrial or commercial processing to produce value-added products from raw materials. The processing of organic (crude oils, natural gas, lumber), inorganic (air, ores, salts) and biological (starches, fats, cellulose) materials into a wide range of useful commodity products, such as plastics, fuels, pharmaceuticals, chemical additives, fibers, fertilizers and foods, is carried out in a controlled process within a framework of environmental sustainability and concern for worker and public safety. Emphasis is on the concept, design, construction and economic operation of equipment that effect the chemical changes and on related research and development.

Figure 1.1.1 Crude Oil Refinery (Image sourced at http://www.filtsep.com/view/16678/energy-materials-processing-filtration-and-the-fuels-of-the-future/, 2014).

Uche Nnaji (ed.) Introduction to Chemical Engineering: For Chemical Engineers and Students, (1–36)

Chemical engineering differs from other types of engineering in the application of knowledge of chemistry and biochemistry, in addition to other chemical engineering principles. The discipline generally involves researching, planning, development, evaluation and operation of chemical, biochemical or physical plants and processes; pollution control systems, changes in composition, heat content; analysis of chemical reactions that take place in mixtures; determination of methodologies for the systematic design, control and analysis of processes, evaluating economics, safety and state of aggregation of materials. It also involves analysis of forces that act on matter that leads to the formation of new or conventional chemical materials and products.

Slin'ko (2003) [1] elaborates that chemical engineering, as a rule, deals with nonequilibrium chemical engineering systems. Consequently, the analysis and description of such systems present substantial difficulties, which become fundamental as the number of structural elements is increased and the system regresses from equilibrium. The technical aspects of chemical

Table 1.1.1 Systems of Interest to Chemical Engineering.

Products	Products of interest to chemical engineering include various types of commodity or specialty polymers; pharmaceuticals; a broad array of inorganic, ceramic, or composite materials; chemicals and materials for personal care products (e.g., cellular phones, optic fiber communication networks), medical products, or automobiles; diagnostic devices; drug delivery systems; and others.
Processes for making products	Processes of interest to chemical engineering include a large variety of industrial manufacturing systems used for the production of chemicals and materials (e.g., chemical plants, petrochemical plants, multipurpose pharmaceutical plants, microelectronics fabrication facilities, food processing plants, biomass to fuel conversion plants); ecological subsystems such as the atmosphere; the human body in its entirety and its parts; and energy devices such as batteries and fuel cells.
Applications of interest	Applications of interest to chemical engineering include monitoring and control of air pollution; extraction of fossil energy; life-cycle analysis, design, and production of "green" or sustainable products; diagnostic devices; drug targeting and delivery systems; combustion systems; solar energy; and many others.

engineering, hence, revolve around managing the behavior of materials and chemical reactions in a closely controlled system—this means predicting and manipulating chemical or biochemical process parameters such as compositions, temperatures, flow rates, and pressures of solids, liquids and gases.

Therefore, another way to explain chemical engineering is to state that it is a discipline that deals with the engineering aspects of chemical and biological systems of interest. The special focus within the discipline on process engineering cultivates a systems perspective that makes chemical engineers extremely versatile and capable of handling a wide spectrum of technical problems. Systems of interest most often include products, processes for making them, and applications for using them. Beyond designing, manufacturing, and using products, chemical engineering also includes finding new ways to measure, effectively analyze, and possibly redesign complex systems involving chemical and biological processes.

1.1.2 Chemical Engineers

A comprehensive description of the chemical engineer may be to say that he or she is the engineer that designs both products and processes, plans and constructs process hardware, manages operations of processes and researches the solutions to environmental problems. Hence, chemical engineers can be directly involved in research and development and responsible for the design, construction and operation of hardware and processes in varied areas such as energy, biomedicine, electronics, food engineering/technology, materials, biotechnology, the environment and so on. Details of these areas of expertise are treated in Chapter 3.

Figure 1.1.2 Chemical Engineers maintain and run plants.

