GLOBAL EDITION

Basic Principles and Calculations in Chemical Engineering

NINTH EDITION

David M. Himmelblau • James B. Riggs

Conversion Factors

Instructions: Locate the given units on the row on the left-hand side of the table. Next, locate the desired units at the top of the column of the table. The conversion factor from the given units to the desired units is listed at the intersection of the row and the column. For example, to convert miles to feet, multiply by 5280.

Length Equivalents

	meter	kilometer	inch	foot	mile
meter	1	10^{-3}	39.37	3.2808	6.214×10^{-4}
kilometer	1000	1	3.937×10^{4}	3280.8	0.6214
inch	0.02540	2.540×10^{-5}	1	0.08333	1.5783×10^{-5}
foot	0.3048	3.048×10^{-4}	12	1	1.894×10^{-4}
mile	1609.3	1.61	6.336×10^{4}	5280	1

Mass Equivalents

	grams	kilograms	metric ton	pounds	ton
grams	1	10^{-3}	10^{-6}	2.2046×10^{-3}	1.102×10^{-6}
kilograms	1000	1	10^{-3}	2.2046	1.102×10^{-3}
metric ton	10^{6}	1000	1	2204.6	1.1023
pounds	453.6	0.4536	4.536×10^{-4}	1	5×10^{-4}
ton	9.072×10^{5}	907.2	0.9072	2000	1

Volume Equivalents

	liters	m^3	in^3	US gallon	ft^3
liters	1	10^{-3}	61.023	0.2642	0.03531
m^3	1000	1	61.023×10^{3}	264.2	35.31
in^3	1.639×10^{-2}	1.639×10^{-5}	1	4.329×10^{-3}	5.787×10^{-4}
US gallon	3.785	3.785×10^{-3}	231	1	0.1337
ft^3	28.32	0.02832	1.728×10^{3}	7.481	1

Force Equivalents

	newtons (N)	pound force (lb_f)
newtons (N)	1	0.2248
pound force (lb_f)	4.448	1

Energy Equivalents

	joule	calorie	kWh	Btu	ft lb_f	hp h
joule	1	0.2390	2.778×10^{-7}	9.478×10^{-4}	0.7376	3.725×10^{-7}
calorie	4.184	1	1.162×10^{-6}	3.97×10^{-3}	3.086	1.558×10^{-6}
kWh	3.6×10^{6}	8.606×10^{5}	1	3412.14	2.655×10^{6}	1.341
Btu	1055	252	2.930×10^{-4}	1	778.16	3.930×10^{-4}
ft lb_f	1.356	0.3241	3.766×10^{-7}	1.285×10^{-3}	1	5.051×10^{-7}
hp h	2.685×10^{6}	6.416×10^{5}	0.7455	2545	1.98×10^{6}	1

Power Equivalents

	J s^{-1}	kW	ft lb_f s^{-1}	Btu s^{-1}	hp
J s^{-1}	1	10^{-3}	0.7376	9.478×10^{-4}	1.341×10^{-3}
kW	1000	1	737.56	0.9478	1.341
ft lb_f s^{-1}	1.356	1.356×10^{-3}	1	1.285×10^{-3}	1.818×10^{-3}
Btu s^{-1}	1055	1.055	778.16	1	1.415
hp	745.7	0.7457	550	0.7068	1

Pressure Equivalents

	mm Hg	in. Hg	kPa	atm	bar	psia
mm Hg	1	0.03937	0.1333	1.316×10^{-3}	1.333×10^{-3}	0.01934
in. Hg	25.4	1	3.386	0.03342	0.03386	0.4912
kPa	7.502	0.2954	1	9.869×10^{-3}	0.01	0.1451
atm	760	29.92	101.3	1	1.013	14.696
bar	750.06	29.53	100	0.9869	1	14.50
psia	51.71	2.036	6.894	0.06805	0.06895	1

BASIC PRINCIPLES AND CALCULATIONS IN CHEMICAL ENGINEERING

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David M. Himmelblau
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Pearson

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Note from the Publisher

This book is published in memory of David M. Himmelblau and James B. Riggs, for their valuable contributions to the field of chemical engineering.

