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EIGHTH EDITION

DAVID M. HIMMELBLAU, JAMES B. RIGGS

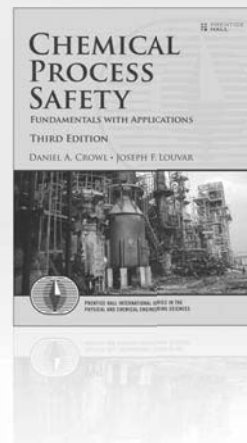
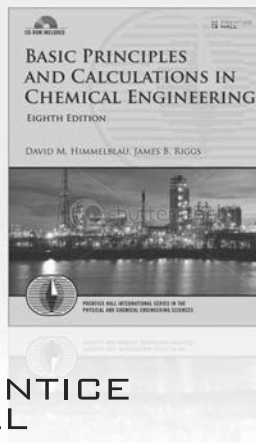
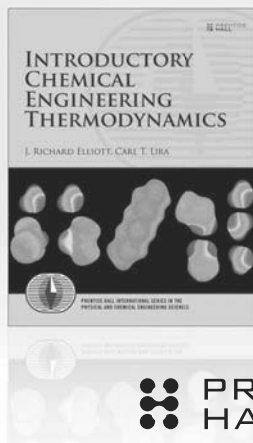
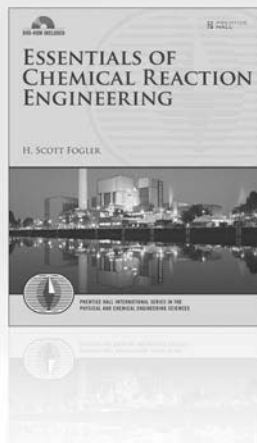


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Basic Principles and Calculations in Chemical Engineering

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BASIC PRINCIPLES AND CALCULATIONS IN CHEMICAL ENGINEERING

EIGHTH EDITION

David M. Himmelblau
James B. Riggs



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*This book is dedicated to the memory of
David M. Himmelblau (1923–2011) and his contribution to
the field of chemical engineering.*







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CONTENTS

PREFACE	xiii	
READ ME	xv	
ACKNOWLEDGMENTS	xix	
ABOUT THE AUTHORS	xx	
<i>PART I</i>	<i>INTRODUCTION</i>	1
CHAPTER 1	WHAT ARE CHEMICAL ENGINEERING AND BIOENGINEERING?	3
1.1	Introduction	3
1.2	A Brief History of Chemical Engineering	4
1.3	Where Do Chemical and Bioengineers Work?	6
1.4	Future Contributions of Chemical and Bioengineering	7
1.5	Conclusion	10
CHAPTER 2	INTRODUCTORY CONCEPTS	11
2.1	Systems of Units	12
2.2	Conversion of Units	17
2.3	Dimensional Consistency	25
2.4	Significant Figures	29
2.5	Validation of Results	36
2.6	The Mole and Molecular Weight	37
		vii

2.7	Choosing a Basis	44
2.8	Density and Specific Gravity	49
2.9	Concentration	55
2.10	Temperature	59
2.11	Pressure and Hydrostatic Head	65
2.12	Flow Rate	78
PART II	MATERIAL BALANCES	99
CHAPTER 3	MATERIAL BALANCES	101
3.1	Introduction to Material Balances	102
3.2	A General Strategy for Solving Material Balance Problems	123
CHAPTER 4	MATERIAL BALANCES WITHOUT REACTION	159
CHAPTER 5	MATERIAL BALANCES INVOLVING REACTIONS	189
5.1	Stoichiometry	190
5.2	Terminology for Reaction Systems	198
5.3	Species Mole Balances	210
5.4	Element Material Balances	226
5.5	Material Balances for Combustion Systems	233
CHAPTER 6	MATERIAL BALANCES FOR MULTI-UNIT SYSTEMS	267
6.1	Primary Concepts	268
6.2	Sequential Multi-Unit Systems	271
6.3	Recycle Systems	290
6.4	Bypass and Purge	306
6.5	The Industrial Application of Material Balances	314

Contents		ix
PART III	<i>GASES, VAPORS, AND LIQUIDS</i>	347
CHAPTER 7	IDEAL AND REAL GASES	349
	7.1 Ideal Gases	350
	7.2 Real Gases: Equations of State	366
	7.3 Real Gases: Compressibility Charts	377
	7.4 Real Gas Mixtures	384
CHAPTER 8	MULTIPHASE EQUILIBRIUM	411
	8.1 Introduction	411
	8.2 Phase Diagrams and the Phase Rule	413
	8.3 Single Component Two-Phase Systems (Vapor Pressure)	425
	8.4 Two-Component Gas/Single-Component Liquid Systems	436
	8.5 Two Component Gas/Two Component Liquid Systems	455
	8.6 Multicomponent Vapor-Liquid Equilibrium	466
PART IV	<i>ENERGY</i>	487
CHAPTER 9	ENERGY BALANCES	489
	9.1 Terminology Associated with Energy Balances	491
	9.2 Types of Energy to Be Included in Energy Balances	496
	9.3 Energy Balances without Reaction	530
CHAPTER 10	ENERGY BALANCES: HOW TO ACCOUNT FOR CHEMICAL REACTION	597
	10.1 The Standard Heat (Enthalpy) of Formation	598
	10.2 The Heat (Enthalpy) of Reaction	603
	10.3 Integration of Heat of Formation and Sensible Heat	614
	10.4 The Heat (Enthalpy) of Combustion	635

CHAPTER 11	HUMIDITY (PSYCHROMETRIC) CHARTS AND THEIR USE	653
	11.1 Terminology	654
	11.2 The Humidity (Psychrometric) Chart	657
	11.3 Applications of the Humidity Chart	666
PART V	SUPPLEMENTARY MATERIAL	681
 CHAPTER 12	ANALYSIS OF THE DEGREES OF FREEDOM IN STEADY-STATE PROCESSES	683
 CHAPTER 13	HEATS OF SOLUTION AND MIXING	708
 CHAPTER 14	THE MECHANICAL ENERGY BALANCE	728
 CHAPTER 15	LIQUIDS AND GASES IN EQUILIBRIUM WITH SOLIDS	756
 CHAPTER 16	SOLVING MATERIAL AND ENERGY BALANCES USING PROCESS SIMULATORS (FLOWSHEETING CODES)	768
 CHAPTER 17	UNSTEADY-STATE MATERIAL AND ENERGY BALANCES	800
APPENDIXES		827
	A ANSWERS TO SUPPLEMENTAL QUESTIONS AND PROBLEMS	829
	B ATOMIC WEIGHTS AND NUMBERS	844
	C TABLE OF THE PITZER Z^0 AND Z^1 FACTORS	845
	D HEATS OF FORMATION AND COMBUSTION	850
	E ANSWERS TO SELECTED PROBLEMS	854

 F	PHYSICAL PROPERTIES OF VARIOUS ORGANIC AND INORGANIC SUBSTANCES	861
 G	HEAT CAPACITY EQUATIONS	873
 H	VAPOR PRESSURES	877
 I	HEATS OF SOLUTION AND DILUTION	878
 J	ENTHALPY-CONCENTRATION DATA	879
 K	THERMODYNAMIC CHARTS	886
 L	PHYSICAL PROPERTIES OF PETROLEUM FRACTIONS	893
 M	SOLUTION OF SETS OF EQUATIONS	902
 N	FITTING FUNCTIONS TO DATA	924
	INDEX	929

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PREFACE

This book is intended to serve 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 twenty 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. One can view the study of the field of chemical engineering 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 off 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 serves to introduce 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 will be 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 3–6)
- Part III Gases, Vapors, and Liquids: how to describe gases and liquids (Chapter 7–8)
- Part IV Energy: how to formulate and solve energy balances (Chapters 9–11)

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 at the end of each section 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 posted in Appendix A, you can determine what it is that you do not fully understand, which is quite an important piece of information. A number of valuable resources are provided to you on the CD that accompanies this book, which includes the physical property software, which provides timesaving access to physical properties for over 700 compounds and elements; Polymath for solving sets of equations, which comes with a 15-day free trial; and the Supplemental Problems Workbook with over 100 solved problems and process equipment descriptions. For more specific information on the resources available with this textbook and the accompanying CD, refer to the “Read Me” section that follows.