Following completion of process and equipment design, chemical engineers, in addition, remain on hand at a production facility to solve problems that occur as the processes continue. When changes occur that upset a running system, chemical engineers analyze samples from the system, looking at parameters such as flow rates, temperatures and pressures to determine where the problem exists. They also work on expanding projects, evaluating new or alternative equipment, and improving existing equipment and processes. Meeting safety, health, and environmental regulations is also a large part of a chemical engineer's work life.

By way of example, the work of the process/chemical engineer can involve any of the following:

- Designing a process to produce or refine a given chemical or biochemical product through all the stages from feedstock to output of the finished product.
- Designing or sizing the various pieces of equipment or process units which make up this process.
- Once a production process is operational, process/chemical engineers can be responsible for managing the production process, improving the efficiency and safety of the process; ensuring products meet the designed specifications, quality standards are maintained, products are produced in a way there can be no harm to the environment; ensuring that the product is produced in a cost-effective manner; seeking ways of optimizing the production process by minimizing cost, recycling energy, reducing man-hours and recovering and utilizing by-products.

Generally, success of a large-scale chemical production and the quality of the products are a function of the elaborate but economical design of the process and equipment and precise control of the production processes by chemical engineers.

Services provided by chemical engineers in a chemical process industry [4] are summarized in Table 1.1.2.

In conclusion, chemical engineers concern themselves with the design of chemical processes and the processing facility where raw materials are turned into valuable products. The necessary skills for chemical engineers encompass all aspects of design, research, management, construction, testing, problem solving (troubleshooting), scale-up, operation, control, and optimization, and require a detailed understanding of the various unit operations and unit processes. The chemical engineer adopts an integrated

Figure 1.1.3 Chemical engineers design, construct and operate plants (Image sourced at: http://en.wikipedia.org/wiki/Chemical_engineering, 2014).

Table 1.1.2 Services Provided by Chemical Engineers for Process Industries.

• Feasibility Studies • Process Synthesis Designs • FEED Studies • Process Technical and Economic Evaluation • Relief/Flare/Vent Studies • Basic Engineering Design Packages • Pilot Plant Design, Evaluation and Scale-up • Greenfield Plant Designs • Plant Commissioning • Plant Retrofits • Process Modeling and Simulation • Process Equipment Specifications • Process and Equipment Troubleshooting • Cost Estimates • Chemical Engineering/Technical Management • Process Planning and Scheduling • Research and Development • Process and Product Development • Plant Investment Due Diligence Evaluation • Process Design	• Process Evaluations • Throughput Debottlenecking • Process Optimization Studies • Energy Conservation Projects • Independent Design Verification • Process Reliability Studies • Existing Equipment Utilization Studies • Technical Bid Reviews • Emissions Limits Process Compliance • Product Specification Improvement Evaluation • Plant Operation Support • Plant Construction Support • Process Safety Management • Turnaround Support • Risk Management Program Development • Process Hazard Analysis Facilitation • Hazards and Operability Studies (HAZOPs) • Operations Training

approach to problem solving, applying his or her specialized knowledge in chemistry, mathematics, physics, kinetics, transport phenomena, reactor and other equipment design, separation techniques and thermodynamics to the study of dynamic systems and processes.

