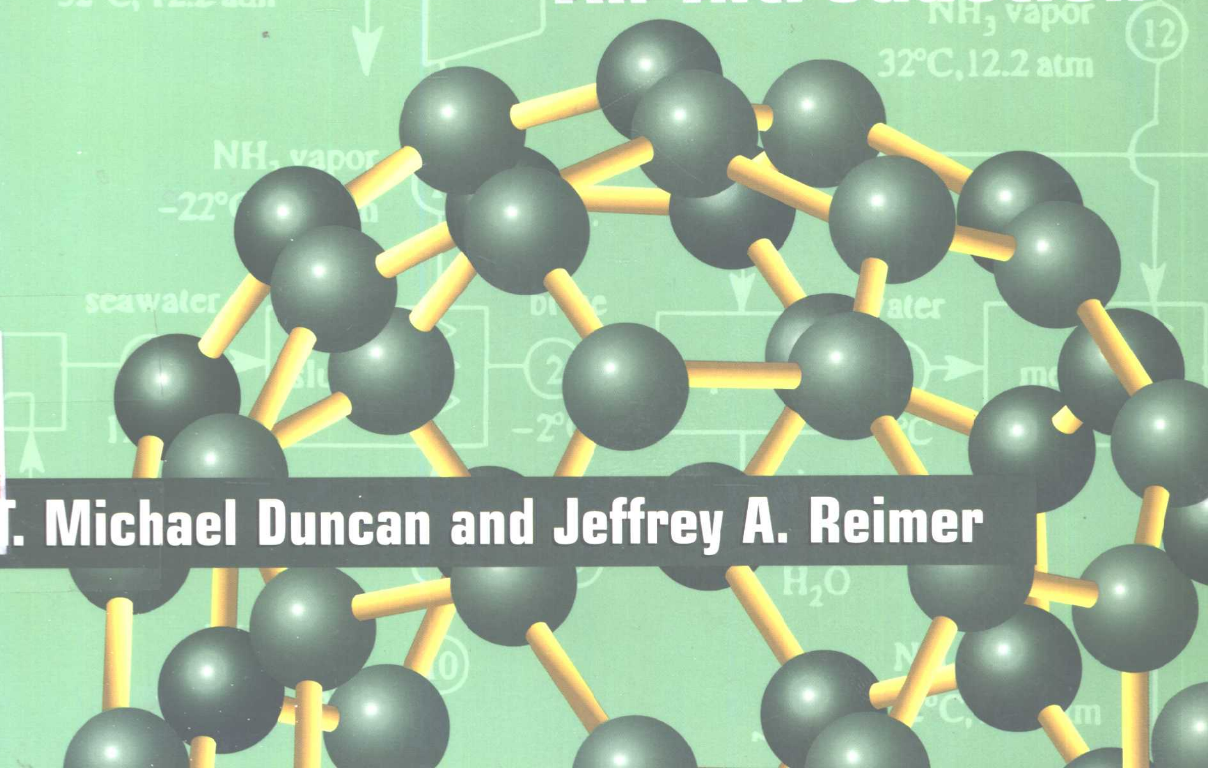
Chemical Engineering Design and Analysis

An Introduction



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Chemical Engineering Design and Analysis

Students taking their first chemical engineering course plunge into the "nuts and bolts" of mass and energy balances and often miss the broad view of what chemical engineers do. This innovative text offers a well-paced introduction to chemical engineering. Through a series of real-world examples and extensive exercises, students learn the basic engineering concepts of design and analysis.

The text has two main objectives:

- To have students practice engineering. Students are introduced to the fundamental steps in design and three methods of analysis: mathematical modeling, graphical methods, and dimensional analysis. In addition, students apply engineering skills, such as how to simplify calculations through assumptions and approximations, how to verify calculations, determine significant figures, use spreadsheets, prepare graphs (standard, semilog, and log–log), and use data maps.
- To introduce the chemical engineering profession. Students learn about chemical engineering by designing and analyzing chemical processes and process units to assess product quality, economics, safety, and environmental impact.

This text will help undergraduate chemical engineering students develop engineering skills early in their studies and encourage an informed decision about whether to pursue this profession. Students in related fields such as chemistry, biology, materials science, and mechanical engineering can use this book to learn the underlying principles of chemical processes and their far-reaching applications.

T. Michael Duncan is an associate professor of chemical engineering at Cornell University and Associate Director of the undergraduate program in the School of Chemical Engineering.

Jeffrey A. Reimer is a professor of chemical engineering at the University of California at Berkeley and faculty scientist at the E. O. Lawrence Berkeley National Laboratory.