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*

READ ME

Welcome to *Basic Principles and Calculations in Chemical Engineering*. 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 consistent strategy for problem solving that can be applied to any problem
3. Figures, sketches, and diagrams to provide a detailed description and reinforcement of what you read
4. A list of the specific objectives to be reached at the beginning of each chapter
5. Self-Assessment Tests at the end of each section, with answers so that you can evaluate your progress in learning
6. A large number of problems at the end of each chapter with answers for about a third of them provided in Appendix E
7. Thought and discussion problems that involve more reflection and consideration than the problem sets cited in item 6
8. Appendixes containing data pertinent to the examples and problems
9. Supplementary references for each chapter
10. A glossary following each section

11. A CD that includes some valuable accessories:
 - a. Polymath—an equation-solving program that requires minimal experience to use. Polymath is provided with a 15-day free trial. Details on the use of Polymath are provided. A special web site gives significant discounts on educational versions of Polymath for various time periods: 4 months, 12 months, and unlimited use: www.polymath-software.com/himmelblau
 - b. Software that contains a physical properties database of over 700 compounds.
 - c. A Supplementary Problems Workbook with over 100 completely solved problems and another 100 problems with answers.
 - d. The workbook contains indexed descriptions of process equipment and animations that illustrate the functions of the equipment. You can instantly access these pages if you want to look something up by clicking on the page number.
 - e. Problem-solving suggestions including checklists to diagnose and overcome problem-solving difficulties that you experience.
 - f. Additional chapters and appendixes
12. A set of steam tables (properties of water) in both SI and American Engineering units in the pocket in the back of the book

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 the interconnections among essentially similar problems will be missed.

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. Look in the CD that accompanies this book to read about learning styles.

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 are in Appendix A. 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. Use the supplement on the CD in the back of the book (print it out if you need to) as a source of examples of additional solved problems with which to practice solving problems.

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

ACKNOWLEDGMENTS

We are indebted to many former teachers, colleagues, and students who directly or indirectly helped in preparing this book, and in particular the present edition of it. We want to thank Professor C. L. Yaws for his kindness in making available the physical properties software database that is the basis of the physical properties package in the CD that accompanies our book, and also thanks to Professors M. B. Cutlip and M. Shacham who graciously made the Polymath software available. Far too many instructors using the text have contributed their corrections and suggestions to list them by name. Any further comments and suggestions for improvement of this textbook would be appreciated.

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ABOUT THE AUTHORS

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 a 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 chemical engineering.

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. He was appointed Professor Emeritus of Chemical Engineering at Texas Tech University after he retired in 2008. In addition, he has a total of over five years of industrial experience in a variety of capacities. His research interests centered on advanced process control and online 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 is the author of two other popular undergraduate chemical engineering textbooks: *An Introduction to Numerical Methods for Chemical Engineers*, Second Edition, and *Chemical and Bio-Process Control*, Third Edition. He currently resides near Austin in the Texas Hill Country.

CHAPTER 1

What Are Chemical Engineering and Bioengineering?

1.1 Introduction	3
1.2 A Brief History of Chemical Engineering	4
1.3 Where Do Chemical and Bioengineers Work?	6
1.4 Future Contributions of Chemical and Bioengineering	7
1.5 Conclusion	10

Your objectives in studying this chapter are to be able to

1. Appreciate the history of chemical engineering and bioengineering
2. Understand the types of industries that hire chemical and bioengineers
3. Appreciate the diversity of the types of jobs in which chemical and bioengineers engage
4. Understand some of the ways in which chemical and bioengineers can contribute in the future to the resolution of certain of society's problems

Looking Ahead

In this chapter we will present some features of the professions of chemical and bioengineering. First, we will present an overview of the history of these fields. Next, we will consider where graduates of these programs go to work. Finally, we will present types of projects in which chemical and bioengineers might participate now and in the future.

1.1 Introduction

Why did you choose to work toward becoming a chemical or bioengineer? Was it the starting salary? Did you have a role model who was a chemical or bioengineer, or did you live in a community in which engineers were prominent? Or were you advised that you would do well as a chemical or bioengineer because

you were adept at math and chemistry and/or biology? In fact, most prospective engineers choose this field without fully understanding the profession (i.e., what chemical and bioengineers actually do and what they are capable of doing). This brief chapter will attempt to shed some light on this issue.

Chemical and bioengineers today hold a unique position at the interface between molecular sciences and macroscopic (large-scale) engineering. They participate in a broad range of technologies in science and engineering projects, involving nanomaterials, semiconductors, and biotechnology. Note that we say “participate” because engineers most often work in multidisciplinary groups, each member contributing his or her own expertise.

1.2 A Brief History of Chemical Engineering

The chemical engineering profession evolved from the industrial applications of chemistry and separation science (the study of separating components from mixtures), primarily in the refining and chemical industry, which we will 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 for the production of glass and soap. During the same time, advances in organic chemistry led to the development of chemical processes for producing synthetic dyes from coal for textiles, starting in the 1850s. In the latter half of the 1800s a number of chemical processes were implemented industrially, primarily in Britain.

And in 1887 a series of lectures on chemical engineering which summarized industrial practice in the chemical industry was presented in 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 U.S. universities embraced the field of chemical engineering by offering fields of study in this area. In 1908, the American Institute of Chemical Engineers was formed and since then 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 a background in chemistry. On the other hand, 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. In the United States, a few chemistry departments were training process engineers by offering degrees in industrial chemistry, and these served as models for other departments as

the demand for process engineers in the CPI began to increase. As industrial chemistry programs grew, they eventually formed separate degree-granting programs as the chemical engineering departments of today.

The acceptance of the “horseless carriage,” which began commercial production in the 1890s, created a demand for gasoline, which ultimately fueled exploration for oil. In 1901, a Texas geologist and a mining engineer led a drilling operation (the drillers were later to be known as “wildcatters”) that brought in the Spindletop Well just south of Beaumont, Texas. At the time, Spindletop produced more oil than all of 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, but ultimately the success of the oil exploration and refining industries led to the widespread availability of automobiles to the general population because of the resulting lower cost of gasoline.

These early industrial chemists/chemical engineers had few analytical tools available to them and largely depended upon their physical intuition to perform their jobs as process engineers. Slide rules were used to perform 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 computing resources that became available in the 1960s were the beginnings of the 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 amount 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.

During the period 1960 to 1980, 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 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, developments in computer hardware made it possible to apply process automation (advanced process control, or APC, and optimization) 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. Because of these economic advantages, APC became widely accepted by industry over the next 15 years and remains an important factor for most companies in the CPI.