1.2 It is the Broadest Branch of Engineering

Chemical engineers are sometimes called "universal engineers" because their scientific and technical mastery are wide. Chemical engineering is broader in scope than the other branches of engineering because it draws on the two main engineering basics: mathematics and physics, as well as chemistry and other life sciences, whereas the other branches are based on only the first two. The discipline is essential in fields where processes involve the chemical or physical transformation of matter. It began as a discipline tied to a single industry, the petrochemical industry, but today it is the discipline that interacts with a broad range of industries and technologies. The scope and versatility of a chemical engineering program of study will continue to open many new opportunities for chemical engineers in the future. Chemical engineers have been trained to think at molecular level—in terms of chemical, biological, and physical transformations, as well as at the process and system level. Thus, innovations have moved from macroscopic toward microscopic, and to the nano and molecular scales. The focus of chemical engineering on molecular transformations, quantitative analysis, processes and multiscale treatment of problems makes the discipline exceptional and provides an ideal basis for productive interactions with a wide range of other science and engineering disciplines at boundaries that are among the most exhilarating technology areas of our time. The field synthesizes knowledge from several disciplines (multidisciplinary) and interacts with researchers from multiple disciplines (interdisciplinary) as illustrated in Figure 1.4.3. The engineering discipline has demonstrated a unique ability to synthesis diverse forms of knowledge from applied sciences and other engineering disciplines into cohesive and effective solutions for many societal needs. This integrative capacity is at the nucleus of the discipline's reason for existence and is its most unique characteristics.

A study group in the US reports that chemical sciences and engineering together have resulted in the most enabling science/technology combination to underpin technology development in every industrial sector.

No other technology is as prevalent and influential as chemical technology in all industries. The field is a lifelong learning experience because it is constantly evolving. While the principles learned in college and university will always be a vital part of a chemical engineer's repertoire (range of work), chemical engineering can change with new discoveries. Given the spread of the discipline, chemical engineers later in their careers might find themselves working in an industry that did not exist when they graduated.

1.3 Chemical Engineering – a General Purpose Technology

Indeed, a discipline that provides the concepts and the methodologies to generate new or improved technologies over a wide range of downstream economic activity may be thought of as an even purer or higher-order, of General-Purpose-Technology (GPT) [5]. This should not be contentious. A steam engine or a dynamo is not a technology; they are examples of tangible capital equipment. "Steam" or "electricity", which means bodies of knowledge about how to produce steam or electricity, respectively, and to use them as sources of power or light, in steam engines or dynamos, are technologies. Similarly, chemical engineering is a body of knowledge about the design of certain technologies. More specifically chemical engineering is a body of knowledge about the design of process plants to produce chemical or other products whose production involves chemical transformations. Chemical engineering has been considered a GPT since it provides essential guidance to the design of a very wide range of plants. Furthermore, there has been both a vertical and horizontal dimension to the outcomes that were generated. The emergence of chemical engineering meant that downstream sectors experienced lower invention costs. But, in addition, there was a powerful horizontal outcome, in the sense that the vast market for petroleum has shaped the development of petrochemicals through the intermediation of chemical engineering.

1.4 Relationship Between Chemical Engineering and the Science of Chemistry

Chemistry is the branch of natural science dealing with the composition of substances and their properties and reactions while engineering is the application of science to commerce or industry. Hence, chemical engineering is the use of knowledge about properties and reactions (chemical knowledge), in addition to other scientific knowledge, to solve practical, real-world problems. To understand the relationship between chemical engineering and the science of chemistry, it is necessary to deal with a widely held view that chemical engineering, like other engineering disciplines, is simply applied science—in this case applied chemistry. Hence, the design and construction of plants dedicated to large-scale chemical processing activities entail an entirely different set of activities and capabilities than those that generate the new chemical entities. This activity begins with laboratory experiment and is followed by implementation of the technology to full-scale production. Such activities as mixing, heating, and contaminant control, which can be carried out with great precision in the laboratory, are immensely more difficult to handle in large-scale operations. By applying critical variables discovered during laboratory experiments, chemical engineers typically anticipate and proffer solutions to scale up problems. Chemical engineers are trained to work quantitatively, using data to support plant design; for example, the number of theoretical plates can affect batch distillations.

Chemical engineers do not have as much laboratory flexibility but can be equally creative through hypothesis, prediction and use of scenarios. [6] Ordinary mixing which is carried out in laboratories using laboratory vessels and equipment becomes a complex science when performed during scale up in stirred tanks. This operation is affected by many equipment- and process-related parameters such as type of mixer, agitator speeds (1000rpm) and/or specific mixing duty the process requires.