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To my son, Maxwell

T. Michael Duncan

To Karen, Jennifer, Jonathan, Charlotte, and Martin

Jeffrey A. Reimer

Preface

Traditional chemical engineering curricula present the first formal course for the major in the sophomore year; it is customarily a course in mass and energy balances. Courses taught earlier in the student calendar are usually either a survey course, in which chemical process industries (or the research interests of the faculty) are summarized, or a course in stoichiometry, emphasizing mass balances in steady-state systems. We concluded that a different freshman course was needed. We wanted a course to strengthen traditional curricula and to encourage students with diverse backgrounds to join the chemical engineering profession.

Professor Duncan had previously assumed responsibility for Engineering 112 at Cornell University, a survey course intended to introduce chemical engineering, but one not required for the major. This course was one of several introductory courses created by Cornell's College of Engineering in the early 1980s. A course to introduce design and analysis was developed and, although well received, suffered from the lack of a suitable textbook. Professor Reimer, who was responsible for the mass and energy balance course at Berkeley, was discouraged by the disparate student motivation and performance in the first required course for the major. Furthermore, the introductory mass and energy balance course was becoming overburdened with multiple (and sometimes conflicting) goals, including application of conservation principles, mathematical modeling, process spreadsheeting, computer methods, problem solving, and reviews of chemical technology. Finally, it was apparent to both of us that some groups were underrepresented in the chemical engineering profession.

In the fall of 1993 we set out to produce a text that dealt with sophisticated issues of engineering design yet assumed only the precollege mathematics, chemistry, and physics typical of a secondary school education. We wanted an inclusive text that described contemporary problems in chemical engineering design and practice, demonstrated various learning and teaching styles, and could be used in all post-secondary school educational formats, including two-year colleges and continuing education programs. This text was intended to allow students to decide early in their undergraduate education whether or not to become a chemical engineer. It was also designed so students could take full advantage of the remainder of their degree program by providing an appropriate context for the ensuing coursework in chemical engineering.

The book is organized so that each concept is introduced within the two most important paradigms of engineering practice: design and analysis. We believe that chemical engineering education should start with the same emphasis with which it ends: design. Therefore we emphasize that students should devise specific plans for chemical and physical processes that are based upon sound economic strategies and thoughtful analysis of key physical and chemical phenomena. We introduce three methods of analysis modeling based upon: (i) fundamental physical laws and constitutive equations, (ii) empirical (and usually graphical) correlations, and (iii) dimensional analysis.

Our text has a number of unusual features vis-à-vis other introductory textbooks. First, we adopt the "just in time" philosophy for introducing chemical engineering concepts, a philosophy that we discovered in Richard Feynman's *Lectures on Physics*. Attempts to comprehensively cover concepts such as energy balances would hopelessly swamp an introductory text with information. Instead we introduce only what students need to know to deal with the problem at hand. Thus we cover the enormous scope of chemical engineering concepts but treat each concept with only cursory depth. Second, we discard the usual assumptions that freshman students cannot comprehend complex phenomena such as combined reaction and diffusion. On the contrary, we believe that many chemical engineering curricula fragment chemical engineering concepts so much that students have difficulty integrating these concepts to solve complex problems after graduation.

Acknowledgments

I am grateful to Bill Olbricht for his ideas when I was developing this syllabus and for his continued encouragement as this textbook was written. Discussions with Thatcher Root refined and expanded my ideas and directed me to seminal resources. Finally, I acknowledge the School of Chemical Engineering at Cornell University for the opportunity to develop this text.

Mike Duncan
Ithaca, New York

I thank Cornell's School of Chemical Engineering, and Bill Olbricht in particular, for the generous support and encouragement given to me in 1993. This support resulted in the start of our manuscript. I also thank my research group during the period 1993–98; their generosity with my time gave me the opportunity to work on this text. I am especially grateful to Jacqueline Mintz of UC Berkeley's GSI Teaching and Resource Center for her kind mentorship on the scholarship of teaching. Finally, I am greatly indebted to Morton M. Denn for his patience and guidance during all my Berkeley years; he is truly one of Berkeley's greatest teachers.

Jeff Reimer
Richmond, California

Several textbooks influenced this work. Two fine textbooks on design – *Process Synthesis* by Dale Rudd, Gary Powers, and Jeffrey Siirola and *Process Modeling* by Morton Denn – inspired us and spawned the material on process design (Chapter 2), mathematical modeling (Chapter 3), and transient processes (Chapter 6).

The topic of mass and energy balances, introduced in Chapter 3 as examples of mathematical modeling, is a mature one in chemical engineering. We are grateful to the authors of two excellent textbooks – Richard Felder and Ronald Rousseau, *Elementary Principles of Chemical Processes*, and William Luyben and Leonard

Wenzel, *Chemical Process Analysis: Mass and Energy Balances* – for permission to adapt and reprint examples and exercises.

We are grateful to the many colleagues, students, and friends that unselfishly gave their time to listen to our ideas, read chapters, work exercises, and make suggestions. We are particularly grateful to Thatcher Root, Alan Foss, Mort Denn, and Claude Cohen.