Beginning in the mid-1990s, new areas came on the scene that took advantage of the fundamental skills of chemical engineers, including the microelectronics industry, the pharmaceutical industry, the biotechnology industry, and, more recently, 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, over 80% of graduating chemical engineers took jobs with the CPI industry and government. By 2000, that number had dropped to 50% because of increases in the number taking jobs with biotechnology companies, pharmaceutical/health care companies, and microelectronics and materials companies. The next section addresses the current distribution of jobs for chemical engineers.

1.3 Where Do Chemical and Bioengineers Work?

Table 1.1, which lists the percentages of all chemical engineers by employment sector between 1996 and 2007, shows that the percentage of chemical engineers in these developing industries (pharmaceutical, biomedical, and microelectronics industries) increased from 7.1% in 1997 to 19.9% in 2005.

Chemical engineers are first and foremost process engineers. That is, chemical engineers are responsible for the design and operation of processes that produce a wide range of products from gasoline to plastics to composite materials to synthetic fabrics to computer chips to corn chips. In addition, chemical engineers work for environmental companies, government agencies including the military, law firms, and banking companies.

The trend of chemical engineering graduates taking employment in industries that can be designated as bioengineering is a new feature of the twenty-first century. Not only have separate bioengineering or biomedical departments been established, but some long-standing chemical engineering departments have modified their names to “chemical and bioengineering” to reflect the research and fresh interests of students and faculty.

Table 1.1 Chemical Engineering Employment by Sector (from AIChE Surveys)

	1996	2000	2002	2005	2007
Chemical, industrial gases, rubber, soaps, fibers, glass, metals, paper	33.3	32.5	25.2	28.1	25.5
Food, ag products, ag chemical	4.5	5.1	5.6	5.7	5.0
Energy, petroleum, utilities	14.1	1.9	5.1	4.5	3.7
Electronics, materials, computers	1.4	1.9	5.1	4.5	3.7
Equipment design and construction	13.8	12.6	10.6	12.6	14.3
Environmental, health, and safety	6.4	4.7	4.4	4.2	3.4
Aerospace, automobile	1.1	0.9	1.8	2.0	2.1
Research and development	3.9	3.8	4.4	4.2	3.4
Government	3.6	3.6	3.5	3.7	4.4
Biotechnology	1.5	2.2	2.4	4.4	3.7
Pharmaceutical, health care	4.2	6.5	6.1	8.4	7.6
Professional (including education)	4.7	4.5	8.6	7.0	8.4
Other	7.4	8.6	9.6	-	1.5

A bioengineer uses engineering expertise to analyze and solve problems in chemistry, biology, and medicine. The bioengineer works with other engineers as well as physicians, nurses, therapists, and technicians. Biomedical engineers may be called upon in a wide range of capacities to bring together knowledge from many technical sources to develop new procedures, or to conduct research needed to solve problems in areas such as drug delivery, body imaging, biochemical processing, innovative fermentation, bioinstrumentation, biomaterials, biomechanics, cellular tissue and genetics, system physiology, and so on. They work in industry, hospitals, universities, and government regulatory agencies. It is difficult to find valid surveys of specific companies or topics to classify bioengineering graduates' ultimate locations, but roughly speaking, one-third of graduates go to medical school, one-third continue on to graduate school, and one-third go to work in industry with a bachelor's degree.

1.4 Future Contributions of Chemical and Bioengineering

The solution of many of the pressing problems of society for the future (e.g., global warming, clean energy, manned missions to Mars) will depend significantly on chemical and bioengineers. In order to more fully explain

the role of chemical and bioengineers and to illustrate the role of chemical and bioengineers in solving society's technical problems, we will now consider some of the issues associated with carbon dioxide capture and sequestration, which is directly related to global warming.

Because fossil fuels are less expensive and readily available, we would like to reduce the impact of burning fossil fuels for energy, but without significantly increasing the costs. Therefore, it is imperative that we develop low-cost CO₂ capture and sequestration technologies that will allow us to do that.

An examination of Figure 1.1 shows the sources of CO₂ emissions in the United States. What category would you attack first? Electric power generation is the number-one source. Transportation sources are widely distributed. No doubt power generation would be the most fruitful.

Carbon capture and storage (CCS) is viewed as having promise for a few decades as an interim measure for reducing atmospheric carbon emissions relatively quickly and sharply while allowing conventional coal-fired power plants to last their full life cycles. But the energy costs, the disposal challenges, and the fact that adding CCS to an existing plant actually boosts the overall consumption of fossil fuels (because of the increased consumption of energy to collect and sequester CO₂, more power plants have to be built so that the final production of net energy is the same) all suggest that CCS is not an ultimate solution.

One interim measure under serious consideration for CCS that might allow existing conventional coal-fired power plants to keep producing until they can be phased out at the end of their full lives involves various known technologies. An existing plant could be retrofitted with an amine scrubber

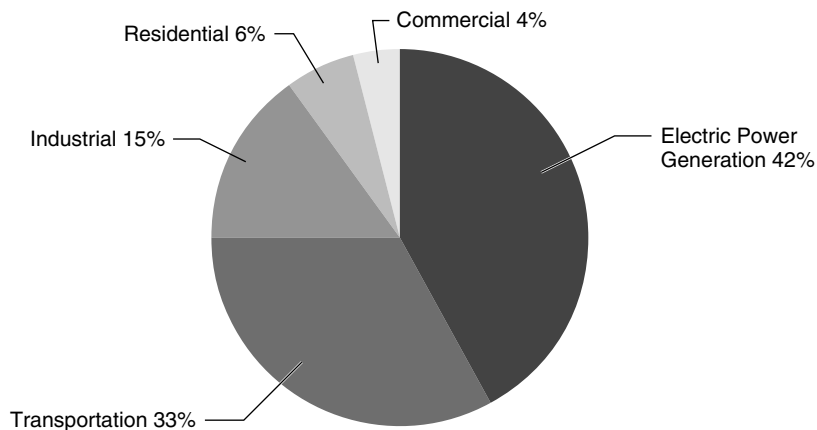


Figure 1.1 Major sources of carbon dioxide emissions in the United States excluding agriculture

to capture 80% to 95% of CO₂ from combustion gases; the CO₂ would then be condensed into a liquid that would be transported and stored somewhere indefinitely where it could not leak into the atmosphere. If several hundreds or thousands of CCS systems were deployed globally this century, each capturing 1 to 5 metric tons of CO₂ per year collectively, they could contribute between 15% and 55% of the worldwide cumulative mitigation effort.

However, the engineering challenges are significant. First, CCS is an energy-intensive process, so power plants require significantly more fuel to generate each kilowatt-hour of electricity produced for consumption. Depending on the type of plant, additional fuel consumption ranges from 11% to 40% more—meaning not only in dollars, but also in additional fossil fuel that would have to be removed from the ground to provide the power for the capture and sequestration, as well as additional CO₂ needing sequestration by doing so. Current carbon-separation technology can increase the price tag of producing electricity by as much as 70%. Put another way, it costs about \$40 to \$55 per ton of carbon dioxide. The annual U.S. output of carbon dioxide is nearly 2 billion tons, which indicates the economic scale of the problem. The U.S. Department of Energy is working on ways to reduce the expenses of separation and capture.