Chemical engineers design processes to ensure the most economical operation. Therefore, economic considerations must obviously play a critical role in the design process. This means that the entire production chain must be planned and controlled for costs. Cost or economic considerations become decisive in an industrial context, and cost considerations are intimately connected to decisions concerning optimal scale plant. Practitioners in this field of engineering have been much more deeply involved in dealing with cost considerations than other engineering professions. This is an interesting feature of chemical engineering. Thus, when a new chemical entity is discovered, an entirely new question, one that is distant from the scientific context of the laboratory, surfaces. How does one go about producing it? A chemical process plant is far from a scaled-up version of the original laboratory equipment.

A simple, multiple enlargement of the dimensions of small-scale experimental equipment would be likely to yield disastrous results.

Experimental equipment may have been made of glass or porcelain. A manufacturing plant will definitely have to be constructed of very different materials. Producing a given useful product by the ton is very different from producing by the ounce. This really is what accounts for the unique importance of a pilot plant, which may be thought of as a device for translating the findings of laboratory research into technically viable and economically efficient large-scale production process.

The translation (of laboratory findings), on the contrary, requires competences that are unlikely to exist at the experimental research level – these include a knowledge of mechanical engineering, chemistry and physics and an understanding of the underlying economics of likely alternative engineering approaches.

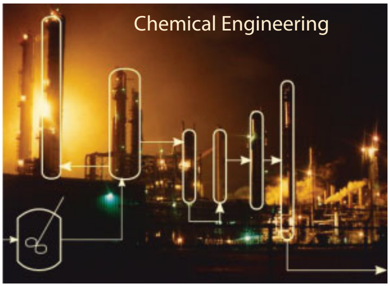

Figure 1.4.1 Chemical Engineering Illustration (Image sourced at University of Pretoria Chemical Engineering Department Website: sitefiles/image/44/2063/chemeng_en.jpg, 2017).

Basically, chemistry aims to realize the required functions by synthesizing new materials, and this results in increasing the number of chemical compounds, but chemical engineering can reduce the number of chemical elements by controlling the shape and nanostructure of materials [8]. Hence, science mainly focuses on the useful product to make, and technology and engineering develops how to make it.

Also, a chemical engineer can both simplify and complicate "showcase" reactions for an economic advantage. Consequently, apart from scaling-up a laboratory finding by technical means, chemical engineers also engineer a system that may improve reaction efficiency. For example, operating at a higher pressure or temperature makes several reactions easier; ammonia, for example, is simply produced from its component elements in a high-pressure reactor. On the other hand, reactions with a low yield can be recycled continuously, which would be complex, strenuous work if done by hand in the laboratory. It is not unusual to build 6-step, or even 12-step evaporators to reuse the vaporization energy for an economic advantage. In contrast, laboratory chemists evaporate samples in a single step.

However, chemistry brings chemical engineers and chemists together. This is because a chemical process is dependent on the intrinsic chemistry, which is independent of scale. Thus, whether a molecule is in a 15ml flask or a $20m^3$ vessel, it will still behave as determined by its surroundings.

1.4.1 Chemical Engineers Take Chemistry Out of the Laboratory and Into the World

The principles of chemistry, mathematics, and physics are applied by chemical engineers to design and operate large-scale chemical manufacturing processes. They translate processes developed in the laboratory and adapt production methods from the small scale in the laboratory into large-scale practical applications for the production of such products as chemicals, pharmaceuticals, plastics, medicines, detergents, and fuels; design plants to maximize yield and minimize costs; evaluate plant operations for performance and product quality.