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CONTENTS

PREFACE

This book serves as an introduction to the principles and techniques used in the field of chemical engineering as well as biological, petroleum, and environmental engineering. Although the range of subjects deemed to be in the province of chemical engineering has broadened over the last thirty years, the basic principles of this field of study remain the same. This book presents the foundation of specific skills and information that are required for the successful undergraduate and postgraduate study of chemical engineering as well as the professional practice of chemical engineering. Moreover, your remaining chemical engineering classes will rely heavily on the skills that you will develop in this course: your ability to solve abstract problems as well as the application of material and energy balances. The study of the field of chemical engineering can be viewed as a tree with material and energy balances being the trunk and the subjects of thermodynamics, fluid flow, heat transfer, mass transfer, reactor kinetics, process control, and process design being the branches of the trunk. From this perspective, it is easy to see the importance of mastering the material that follows.

The primary objective of this book is to teach you how to systematically formulate and solve material and energy balance problems. More important, you should learn to systematically formulate and solve all types of problems using the methods presented in this text. In addition, this text introduces you to the breadth of processes that chemical engineers work with, from the types of processes found in the refining and chemical industries to those found in bioengineering, nanoengineering, and the microelectronics industries. While the analysis used in this book is based largely on a macroscopic scale (i.e., representing a complex system as a uniform system), your later engineering courses will teach you how to formulate microscopic material and energy balances that can be used to more completely describe these systems. In fact, you will learn in these classes that to formulate a microscopic balance you only have to apply the balances presented in this textbook to a very small volume inside the process of interest.

This text is organized as follows:

- Part I, Introduction: Background information (Chapters 1–2)
- Part II, Material Balances: How to formulate and solve material balances (Chapters 3–5)
- Part III, Gases, Vapors, and Liquids: How to describe gases and liquids (Chapter 6–7)
- Part IV, Energy Balances: How to formulate and solve energy balances (Chapters 8–9)
- Part V, Unsteady-State Material and Energy Balances: How to use a macroscopic approach to describe the behavior of unsteady-state systems (Chapters 10–11)
- Additional material is available on the companion website: Chapters 12–14 and Appendixes E–M; go to https://media.pearsoncmg.com/intl/ge/abp/resources/products/product.html#student,isbn=9781292440934

Expecting to absorb the information and skills in this text by reading and listening to lectures is a bit naïve. It is well established that one learns by doing, that is, applying what you have been exposed to. In this regard, our text offers a number of resources to assist you in this endeavor. Probably the most important resources for your study of this material are the Self-Assessment Tests in each chapter in the book. In particular, the Self-Assessment questions and problems are particularly valuable because by answering them and comparing your answers to the answers that follow, you can determine what it is that you do not fully understand, which is quite an important piece of information.

This edition was written with MATLAB® and Python™ integrated into the text. MATLAB and Python codes are presented for solving systems of linear equations, determining the number of independent equations in a system of linear equations, solving a single nonlinear equation, applying cubic spline interpolation to a set of nonlinear data, and integrating initial value ordinary differential equations. In each case, the built-in functions used to accomplish these tasks are presented and described in a standalone fashion.

It is our sincere hope that this textbook and materials not only inspire you to continue to pursue your goal to become a chemical engineer but also make your journey toward that goal easier.

Jim Riggs
Austin, Texas
November 2021

HOW TO USE THIS BOOK

Welcome to *Basic Principles and Calculations in Chemical Engineering, Ninth Edition*. Several tools exist in the book in addition to the basic text to aid you in learning its subject matter. We hope you will take full advantage of these resources.

Learning Aids

1. Numerous examples worked out in detail to illustrate the basic principles
2. A systematic problem-solving strategy that can be applied to any problem
3. Figures, sketches, and diagrams to provide a detailed description and reinforcement of what you read
4. At the beginning of each chapter, a list of the specific objectives to be reached
5. Self-Assessment Tests with answers in each chapter so that you can evaluate your progress in learning
6. A large number of problems at the end of each chapter with answers provided in Appendix D
7. Appendixes containing data pertinent to the examples and problems
8. Supplementary references for each chapter
9. A glossary at the end of each chapter

Scan through the book now to locate these features.

Good Learning Practices (Learning How to Learn)

You cannot put the same shoe on every foot.