By far, the most cost-effective option is partnering CCS not with older plants, but with advanced coal technologies such as integrated-gasification combined-cycle (IGCC) or oxygenated-fuel (oxyfuel) technology. There is also a clear need to maximize overall energy efficiency if CCS itself is not merely going to have the effect of nearly doubling both demand for fossil fuels and the resultant CO₂ emitted.

Once the CO₂ has been captured as a fairly pure stream, the question is what to do with it that is economical. In view of the large quantity of CO₂ that must be disposed of, disposal, to be considered a practical strategy, has to be permanent.

Any release of gas back into the atmosphere not only would negate the environmental benefits, but it could also be deadly. In large, concentrated quantities, carbon dioxide can cause asphyxiation. Researchers are fairly confident that underground storage will be safe and effective.

This technology, known as carbon sequestration, is used by energy firms as an oil-recovery tool. But in recent years, the Department of Energy has broadened its research into sequestration as a way to reduce emissions. And the energy industry has taken early steps toward using sequestration to capture emissions from power plants.

Three sequestration technologies are actively being developed: storage in saline aquifers in sandstone formations [refer to S. M. Benson and T. Surles, "Carbon Dioxide Capture and Storage," *Proceed. IEEE*, **94**, 1795 (2006)], where the CO₂ is expected to mineralize into carbonates over time;

injection into deep, uneconomic coal seams; and injection into depleted or low-producing oil and natural-gas reservoirs.

Preliminary tests show that contrary to expectations, only 20% maximum of CO₂ precipitates form carbonate minerals, but the majority of the CO₂ dissolves in water. Trapping CO₂ in minerals would be more secure, but CO₂ dissolved in brine is an alternate disposal outcome.

Other suggestions for the reduction of CO₂ emissions include permanent reduction in demand, chemical reaction, various solvents, use of pure O₂ as the oxidant, and so on. See J. Ciferno et al., *Chemical Engineering Progress*, 33–41 (April, 2009), and F. Princiotta, “Mitigating Global Climate Change through Power-Generation Technology,” *Chemical Engineering Progress*, 24–32 (November, 2007), who have a large list of possible avenues of approach. The bottom line is that a solution for CO₂ emissions reduction is not just a matter of solving technical problems but a matter of cost and environmental acceptance. Based on the nature of these challenges, it is easy to see that chemical and bioengineers will be intimately involved in these efforts to find effective solutions.

1.5 Conclusion

The chemical engineering profession evolved from society’s need for products and energy. Today and into the future, chemical and bioengineers will continue to meet society’s needs using their process knowledge, their knowledge of fundamental science, and their problem-solving skills.

Looking Back

In this chapter we reviewed the history of chemical engineering and presented information on the current and projected future status of the profession.

Glossary

Chemical process industries (CPI) The chemical and refining industries.

Computer-aided design (CAD) packages Software programs that are used to design and/or analyze systems including chemical processes.

Web Site

www.pafko.com/history/h_what.html

INDEX

In this index the page numbers in *italic* refer to pages in Chapters 12 through 17, and Appendixes F through N, which are located on the CD that accompanies this book. Pages in the problem Workbook are indexed separately, and that index will be found in the Workbook itself as well as proceeding this index..

A

Absolute pressure (psia), 68, 71–72, 468
Absolute temperature, 60
Absorbers, 412
Accumulation, material balance, 103
Acentric factors, 375, 845–849
Adiabatic cooling line, 659–665
Adiabatic reaction, 622–626
Adiabatic systems, energy balances, 492–493
Adsorbate, 757
Adsorbent, 757
Adsorption, gases or liquids on solids
 definition, 757
 practice problems, 766–767
Adsorption isotherms
 combining with material balance, 762–763
 curves for, 757–759
 fitting to experimental data, 760
 Freundlich, 758–761
 Langmuir, 759–761
AE system of units, 13, 15
Air, average molecular weight, 40–41
Airplane crash, 12
Ali Baba and the 39 camels, 46–47

Answers to questions and problems, 829–843, 854–859
Antoine equation, 425–427
API scale, 52
Armour’s laws of ignorance, 130
Atmospheric pressure, 70
Atomic weight, 38–42
Atomic weights and numbers, table of, 844
Average molecular weight, 40–41
Azeotropes, 459

B

Bank statement analogy for material balance, 102–103
Barite fusion, 227–230
Barometric pressure, 68
Bases, changing, 47–48
Basic dimensions. *See* Fundamental dimensions.
Basic units. *See* Fundamental units.
Basis
 changing bases, 47–48
 choosing, 44–48
 definition, 44
 practice problems, 90–91

- Batch processes
 - definition, 111
 - distillation, material balances for
 - unsteady-state processes, 810–812
 - work performed by, 732–733
 - Benedict-Webb-Rubin (BWR) equation, 368
 - Bernoulli equation, 742
 - Bioengineering, 4–10
 - Bioengineers, 7
 - Biomass, heating, 561–563
 - Bioreactor analysis, 221–224
 - Block diagrams, 269
 - BOD (biochemical oxygen demand), 245
 - Boiling, 415
 - Boundaries, 108, 492
 - Bubble point
 - calculating, 462–465
 - definition, 415
 - Burning. *See* Combustion.
 - BWR (Benedict-Webb-Rubin) equation, 368
- C**
- CAD (computer-aided design), 5
 - Calcination process, modeling, 816–817
 - Carbon sequestration, 9–10
 - Careers in chemical/bioengineering, 4–10
 - CCS (carbon capture and storage), 8–10
 - Cells, concentrating with centrifuges, 117–118
 - Cellular product, 244
 - Celsius (°C) scale, 60
 - Centrifuges, concentrating cells, 117–118
 - Checking for errors. *See* Validating results.
 - Chemical engineering, 4–10
 - Chemical process industries (CPI), 4–6
 - Chemisorption, 757
 - Chen's equation, 522
 - Chinook wind, 453
 - Citric acid production, 626–629
 - Closed processes, 108
 - Closed systems, 108, 492
 - CO₂ emissions, 8–10
 - Coal
 - combustion, 240–245
 - heating value, 638–639
 - COD (chemical oxygen demand), 245
 - Coefficient of performance (COP), 737, 748
 - Combustion, material balance
 - BOD (biochemical oxygen demand), 245
 - cellular product, 244
 - coal, 240–245
 - COD (chemical oxygen demand), 245
 - complete combustion, 234
 - excess air (oxygen), 234–236
 - extracellular product, 244
 - flue gas, 234
 - fuel cells, 237–239
 - generating electricity from methane, 237–239
 - ideal gases, 360–364
 - nitrogen source, 243
 - overview, 233
 - oxygen demand, 245
 - partial combustion, 234
 - practice problems, 261–266
 - stack gas, 234
 - substrates, 243
 - theoretical air (oxygen), 234
 - ThOD (theoretical oxygen demand), 245
 - TOD (total oxygen demand), 245
 - wet basis, 234
 - Combustion gases, enthalpies of, 871–872
 - Combustion temperature. *See* Adiabatic reaction.
 - Complete combustion, 234
 - Component balance, 145
 - Compounds, definition, 40
 - Compressibility, real gases
 - compressibility charts, 377–383, 406–408
 - critical state, 372–376