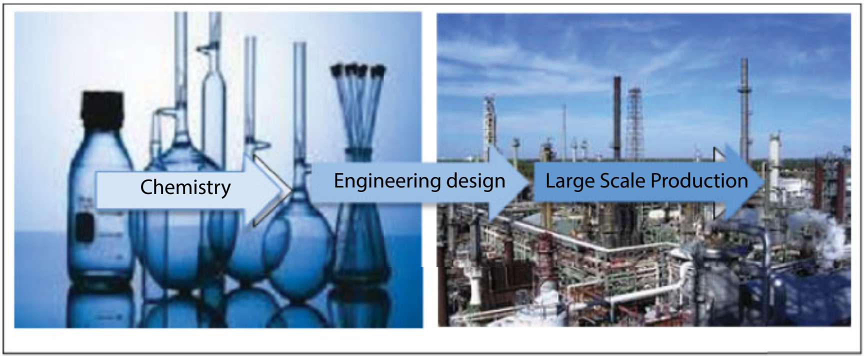

Figure 1.4.2 From Chemistry Laboratory to Large-Scale Production.

In the chemical manufacturing sector, the chemist may be the main agent in the development of new products, but the design of the industrial manufacturing technology for new products, as well as improving the technologies for manufacturing old products, is the chemical engineers' expertise. Hence, they develop technologies that will utilize network of organizations to take processes from chemists' ideas into production.

Imagine designing a chemical plant that produces $2.5*10^5$ metric tonnes per annum of 4-hydroxy-2-butanone by dehydrogenation of 2, 4-hydroxy butanol. This scale up requires development of a technology (the process) which will include various large equipment (hardware) which design also will involve applying engineering principles. Take for example, a chemical engineer who works in an area that produces hexamethylene diamine—a molecule used in the production of nylon. His or her main work may involve applying chemists' findings to large-scale production. Hence, this engineer takes up what a chemist does—synthesize a small amount of a material—and scales it up to the level of producing several hundred tons per day. This process includes determining how to separate the desired product from its impurities or by-products. Other activities of the engineer may focus on chemical kinetics, fluid flow and heat transfer on a large scale—techniques that do not pose problem with smaller reactions in beakers. Consequently, the engineer would ultimately design equipment that will accommodate these concerns.

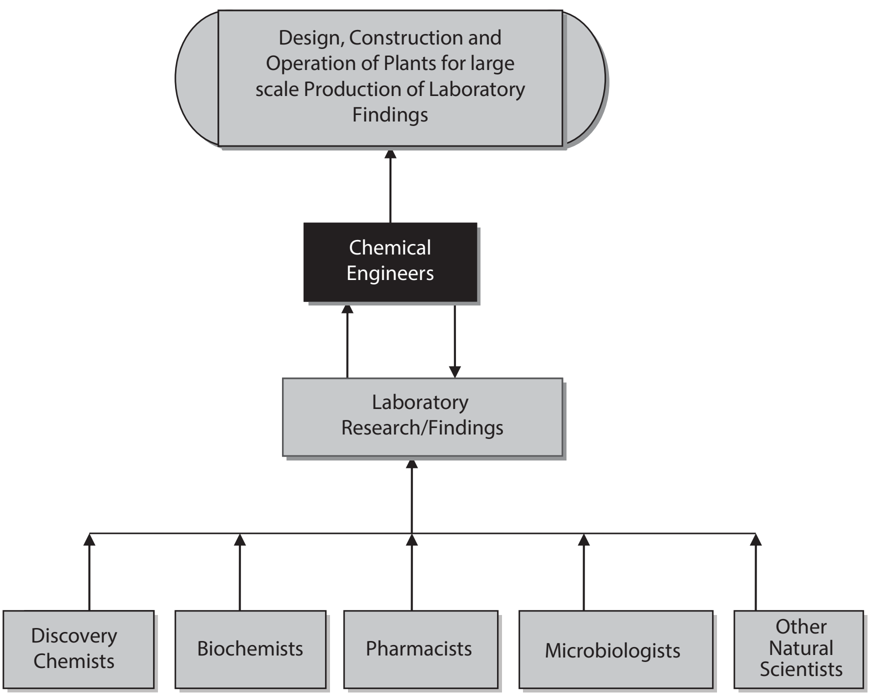

Figure 1.4.3 Relationship between Chemical Engineers and other Scientists.