—Publilius Syrus

Those who study learning characteristics and educational psychologists say that almost all people learn by practicing and reflecting, and not by watching and listening to someone else telling them what they are supposed to learn. "Lecturing is not teaching and listening is not learning." You learn by doing.

Learning Involves More than Memorizing

Do not equate memorizing with learning. Recording, copying, and outlining notes or the text to memorize problem solutions will be of little help in really understanding how to solve material and energy balance problems. Practice will help you to be able to apply your knowledge to problems that you have not seen before.

Adopt Good Learning Practices

You will find that skipping the text and jumping to equations or examples to solve problems may work sometimes but in the long run will lead to frustration. Such a strategy is called "formula-centered" and is a very poor way to approach a problem-solving subject. By adopting it, you will not be able to generalize, each problem will be a new challenge, and you will miss the interconnections among essentially similar problems.

Various appropriate learning styles (information processing) do exist; hence you should reflect on what you do to learn and adopt techniques best suited to you. Some students learn through thinking things out in solitary study. Others prefer to talk things through with peers or tutors. Some focus best on practical examples; others prefer abstract ideas. Sketches and graphs used in explanation usually appeal to most people. Do you get bored by going over the same ground? You might want to take a battery of tests to assess your learning style. Students often find such inventories interesting and helpful.

Whatever your learning style, what follows are some suggestions to enhance learning that we feel are appropriate to pass on to you.

Suggestions to Enhance Learning

1. Each chapter in this book will require three or more hours to read, assimilate, and practice your skills in solving pertinent problems. Make allowance

in your schedule so that you will have read the pertinent material **before** coming to class. Instead of sitting in class and not fully understanding what your professor is discussing, you will be able to raise your understanding to a much higher level. It is not always possible, but it is one of the most efficient ways to spend your study time.

2. If you are enrolled in a class, work with one or more classmates, if permitted, to exchange ideas and discuss the material. But do not rely on someone to do your work for you.
3. Learn every day. Keep up with the scheduled assignments—don't get behind, because one topic builds on a previous one.
4. Seek answers to unanswered questions right away.
5. Employ active reading; that is, every five or ten minutes, stop for one or two minutes and summarize what you have learned. Look for connecting ideas. Write a summary on paper if it helps.

Suggestions for How to Use This Book Effectively

How can you make the best use of this book? Read the objectives before and after studying each section. Read the text, and when you get to an example, first cover up the solution and try to solve the stated problem. Some people, those who learn by reading concrete examples, might look at the examples first and then read the text. After reading a section, solve the Self-Assessment Problems at the end of the section. The answers follow. After completing a chapter, solve a few of the problems listed at the end of the chapter. R. P. Feynman, the Nobel laureate in physics, made the point: "You do not know anything until you have practiced." Whether you solve the problems using hand calculators or computer programs is up to you, but use a systematic approach to formulating the information leading to a proper solution.

This book functions as a savings account—what you put in, you get out, with interest.

Please visit https://media.pearsoncmg.com/intl/ge/abp/resources/products/product.html#student,isbn=9781292440934 for access to updates and/or corrections as they become available.

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Jim Riggs

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David M. Himmelblau was the Paul D. and Betty Robertson Meek and American Petrofina Foundation Centennial Professor Emeritus in Chemical Engineering at the University of Texas, where he taught for 42 years. He received his B.S. from MIT in 1947 and his Ph.D. from the University of Washington in 1957. He was the author of 11 books and over 200 articles on the topics of process analysis, fault detection, and optimization, and served as President of the CACHE Corporation (Computer Aids for Chemical Engineering Education), as well as Director of the AIChE. His book, *Basic Principles and Calculations in Chemical Engineering,* has been recognized by the American Institute of Chemical Engineers as one of the most important books in this field.