- Compressibility charts, 377–383, 406–408
- Compressibility factor, 373, 378–383
- Computer-aided design (CAD), 5
- Concentration
- definition, 55
 - examples of, 56
 - mass concentration, 56
 - molar concentration, 56
 - practice problems, 91–94
- Condensation
- at constant temperature, 417–418
 - definition, 415
 - two component gas/single-component liquid systems, 441–449
- Conservation of energy, energy balances, 499–500, 530–532
- Consumption, material balance, 103–104
- Continuous distillation column, 165–167
- Continuous filtration, recycle systems, 294–297
- Continuous processes, 111
- Conversion. *See also* Systems of units; *specific conversions.*
- in biological materials, 20–21
 - frequent flier miles to U.S. miles, 23
 - in heat capacity equations, 520
 - moles/mass, 38–39
 - nanotechnology, 20
 - overview, 17
 - pound mass *vs.* pound force, 21–23
 - practice problems, 83–85
 - reaction systems, 203
 - temperature, 62–64
 - weight *vs.* mass, 22–23
- Conversion factors
- definition, 17
 - example, 20
 - pressure, 66
 - tables of, 18–19
- Cooling, humidity charts for, 668–669
- Cooling towers, humidity charts for, 669–671
- COP (coefficient of performance), 737, 748
- Corrected, 389
- Corresponding states, 373
- Cox chart, 432–435
- CPI (chemical process industries), 4–6
- Critical state, 372–376
- D**
- Dalton's law, 357–358
- Decimal points. *See* Significant figures.
- Degree of completion, 203
- Degree-of-freedom analysis
- definition, 135
 - example, 135–138
 - multi-unit systems, 695–698
 - processes using element balances, 691–692
 - processes using species balances, 693
- Degree-of-freedom analysis, steady-state processes
- components (species), 685
 - equations, 685–687
 - example, 687–690
 - number of degrees, 684
 - overview, 684–687
 - practice problems, 700–707
 - process specification, 690–691
 - stream variables, 685
 - variables, 684
- Degrees of superheat, 416
- Density
- calculating, 51–52
 - definition, 49
 - overview, 49–54
 - practice problems, 91
- Dependent equations, 134
- Derived dimensions, 13
- Derived units, 13
- Dew point, calculating
- from relative humidity, 656
 - two component gas/single-component liquid systems, 437–440

- Dew point, calculating (*Continued*)
 two component gas/two-component liquid systems, 462–465
- Dew point, definition, 416
- Difference equations, 104
- Differential equations, 105
- Dilution, heats of, 878
- Dimensional consistency
 dimensionless groups, 26
 of equations, 25–27
 nondimensional groups, 26
 overview, 25
 practice problems, 85–88
 van der Waals' equation, 25
- Dimensionless groups, 26
- Dimensions, 13
- Dissolution, heats of, 709–715
- Distillation, definition, 412
- Distribution coefficient. *See* *K*-value.
- DNA
 efficiency of recovery, 115–116
 micro-dissection, 31–34
- Dry-bulb temperature, 654
- Drying, 174–176
- E**
- Efficiency
 COP (coefficient of performance), 737
 definition, 735–736
 energy conservation, 737
 general, 737
 heat engine, 737
 hydroelectric plants, 736
 mechanical, 737
 plants, 738
 processes, 737
 refrigeration cycle, 737
- Egg trick, 159, 181
- Electrical work, 502
- Electricity, generating from methane, 237–239
- Element material balances
 degree-of-freedom analysis, 691–692
 overview, 226–232
 practice problems, 261
- Endothermic reactions, 598
- Energy, definition, 497
- Energy balances. *See also* Mechanical energy balance.
 adiabatic systems, 492–493
 boundaries, 492
 closed systems, 492
 combined with material balances, 552–554
 conservation of energy, 499–500, 530–531
 equilibrium state, 492
 flowsheeting codes. *See* Process simulation.
 isobaric systems, 492–493
 isochoric systems, 492–493
 isothermal systems, 492–493
 mixing, effects of, 715–722
 open systems, 492
 path variables, 493–494
 phase, 492
 practice problems, 569–572
 state of a system, 492–493
 state variables, 493
 steady-state, 492
 surroundings, 492
 system, 492
 transient state, 492
- Energy balances, energy caused by reactions
 adiabatic reaction, 622–626
 endothermic reactions, 598
 exothermic reactions, 598
 heat of combustion, 635–642, 651–652
 heat reaction, 603–614, 645–650
 reference state, 598
 sensible heat, 614–635, 650–651
 standard heat of combustion, 635
 standard heat of formation, 598–603, 614–636, 643–644, 650–651
 standard state, 598
- Energy balances, enthalpy (*H*)
 absolute value, 515

- calculating change in, 515
- overview, 514–518
- phase transitions, 516–517, 522–525
- single phase, 514
- tables and charts of, 525–529
- Energy balances, properties
 - computer databases of, 529–530
 - definition, 492
 - extensive, 492
 - intensive, 492
- Energy balances, types of energy
 - heat (Q), 497–501
 - heat capacity, 511–513, 518–522
 - heat of condensation, 517
 - heat of fusion, 517
 - heat of solidification, 517
 - heat of sublimation, 517
 - heat of vaporization, 517
 - internal energy (U), 511–513
 - kinetic energy (KE), 507–508
 - latent heat changes, 516
 - phase transitions, 516
 - potential energy (PE), 508–511
 - practice problems, 572–580
 - sensible heat changes, 516
 - work (W), 501–507
- Energy balances without reactions
 - conservation of energy, 530–532
 - general energy balance for open systems, 542–546
 - practice problems, 580–595
 - steady-state, closed systems, 541–542
 - steady-state, open systems, 546–557
 - unsteady-state, closed systems, 533–541
 - unsteady-state, open systems, 557–566
- Energy conservation. *See* Conservation of energy.
- Enthalpy (H)
 - of combustion gases, 871–872
 - of hydrocarbon vapor, 869
 - of nitrogen, 870
 - of sulfur compound vapors, 870
- Enthalpy (H), energy balances
 - absolute value, 515
 - calculating change in, 515
 - of combustion. *See* Heats of, combustion.
 - of formation. *See* Standard heat of formation.
 - overview, 514–518
 - phase transitions, 516–517, 522–525
 - single phase, 514
 - tables and charts of, 525–529
- Enthalpy-concentration diagrams, 718–720, 879–884
- Equation solutions
 - independent linear equations, 889–900
 - independent nonlinear equations, 900–904
- Equation-based process simulation, 772–777
- Equations. *See also specific equations.*
 - degree-of-freedom analysis, steady-state processes, 685–687
 - dimensional consistency, 25–27
 - element balance, 894–895
 - homogenous, 897
 - independent components in the Gibbs phase rule, 899–900
 - nonhomogenous, 898–899
 - reaction, 895
- Equations, independent
 - element balance, 894–895
 - linear, 891–894
 - nonlinear, 900–904
 - reaction, 895
- Equations, linear
 - definition, 889–890
 - independent, identifying, 891–894
 - vs.* nonlinear, 139
 - set of independent, 890–891, 896–897
- Equations, nonlinear
 - independent, 900–904
 - vs.* linear, 139
 - Newton's method, 900–904
- Equations of state, 366–372, 403–406
- Equilibrium, humidity charts, 659