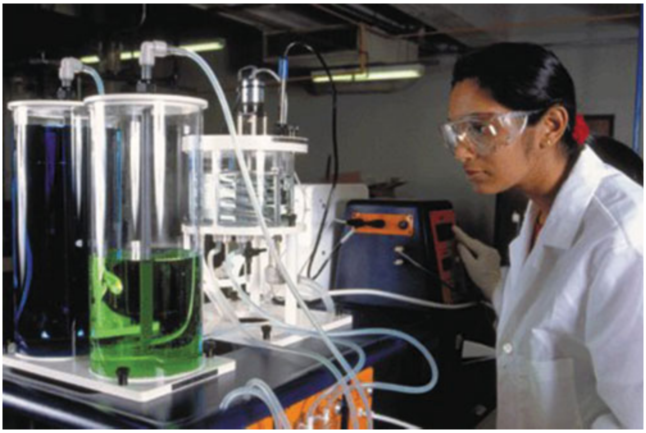

Figure 1.4.4 A Chemist Working in the Laboratory (Image sourced at: http://bobtrade.net/more-details/pages-under-slider/popular-courses/chemical-engineering/, 2012).

Figure 1.4.5 A Chemical Engineer in the Plant.

1.5 Historical Development of Chemical Engineering

The key events and activities of some people that led to the development and emergence of chemical engineering are succinctly discussed in this section. The chemical engineering discipline unarguably can be said to have evolved systematically in the following way:

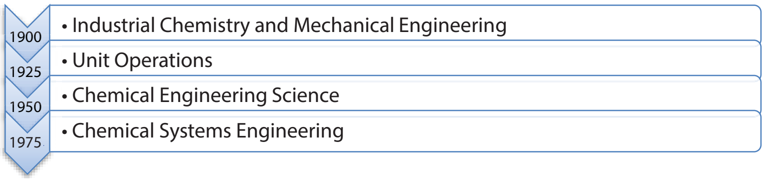

Figure 1.5.1 Evolution of Chemical Engineering.

1.5.1 Industrial Chemistry and Mechanical Engineering

Sulfuric Acid Production

The relationship between chemistry and chemical engineering has been established in section 1.4 of this chapter. Thus, it will not be surprising that development of chemical engineering is being traced to industrial chemistry. Industrial chemistry was being practiced in the 1800s but it was not until the 1880s that engineering rudiments required to control chemical processes were being recognized as a distinct professional activity. Historians agree that chemical engineering was developed in the twentieth century. By this time, organic chemistry was almost a century old, and inorganic chemistry was far older.

Sulfuric acid was first among certain chemicals that became necessary to sustain economic growth in the eighteenth century as the Industrial Revolution soared. In fact, a nation's industrial might could be gauged solely by the vigor of its sulfuric acid industry. Hence the need for optimal production of sulfuric acid arose. The Lead-Chamber Method, which required air, water, sulfur dioxide, a nitrate, and a large lead container, was being used (since 1749) to create sulfuric acid. Nitrate was always the most expensive because they are lost to the atmosphere at the final stage of the process in the form of nitric oxide; hence, necessitating a make-up stream of fresh nitrate. This extra nitrate had to be imported in the form of sodium nitrate from Chile. John Glover helped solve this problem in 1859, by introducing a mass transfer tower to recover the nitrate being lost to the atmosphere. Sulfuric acid at the stage where it still contains nitrates was trickled downward against upward flowing burner gases in the tower. By so doing, the nitric oxide could be reused when the flowing gases which had previously absorbed lost nitric oxide were recycled back into the lead chamber.