James B. Riggs earned his B.S. in 1969 and his M.S. in 1972, both from the University of Texas at Austin. In 1977, he earned his Ph.D. from the University of California at Berkeley. Dr. Riggs was a university professor for 30 years, the first five years being spent at West Virginia University and the remainder at Texas Tech University. In addition, he had more than five years of industrial experience in a variety of capacities. His research interests centered on advanced process control and process optimization. During his academic career he served as an industrial consultant and founded the Texas Tech Process Control and Optimization Consortium, which he directed for 15 years. Dr. Riggs authored several other popular undergraduate chemical engineering textbooks: *Computational Methods for Chemical Engineers, Programming with MATLAB for Engineers,* and *Chemical and Bio-Process Control, Fifth Edition.*

Dr. Vivek Utgikar (reviewer) is a professor of chemical engineering in the Department of Chemical and Biological Engineering at the University of Idaho. He has also served as the director of the Nuclear Engineering program and the associate dean of Research and Graduate Education for the College of Engineering at the University of Idaho. Dr. Utgikar has an extensive teaching portfolio that includes a broad range of fundamental and advanced engineering courses such as transport phenomena, kinetics, thermodynamics, energy storage, electrochemical engineering, hydrogen, and spent nuclear fuel disposition/management. His research interests include advanced energy systems, nuclear fuel cycle, modeling of multiphase systems, and bioremediation. He was a National Research Council associate at the National Risk Management Research Laboratory of the US Environmental Protection Agency in Cincinnati, Ohio, prior to joining the University of Idaho. Dr. Utgikar is a registered professional engineer with process development, design, and engineering experience in the chemical industry and holds a PhD in chemical engineering from the University of Cincinnati. His other degrees include bachelor's and master's degrees in chemical engineering from Mumbai University, India. He is the author of *Fundamental Concepts and Computations in Chemical Engineering* and *Chemical Processes in Renewable Energy Systems*, both from Pearson.

PART I

INTRODUCTION

CHAPTER 1

Introduction to Chemical Engineering

Chapter Objectives

- Have a general knowledge of the evolution of chemical engineering.
- Understand what chemical engineering is and the types of jobs chemical engineers perform.
- Appreciate some of the issues associated with sustainability and green engineering.
- Understand the importance of ethics in the practice of engineering.

Introduction

Chemical engineers deal with processes that convert raw materials into useful products. Many times, these processes involve reactions followed by purification of the products, such as chemical reactions followed by concentration of the products, biological reactions followed by systems that recover and purify the products, or reactions and recovery of products on a nanometer scale. Overall, chemical engineers are process engineers—that is, chemical engineers deal with processes that produce a wide range of products.

1.1 A Brief History of Chemical Engineering

Chemical engineering evolved from the industrial applications of chemistry and separation science (i.e., the study of separating components from mixtures) primarily in the refining and chemical industry, which we refer to here as the **chemical process industries, CPI**. The first high-volume chemical process was implemented in 1823 in England for the production of soda ash, which was used to produce glass and soap.

In 1887, a British engineer, George E. Davis, presented a series of lectures on chemical engineering that summarized industrial practice in the chemical industry in Great Britain. These lectures stimulated interest in the United States and to some degree led to the formation of the first chemical engineering curriculum at MIT in 1888. Over the next 10 to 15 years, a number of US universities embraced the field of chemical engineering by offering curriculum in this area. In 1908, the American Institute of Chemical Engineers was formed and since has served to promote and represent the interests of the chemical engineering community.

Mechanical engineers understood the mechanical aspects of process operations, including fluid flow and heat transfer, but they did not have backgrounds in chemistry. Conversely, chemists understood chemistry and its ramifications but lacked the process skills. In addition, neither mechanical engineers nor chemists had backgrounds in separation science, which is critically important to the CPI. As a result, the study of chemical engineering evolved to meet these industrial needs.

The acceptance of the "horseless carriage," which began commercial production in the 1890s, created a demand for gasoline that ultimately fueled exploration for oil. In 1901, Patillo Higgins, a Texas geologist, and Anthony F. Lucas, a mining engineer, later to be known as "wildcatters," led a drilling operation that brought in the Spindletop Well just south of Beaumont, Texas. At the time, Spindletop produced more oil than all the other oil wells in the United States. Moreover, a whole generation of wildcatters was born, resulting in a dramatic increase in the domestic production of crude oil, which created a need for larger-scale, more modern approaches to crude refining. As a result, a market developed for engineers who could assist in the design and operation of processing plants for the CPI. The success of oil exploration was to some degree driven by the demand for gasoline for the automobile industry, and ultimately, it led to the widespread adoption of automobiles for the general population due to the resulting lower cost of gasoline.