- Equilibrium pressure, 415
 Equilibrium ratio K . *See* K -value.
 Equilibrium state, energy balances, 492
 Error checking. *See* Validating results.
 Evaporation, 416
 Evaporation of a liquid, work performed during, 730–731
 Exactly specified, 135
 Excess air (oxygen), 234–236
 Excess reactants, 201–202
 Exothermic reactions, 598
 Extent of reaction, 198–201
 Extracellular product, 244
 Extraction processes, definition, 412
- F**
- Fahrenheit ($^{\circ}\text{F}$) scale, 60
 Flow rate, 78
 Flow systems. *See* Open systems.
 Flow work, 502–503
 Flowsheeting codes. *See* Process simulation.
 Flowsheets. *See* Process simulators.
 Flue gas, 234
 Fluid warmer, 550–551
 Force, definition, 21
 Freezing, 416
 Frequent flier miles, converting to U.S. miles, 23
 Fresh feed, recycle systems, 291
 Freundlich isotherms, 758–761
 Friction factors, 742
 Fuel cells, 237–239
 Functions, fitting to data, 905–908. *See also* Variables.
 Fundamental dimensions, 13
 Fundamental units, 13
 Fusion. *See* Melting.
- G**
- Gas chromatographic column, separating compounds, 171–174
 Gases. *See also* Ideal gases; Real gases. density, 356–357
 in equilibrium with solids. *See* Adsorption, gases or liquids on solids.
 multiphase equilibrium, 413
 noncondensable, 413
 partial pressure, 357
 separating with a membrane, 162–166
 specific gravity, 357
 Gasoline, material balance for blending, 118–119
 Gauge pressure (psig), 68
 General energy balance
 for multi-reaction processes, 617–622
 for multi-unit processes, 629–634
 for open systems, 542–546
 General material balances, 104
 Generalized compressibility. *See* Compressibility charts.
 Generalized equation of state, 373–375
 Generation, material balance, 103–104
 Gibbs' phase rule, 421, 899–900
 Giragossian, Garabed, 531–532
 Gordon's law, 124
 Gram mole, 37
 Green chemistry, 605–606
 Gross product, recycle systems, 291
 Group contribution method, 376
- H**
- H (enthalpy). *See* Enthalpy (H).
 Heads of fluids, 746
 Heat (Q), in energy balances, 497–501
 Heat capacity, 511–513, 518–522
 Heat capacity equations, 873–876
 Heat engine efficiency, 737
 Heat reaction, 603–614, 645–650
 Heat transfer, 497–498
 Heating value, 637–638
 Heats of
 combustion, 635–642, 651–652
 condensation, 517

- dilution, 878
 - dissolution, 709–715
 - formation. *See* Standard heat of formation.
 - fusion, 517
 - mixing, 709–715
 - practice problems, 724–727
 - solidification, 517
 - solution, 709–715, 878
 - solution at infinite dilution, 710
 - sublimation, 517
 - vaporization, 517
 - Hemodialysis, 176–178
 - Henry's law, 457
 - HHV (higher (gross) heating value), 637–639
 - Holborn equation, 368
 - Home heating, humidity charts for, 667
 - Homogenous equations, 897
 - Howe's law, 124
 - Humid heat, 673
 - Humid volume, 660
 - Humidification, 659–665, 668–669
 - Humidity, 654
 - Humidity charts
 - adiabatic cooling line, 659–665
 - definition, 657
 - dew point, calculating, 656
 - dry-bulb temperature, 654
 - equilibrium, 659
 - humid heat, 673
 - humid volume, 660
 - humidification, 659–665
 - humidity, 654
 - practice problems, 674–677
 - properties of moist air, 663–665
 - relative humidity, 654, 656
 - wet-bulb line, 658–659
 - wet-bulb temperature, 654–655
 - Humidity charts, uses for
 - cooling and humidification, 668–669
 - cooling towers, 669–671
 - home heating, 667
 - practice problems, 677–680
 - Hydrocarbon vapor, enthalpies of, 869
 - Hydrocracking, 230–232
 - Hydroelectric plants, efficiency, 736
 - Hydrostatic head, 66–68, 95–97
- I**
- Ideal critical specific volume, 379
 - Ideal gas constant, 351
 - Ideal gas law, 351–357
 - Ideal gas mixtures, 357–360
 - Ideal gases. *See also* Gases; Real gases.
 - enthalpies, 514
 - heat capacities, 519
 - internal energy, 514
 - material balance, 360–364
 - practice problems, 391–403
 - S.C. (standard conditions), 352–354
 - volume, calculating, 353–356
 - volumetric flow rate, 356
 - Ideal reduced volume, 379
 - Ideal reversible processes, 729–735
 - Ideal solution relations, 455–457
 - Ideal solutions, 709
 - Implicit equations, 146
 - Incremental (differential) heat of solution, 710
 - Independent equations, 133–135
 - Independent linear equations, 889–900
 - Independent nonlinear equations, 900–904
 - Industrial applications for material balance, 314–316
 - Initial condition, material balance, 103
 - Inorganic substances, physical properties of, 861–872
 - Inputs, material balance, 103
 - Integral heat of solution, 710
 - Intensive properties, 421
 - Internal connections, 274
 - Internal energy (U), 511–513

Invariant systems, 423
 Irreversible processes, 729
 Isobaric systems, energy balances, 492–493
 Isochoric systems, energy balances, 492–493
 Isothermal systems, energy balances, 492–493

J

Jobs in chemical/bioengineering, 4–10

K

Kammerling-Onnes equation, 368
 Kay's method, 384
KE (kinetic energy), 507–508
 Kelvin (K) scale, 60
 Kg mole, 37–38
 Kidneys, dialysis, 176–178
 Knowns, 126–132
 Korean Air Lines freighter crash, 12
K-value (vapor-liquid equilibrium ratio), 460–462

L

Langmuir isotherms, 759–761
 Latent heat changes, 516
 Law of corresponding states. *See* Corresponding states.
 Least squares application, 906
 LHV (lower (net) heating value), 637–639
 Limiting reactants, 201–202
 Linear equations. *See* Equations, linear.
 Liquid water properties, 429
 Liquids in equilibrium with solids. *See* Adsorption, gases or liquids on solids.

M

Manometer, 71–72
 Mars Climate Orbiter, 17
 Mass

calculating, 52–54
 converting to/from moles, 38–39
vs. weight, 22–23

Mass concentration, 56
 Mass flow rate, 78
 Mass fraction, 41–42, 56
 Mass of reactants, calculating, 194
 Mass per unit volume, 56
 Material balance
 accumulation, 103
 bank statement analogy, 102–103
 combined with energy balances, 552–554
 consumption, 103–104
 definition, 102
 flowsheeting codes. *See* Process simulation.
 general, 104
 generation, 103–104
 industrial applications, 314–316
 initial condition, 103
 inputs, 103
 for multiple components, 112–119
 outputs, 103
 practice problems, 147–154
 process analysis, 314
 process optimization, 314
 process simulators, 314
 for single components, 105–107
 Material balance for multi-unit systems.
 See also Recycle systems.
 block diagrams, 269
 bypass streams, 306–309, 343–345
 independent equations, 273
 internal connections, 274
 mixers, 270
 number of material balances, determining, 274–276
 overall process, 274
 overall total material balance, 271
 practice problems, 318–328
 process flowsheets, 268–270
 purge streams, 306–307, 309–312, 343–345