Leblanc and Solvay Process

Nicolas Leblanc invented a process for the production of soda ash (sodium carbonate, Na_2CO_3) and potash (potassium carbonate, K_2CO_3), collectively called alkali. The process became known as Le Blanc process. These Alkali compounds were used in a wide range of products including glass, soap, and textiles and were as a result in high demand. The process yields undesirable by-gaseous products. Problems caused to the environment by the by-gaseous products (calcium sulfide), health effects, and elaborate and often complex engineering efforts ushered in the Solvay process (in 1873) which replaced Leblanc's method for producing Alkali. Ernest Solvay invented this process.

George E. Davis

After 1850, "chemical engineering" describing the use of mechanical equipment in chemical industries became common vocabulary in England. George Davis is regarded as the founding father of chemical engineering by many authors. He was a heretofore unremarkable Alkali Inspector from the Midlands region of England. His career in chemistry started in a chemical industry in Manchester. He then worked as a chemist at Brearley and Sons for three years; then as an inspector for the Alkali Act of 1863. In 1872 he was employed as manager at the Lichfield chemical company in Staffordshire. Notable in his work at the time is the tallest chimney in the UK, with a height of more than 200 feet (61m). In 1880 George Davis acted upon ideas of a discipline of chemical engineering and proposed the formation of a "Society of Chemical Engineers". The attempt was unsuccessful, yet he continued to boldly promote chemical engineering. In 1884 Davis became an independent consultant applying and synthesizing the chemical knowledge he had accumulated over the years. As an industrial consultant and inspector, Davis visited a great variety of chemical processing plants. He was keen to identify broad features in common to all chemical factories. Hence, he published in 1887 a series of 12 lectures on chemical engineering, at Manchester Technical School (which became University of Manchester Institute of Science and Technology). He proposed a chemical engineering course which would be organized around individual chemical operations, later to be called "unit operations." Davis explored these operations empirically and presented operating practices in use by the British chemical industry.

Consequently, some felt his lectures simply shared English know-how with the rest of the world. His effort once more fizzled in Britain but his dream was eventually established in America. One would assume here that Davis failed in establishing chemical engineering in British universities because to develop a discipline emphasizing general principles was more suited to universities than commercial firms. Academic and government attitudes therefore may have played a role. Another suggested reason why Davis's proposal was not fully accepted in Britain was because Henry Edward Armstrong, who started a degree course in chemical engineering three years earlier,



George Davis Fritz Haber Carl Bosch

Figure 1.5.2 Men that Steered Chemical Engineering Discipline (Photo Courtesy of BASF at: https://www.thechemicalengineer.com, 2017).

could not make it. Armstrong's course did not succeed because employers would rather employ a chemist and a mechanical engineer than a chemical engineer, at that time. Davis expanded on the 12 lectures, and 14 years later authored a book, *A Handbook of Chemical Engineering*, published in 1901.

Emergence of Chemical Engineering Degree

Lewis Norton, a chemistry professor at the Massachusetts Institute of Technology (MIT) in 1888 initiated the first four-year bachelor program in chemical engineering entitled "Course X" (ten); just a few months after the lectures of George Davis. Norton's course was contemporaneous and simply merged chemistry and engineering subjects (mechanical engineering). University of Pennsylvania and Tulane University and other colleges soon followed MIT's lead by initiating their own four-year programs. However, at this early stage, chemical engineering was tailored to fulfill the needs of the chemical industry. Practitioners of chemical engineering at the time faced difficulty convincing engineers that they were engineers and chemists that they were not chemists. In 1905, unit operations was introduced into the course by William Hultz Walker and by the 1920s this had become an important aspect of the discipline of chemical engineering at MIT, other US universities and Imperial college London. The discipline gradually began to metamorphose into an independent profession when the American Institute of Chemical Engineers (AIChE) was formed in 1908. The AIChE defined chemical engineering to be a separate science which is based on unit operations. During the First World War, the British army faced shortage of munition (stock of shells) in the Great Shell crisis. It was at this time that Kenneth Bingham Quinan designed and led the large-scale manufacture of efficient (high) explosives and propellants. The success of this effort eventually gave rise to formation of the Institution of

Chemical Engineers (IChemE) in Britain in 1922. Quinan later became the first vice president of the institution.