Contents

1

An Overview of Chemical Engineering

THIS TEXTBOOK has two goals. The first is to describe the chemical engineering profession. We will use contemporary applications of chemical engineering to introduce fundamental concepts. The applications include case studies and chemical processes from the technical literature and the popular press. The second goal is to introduce and develop basic engineering skills. Chief among these skills are design – the ability to conceive and develop plans – and analysis – the methodology to model and evaluate chemical and physical processes.

Some of the concepts introduced in this text are complex and usually require an entire course and its prerequisites to appreciate fully. You must be willing, therefore, to set aside questions about the basis for certain material or the origins of certain equations or relationships. We will, however, attempt to provide at least a heuristic description of the material's origin and point to where in the chemical engineering curriculum the material is discussed in more detail.

Finally, in this text we attempt to appeal to a variety of learning and thinking styles. We appreciate that not all students prefer to think globally, reason deductively, or perceive visually. In each of the exercise sets we have attempted to invoke different styles of learning to make learning chemical engineering as inclusive as possible.

1.1 Chemical Engineering

Chemical engineers create processes based upon physical and chemical change. The processes may yield marketable items, such as gasoline or penicillin, or noncommercial items, such as clean air or clean water. The processes are created by integrating principles from basic sciences – traditionally chemistry, physics, and mathematics – with consideration of economics, environmental impact, and employee safety. Several textbooks in chemical engineering have introductory chapters on the chemical engineering profession. At the end of this chapter we list some of the most frequently used texts. We encourage you to browse through the introductory chapters of these books. Their subsequent chapters will give you a glimpse of topics in the chemical engineering curriculum.

The chemical engineering profession, barely 100 years old, began as an interface between chemistry and mechanical engineering. The principal goal in the early days of chemical engineering was to commercialize chemical reactions developed at a chemist's bench. In 1983 a list of the top ten achievements of chemical engineering was compiled on the occasion of the seventy-fifth anniversary of the American Institute of Chemical Engineers (AIChE), a national organization with approximately 60,000 members. The AIChE used two criteria to form this list: first, the degree to which the achievement was an innovative and creative response to a societal need, and second, the historical impact of the process. These achievements are summarized as follows:

Synthetic rubber. Elastic materials, such as automobile tires and drive belts, are an integral part of everyday life. The annual production of rubber in 1983 was twenty-two billion pounds. Remarkably, this industry was developed in only two years, just in time to replace shortages of natural rubber during World War II.

Antibiotics. In 1918 an influenza epidemic killed twenty million people worldwide, one-half 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 the subsequent availability to people worldwide.

Polymers. Plastics – such as PVC, nylon, polystyrene, and polyethylene – are the predominant materials for consumer products. Plastics have replaced wood, metal, and glass in many applications because of their superior strength/weight ratio, chemical resistance, and mechanical properties.

Synthetic fibers. Methods to produce fine threads of polymers allow us to rely less on exploiting plants and animals for clothing, carpets, and fabrics.

Cryogenic separation of air into O_2 and N_2. The present production is about 10^{12} cubic feet per year. N_2 is a key reagent for fertilizer and is used as a cryogen. O_2 is used in medicine and metals processing.

Separation of nuclear isotopes: $^{235}U/^{238}U$; $^{12}C/^{14}C$; $^{16}O/^{18}O$. Isotopically enriched uranium changed the world for better and for worse in 1945. Nuclear energy continues to be a viable supplement to fossil fuels. Medical research, diagnostics, and treatments require isotopically enriched elements.

Catalytic cracking of crude oil. Crude oil was once distilled into light and heavy fractions (kerosene, gasoline, lubricating oil); the range of oil products was limited by the physical mixture of the raw material. Catalytic cracking systematically decomposes oil molecules into molecular building blocks that may be used to construct complex chemicals. The ability to make high octane fuel was a crucial factor in the Battle of Britain and World War II.

Pollution control. Chemical engineers can work to design processes with minimal offending by-products and devise strategies to restore polluted sites.

Fertilizers, especially ammonia. New fertilizers have improved agricultural productivity and helped to feed the world.

Biomedical engineering. 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.

The contributions of chemical engineers influenced the evolution of modern society. Most of the top ten achievements listed above came during the heyday of engineering – when it seemed that society's needs could be met by technology, with engineers being 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 curricula attempts to sensitize students to these issues by encouraging studies in humanities, social sciences, and ethics.

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. Some frontier areas of chemical engineering include:

Production of novel materials. Chemical engineers will design processes to produce ceramic parts for engines, high-temperature 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 fancy proteins. Whereas chemical processes are typically continuous – reactants constantly enter and products constantly leave – bioprocesses tend to be batch – add reactants, wait, then remove products. Finally, whereas traditional chemical processes, such as petrochemicals, tolerate rough separations (~99.44% pure), bioproducts will require more rigorous isolation.