- with reaction, 282–284
 - separators, 270
 - sequential combination of units, 271–278
 - splitters, 270
 - subsystems, 269–270
 - sugar recovery process, 284–287
 - without reaction, 278–282
- Material balance problems, solving
- Armour's laws of ignorance, 130
 - check answers, 141–142
 - choose a basis, 130–131
 - degree-of-freedom analysis, 132–138
 - identify known information, 126–129
 - identify unknown information, 131–132
 - label the diagram, 126–129
 - linear equations *vs.* nonlinear, 139
 - novice *vs.* expert, 142–143
 - obtaining missing data, 129–130
 - overview, 123–124
 - practice problems, 154–158
 - problem statement, 124–125
 - sketch the process, 126
 - solve equations, 140
 - specify system boundaries, 126
 - summary of steps, 142
 - write equations, 138–140
- Material balance with reactions. *See also* Reaction systems; Species mole balances.
- balancing a reaction equation for a biological reaction, 193
 - BaSO₄ fusion, 227–230
 - calculating the mass of reactants, 194
 - element balances, 226–232
 - hydrocracking, 230–232
 - for multiple reactions, 195–197
 - steps involved, 191–193
- Material balance with reactions, combustion
- BOD (biochemical oxygen demand), 245
 - cellular product, 244
 - coal, 240–245
 - COD (chemical oxygen demand), 245
 - complete combustion, 234
 - excess air (oxygen), 234–236
 - extracellular product, 244
 - flue gas, 234
 - fuel cells, 237–239
 - generating electricity from methane, 237–239
 - ideal gases, 363–364
 - nitrogen source, 243
 - overview, 233
 - oxygen demand, 245
 - partial combustion, 234
 - practice problems, 261–266
 - stack gas, 234
 - substrates, 243
 - theoretical air (oxygen), 234
 - ThOD (theoretical oxygen demand), 245
 - TOD (total oxygen demand), 245
 - wet basis, 234
- Material balance without reaction
- continuous distillation column, 165–167
 - drying, 174–176
 - hemodialysis, 176–178
 - ideal gases, 363–364
 - kidneys, dialysis, 176–178
 - mixing sulfuric acid, 168–171
 - practice problems, 181–188
 - separating gases with a membrane, 162–166
 - separation with gas chromatographic column, 171–174
 - streptomycin extraction, 160–162
 - tie components, 175
- Maximum extent of reaction, 201–202
- Mechanical efficiency, 737
- Mechanical energy, 749

- Mechanical energy balance
 - Bernoulli equation, 742
 - friction factors, 742
 - orifice coefficients, 742
 - overview, 740–742
 - pumping water, 744–746
 - steady-state, examples, 742–746
 - Mechanical work, 502, 504–505
 - Melting, 416
 - Melting curve, 416
 - Methane, generating electricity from, 237–239
 - Minimal set of equations, 217
 - Mixers, 270
 - Mixing
 - effects on energy balances, 715–722
 - heats of, 709–715
 - Mixtures, gases, 384–386, 408–410
 - Modular-based process simulation, 772, 777–781
 - Molar concentration, 56
 - Molar flow rate, 78
 - Mole fraction
 - concentrations, 56
 - definition, 41–42
 - Molecular weight
 - overview, 38–42
 - practice problems, 89–90
 - Moles. *See also* Species mole balances.
 - calculating, 52–54
 - converting to/from mass, 38–39
 - definition, 37
 - gram mole, 37
 - kg mole, 37–38
 - per unit volume, 56
 - pound mole, 37
 - practice problems, 89–90
 - ratio of, 203–204
 - Multicomponent liquid-vapor equilibrium, 466–467, 486
 - Multiphase equilibrium. *See also* Single-component two-phase systems; Two component gas/ single-component liquid systems; Two component gas/two-component liquid systems.
 - boiling, 415
 - bubble point, 415
 - condensation, 415, 417–418
 - degrees of superheat, 416
 - dew point, 416
 - equilibrium pressure, 415
 - evaporation, 416
 - freezing, 416
 - gases, 413
 - intensive properties, 421
 - invariant systems, 423
 - melting, 416
 - melting curve, 416
 - multicomponent liquid-vapor equilibrium, 466–467, 486
 - noncondensable gases, 413
 - normal boiling point, 416
 - normal melting point, 416
 - phase diagrams, 413–419
 - phase rule, 419–424
 - quality, 418
 - saturated liquid/vapor, 416
 - subcooled liquid, 416
 - sublimation, 416
 - sublimation curve, 416
 - sublimation pressure, 416
 - supercritical region, 416
 - superheated vapor, 416
 - total system volume, 421
 - triple point, 414
 - two-phase regions, 418
 - vapor, 413
 - vapor pressure, 415
 - vaporization, 416, 417–418
- N**
- Nanotechnology, 20
 - Negative accumulation, 146
 - Newton's method, 900–904
 - Nitrogen
 - for cell growth, 56–57

enthalpies of, 870
source, 243
Noncondensable gases, 413
Nonflow systems. *See* Closed systems.
Nonhomogenous equations,
898–899
Nonideal gases. *See* Real gases.
Nonlinear equations. *See* Equations,
nonlinear.
Normal boiling point, 416
Normal melting point, 416
Normalized. *See* Corrected.

O

Once-through conversion, recycle
systems, 297
Open processes, 108
Open systems
definition, 108
energy balances, 492
general energy balance, 542–546
Open systems, energy balances without
reactions
general energy balance, 542–546
steady-state, 546–557
unsteady-state, 557–566
Organic substances, physical properties
of, 861–872
Orifice coefficients, 742
Oscillating reactions, unsteady-state
process material balances,
812–814
Outputs, material balance, 103
Overall conversion, recycle systems, 297
Overall process, 274
Overall (net) product, recycle systems,
291
Overall total material balance, 271
Overspecified, 135
Oxygen demand, 245

P

Paniker, P. K. N., 49
Partial combustion, 234

Parts per billion (ppb), 56
Parts per billion by volume (ppbv),
56
Parts per million (ppm), 56, 57–58
Parts per million by volume (ppmv),
56
Path variables, energy balances,
493–494
PE (potential energy), 508–511
Peng-Robinson (PR) equation, 368
Perpetual motion machine, 531–532
Phase
definition, 350, 421
energy balances, 492
Phase diagrams
overview, 413–419
practice problems, 470–472
vapor-liquid equilibria, 457–459
Phase equilibrium, 421. *See also*
Multiphase equilibrium.
Phase rule, 419–424, 470–472
Phase transitions, 516–517, 522–525
Pitzer acentric factors. *See* Acentric
factors.
Plants (factories), efficiency, 738
Plasma etching, 538–539
Point. *See* State.
Point function. *See* State variables.
Potential energy (*PE*), 508–511
Pound force, 21–23
Pound mass, 21–23
Pound mole, 37
Power, definition, 502
ppb (parts per billion), 56
ppbv (parts per billion by volume),
56
ppm (parts per million), 56, 57–58
ppmv (parts per million by volume),
56
PR (Peng-Robinson) equation, 368
Pressure
absolute (psia), 68
absolute *vs.* relative, 68, 71–72
atmospheric pressure, 70