These early industrial chemists/chemical engineers had few analytical tools available to them and largely depended on their physical intuition to perform their jobs as process engineers. Slide rules were used for performing calculations, and by the 1930s and 1940s, a number of nomographs were developed to assist them in the design and operation analysis of processes for the CPI. Nomographs are charts that provide a concise and convenient means to represent physical property data (e.g., boiling point temperatures or heat of vaporization) and can also be used to provide simplified solutions of complex equations (e.g., pressure drop for flow in a pipe). The availability of computing resources in the 1960s was the beginning of computer-based technology that is commonplace today. For example, since the 1970s, **computer-aided design (CAD) packages** have allowed engineers to design complete processes by specifying only a minimum of information; all the tedious and repetitive calculations are done by the computer in an extremely short period of time, allowing the design engineer to focus on the task of developing the best possible process design.

In 1959, Professors Bird, Stewart, and Lightfoot of the Department of Chemical Engineering at the University of Wisconsin published their textbook *Transport Phenomena* that covered fluid flow, heat transfer, and mass transfer. This book was widely adopted throughout the chemical engineering community and provided a much more mathematical and abstract analysis of these topics than had previously been used. The widespread use of this book ushered in a much more analytical approach to chemical engineering than the more empirical approach that preceded it.

During the period 1960–80, the CPI also made the transition from an industry based on innovation in which the profitability of a company depended to a large degree on developing new products and new processing approaches to a more mature commodity industry in which the financial success of a company depended on making their products using established technology more efficiently, resulting in less expensive products.

Globalization of the CPI markets began in the mid-1980s and led to increased competition. At the same time, development in computer hardware made it possible to apply process automation more easily and reliably than ever before. These automation projects provided improved product quality while increasing production rates and overall production efficiency with relatively little capital investment.

Beginning in the mid-1990s, new areas came on the scene that took advantage of the fundamental skills of chemical engineers, including the microelectronic industry, the pharmaceutical industry, the biomedical industry, and nanotechnology. Clearly, the analytical skills and the process training made chemical engineers ideal contributors to the development of the production operations for these industries. In the 1970s, more than 80% of graduating chemical engineers took jobs with the CPI and government. By 2000, that number had dropped to 50% due to increases in the number taking jobs with biotechnology companies, pharmaceutical/health care companies, and electronics and materials companies.

1.2 Types of Jobs Chemical Engineers Perform

Chemical engineers perform a wide range of jobs. Moreover, during your career, you are likely to have a number of different types of jobs. Following are the general types of jobs that chemical engineers perform:

- **Operations:** Operations engineers, or process engineers, are the first line of technical support for a processing plant. These engineers spend a lot of their time in the plant monitoring the operations and solving operational problems. When a serious technical problem occurs in the middle of the night, the operations engineer for that process is called in to resolve the problem. Many young chemical engineers start out as operations engineers for a few years so that they can become familiar with plant operations before they move to other assignments. This job also provides companies a view of how young engineers handle responsibility as well as how effectively they are able to work with others.
- **Technical sales:** Many products today are highly technical in nature and the consumer of these products often requires technical assistance to fully utilize them. Technical sales engineers provide that service as well as acquire new customers. Obviously, sales engineers need to be able to work effectively with their customers and to fully understand the technical issues associated with their company's products in order to maintain customer satisfaction.
- **Design:** Design is developing something new that meets a defined need and is used to develop new products and services, many times using teams of engineers. Design is a challenging endeavor because there is no limit to how many new ways something can be designed. Therefore, design requires creativity and experience. As a result, design teams often are made up of members with a wide range of experience and training. It is the design team's job to determine the best design for a product considering technical feasibility, economic viability, and the definition of the need for the end user.
- **Consulting:** Consulting companies specialize in specific areas of engineering—safety, design, control, and so on. When an operating company needs a consultant's expertise, it simply contracts with the consulting company for the needed services. Because consulting companies provide technical services on an as-needed basis, the company that hires a consultant does not have to employ an expert in a particular field as a full-time employee. Consulting companies often hire engineers who have many years of engineering experience in specific technical areas. Individuals also serve as industrial consultants after years of experience in industry, academia, or government laboratories.