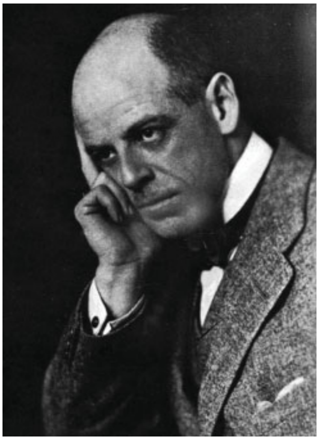

Figure 1.5.3 Kenneth Bingham Quinan (Picture sourced at: https://www.thechemicalengineer.com/features/cewctw-keith-bingham-quinan-and-colleagues-an-explosive-start, 2017).

But by the 1940s, it had become obvious that unit operations alone were not sufficient to develop chemical reactors; hence transport phenomena, process system engineering and other novel concepts started to gain much focus. Thermodynamics, which included properties of gases and liquids, and applications of both first and second laws, were also introduced at the time.

Furthermore, it is worth stating that, surprisingly, chemical engineering did not come to Germany early, yet industrial chemists and mechanical engineers in that country had been having strong collaboration, leading to invention and industrialization of the Haber-Bosch process in early 1908 to 1911 [10]. Fritz Haber, who was a chemist, invented a method for synthesizing ammonia and this requires temperatures up to 500°C and pressures up to 1000 atmospheres [11]. Because such high temperature and pressure were enormously difficult to attain on the industrial scale, his invention might have remained a laboratory curiosity. Hence, Carl Bosch, a mechanical engineer, scaled up the process leading to ammonia production. Both received the Nobel Prize award.

The chemical engineering degree program at the time was developed to fulfill the need of chemical process industries (CPI). An academic curriculum was established to train students that can fit into the industry immediately after graduation, to serve this need. Meanwhile, competition amongst various chemical companies around the world was intense. Some dishonest individuals even did many unethical acts, which included trying to outdo one another by bribing agents to contaminate others' products. Yet this did not provide the much-needed competitive edge. Competition, however, contributed to reshaping the chemical engineering curriculum. By this time companies started thinking of ways of lowering cost through optimizing production process to beat competition. This led to innovative ideas such as continuous production process, by-product recycling, and other critical optimization techniques and automatic controls to continuous processing in many chemical industries. At this stage, an entirely new generation of engineering practitioners that had distinct dexterity was born. CPI's would now have the opportunity of employing chemical engineering graduates over mechanical engineering or chemistry graduates. Up until date, process optimization remains the core drive of every chemical process engineer. Success of these innovative ideas led to some CPI's establishing a dedicated research and development (R&D) department for continuous study of more ways of lowering cost. For these companies that are inclined to innovation, another breed of chemical engineering graduate is required. A kind of chemical engineering science graduates and chemical engineering technology graduates were hence born. Over time academic research has had a strong push toward science, largely due to the emergence of areas like nanotechnology and biotechnology, which consequently has caused some disconnect between academia and industry. The evolution of chemical engineering is summarized in Table 1.5.1.

Table 1.5.1 Chronological History of the Emergence of Chemical Engineering.

1859	Sulfuric Acid Production	John Glover helped solve problem of losing nitrate to the atmosphere, by introducing a mass transfer tower to recover the nitrate.
1873	Le Blanc and Solvay Process	Ernest Solvay invented a process that helped solve the problem caused to the environment by the by-gaseous products from Nicolas Leblanc's process for alkali production.
1880	George Davis	George Davis, regarded as the founding father of chemical engineering, acted upon ideas of a discipline of chemical engineering and proposed the formation of a "Society of Chemical Engineers". The attempt was unsuccessful.

(*Continued*)