- Pressure (*Continued*)
- barometric, 68
 - conversion, 70–71
 - conversion factors, 66
 - definition, 65
 - differences, calculating, 74–75
 - gauge pressure, 68
 - gauge (psig) scale, 68
 - hydrostatic, 66–68, 95–97
 - practice problems, 95–97
 - standard atmosphere, 70
 - static columns, 66
 - vacuum, 68, 72–73
- Problem solving, novices *vs.* experts, 142–143
- Process analysis, material balance, 314
- Process feed, recycle systems, 291
- Process flowsheets, 268–270
- Process matrix, 777
- Process optimization, material balance, 314
- Process simulation
- definition, 768
 - equation-based method, 772–777
 - modular-based method, 772, 777–781
 - overview, 768–773
 - practice problems, 782–799
 - process matrix, 777
 - vendors of commercial simulators, 771
- Process simulators, material balance, 314
- Processes
- batch, 111
 - closed, 108
 - continuous, 111
 - efficiency, 737
 - ideal reversible, 729–735
 - irreversible, 729
 - open, 108
 - pseudo steady-state, 109
 - quasi steady-state, 109
 - reversible, 729
 - semi-batch, 111
 - steady-state, 108–110
 - unsteady-state, 110–111
 - visual diagrams of. *See* Process flowsheets.
- Properties
- definition, 349
 - intensive, 421
 - liquid water, 429
 - saturated water, 427–428
- Properties, physical
- inorganic substances, 861–872
 - organic substances, 861–872
 - petroleum fractions, 887–888
 - tables of, 861–872
- Pseudo steady-state processes/systems, 109
- Pseudocritical constants, 378
- Pseudocritical ideal volume, 385
- Pseudocritical values, 384
- Pseudoreduced ideal volume, 385
- Pseudoreduced variables, 385
- psia (absolute pressure), 68, 71–72, 468
- psig (gauge pressure), 68
- Psychrometric charts. *See* Humidity charts.
- Psychrometric line. *See* Wet-bulb line.
- Pumping water
- mechanical energy balance, 744–746
 - power calculation, 554–555
- Q**
- Q (heat). *See* Heat.
- Quality, 418
- Quasi steady-state processes/systems, 109
- R**
- Rankine (°R) scale, 60
- Raoult's law, 455–457
- Reactants, calculating mass of, 194
- Reaction equations, balancing for a biological reaction, 193

- Reaction systems. *See also* Material balance with reactions.
calculations, 205–208
conversion, 203
degree of completion, 203
excess reactants, 201–202
extent of reaction, 198–201
limiting reactants, 201–202
maximum extent of reaction, 201–202
practice problems, 253–258
ratio of the moles, 203–204
selectivity, 203–204
yield, 204–205
- Real gases. *See also* Gases; Ideal gases.
acentric factor, 375
compressibility factor, 373, 378–383
corresponding states, 373
critical state, 372–376
enthalpies, 514
equations of state, 366–372, 403–406
generalized equation of state, 373–375
group contribution method, 376
ideal critical specific volume, 379
ideal reduced volume, 379
internal energy, 514
Kay's method, 384
mixtures, 384–386, 408–410
pseudocritical constants, 378
pseudocritical ideal volume, 385
pseudocritical values, 384
pseudoreduced ideal volume, 385
pseudoreduced variables, 385
reduced variables, 373
supercritical fluids, 373
UNIFAC method, 376
UNIQUAC method, 376
virial equations, 369
- Real gases, compressibility
compressibility charts, 377–383, 406–408
critical state, 372–376
- Real gases, pressure calculations
compressibility factor, 382–383
real gas mixtures, 385–386
- Redlich-Kwong (RK) equation, 370–372
- Real gases, volume calculations
compressibility factor, 380–382
real gas mixtures, 385–386
Redlich-Kwong (RK) equation, 370–372
- Real solutions, 709
- Recycle stream, 290–291
- Recycle systems. *See also* Material balance for multi-unit systems.
continuous filtration, 294–297
fresh feed, 291
gross product, 291
once-through conversion, 297
overall conversion, 297
overall (net) product, 291
practice problems, 328–343
process feed, 291
with reaction, 297–303
recycle stream, 290–291
reflux, 293
without reaction, 293–297
- Redlich-Kwong (RK) equation, 368, 370–372
- Reduced variables, 373
- Reference state, 598
- Reference substance, 433
- Reference substance plots, 432–435, 568
- Reflux, 293
- Refrigeration cycle efficiency, 737
- Relative error, 81
- Relative humidity, 654, 656
- Relative saturation. *See* Relative humidity.
- Relative temperature, 60
- Required air (oxygen). *See* Theoretical air.
- Reversible processes, 729
- Riedel's equation, 523
- RK (Redlich-Kwong) equation, 368, 370–372
- Rounding to significant figures, 30

- S**
- Saturated liquid/vapor, 416
 - Saturated water properties, 427–428
 - Saturation, two component gas/single-component liquid systems, 437–440
 - S.C. (standard conditions), 352–354
 - Selectivity, 203–204
 - Semi-batch processes, 111
 - Sensible heat, 614–635, 650–651
 - Sensible heat changes, 516
 - Separation systems, examples of, 412–413
 - Separation with gas chromatographic column, 171–174
 - Separators, 270
 - Sequential combination of units, 271–278
 - Set of independent equations, 890–891, 896–897
 - Shaft work, 502–503
 - SI system of units
 - vs.* AE system of units, 13
 - definition, 13
 - prefixes, 14
 - summary of units, 14
 - Significant figures, 29–36, 88
 - Simulation. *See* Process simulation.
 - Single phase enthalpy, 514
 - Single-component two-phase systems.
 - See also* Multiphase equilibrium.
 - Antoine equation, 425–427
 - liquid water properties, 429
 - practice problems, 472–476
 - prediction via equations, 425–427
 - saturated water properties, 427–428
 - steam tables, 427–432
 - superheated steam properties, 428–429
 - thin film deposition, 426–427
 - vaporizing metals, 426–427
 - Single-component two-phase systems, vapor pressures
 - reference substance, 433
 - from reference substance plots, 432–435
 - from tables, 427–432
 - Single-pass fraction conversion. *See* Once-through conversion.
 - Smokestack emissions, 446–449
 - SO₂ emissions, 639–640
 - Soave-Redlich-Kwong (SRK) equation, 368
 - Solutes, 709
 - Solution
 - definition, 81
 - heats of, 709–715, 878
 - Solution at infinite dilution, heats of, 710
 - Solvents, 709
 - Species mole balances. *See also* Material balance with reactions.
 - bioreactor analysis, 221–224
 - degree-of-freedom analysis, 693
 - minimal set of equations, 217
 - multiple-reaction processes, 216–224
 - practice problems, 258–261
 - single-reaction processes, 210–214
 - for a specified fraction conversion, 214–216
 - Specific gravity
 - calculating density, 51–52
 - calculating mass and moles, 52–54
 - definition, 50–52
 - practice problems, 91
 - Specific volume, definition, 50
 - Splitters, 270
 - SRK (Soave-Redlich-Kwong) equation, 368
 - Stack gas, 234
 - Standard atmosphere, 70
 - Standard conditions (S.C.), 352–354
 - Standard conditions of temperature, 60
 - Standard heat of combustion, 635, 850–853
 - Standard heat of formation
 - converting from standard heat of combustion, 636

- definition, 598
 - integration with sensible heat, 614–635, 650–651
 - overview, 598–603
 - practice problems, 643–644
 - table of, 850–853
- Standard state, 598
- State of a system
- definition, 349
 - energy balances, 492–493
- State variables, energy balances, 493
- Static columns, 66
- Steady-state
- closed systems, energy balances
 - without reactions, 541–542
 - energy balances, 492
 - open systems, energy balances
 - without reactions, 546–557
 - processes/systems, 108–110
- Steam tables, 427–432
- Stoichiometric coefficients, 192
- Stoichiometric quantity, 192
- Stoichiometric ratios, 192
- Stoichiometry, definition, 190
- Stoichiometry, solving problems with
- balancing a reaction equation for a biological reaction, 193
 - calculating the mass of reactants, 194
 - for multiple reactions, 195–197
 - practice problems, 248–253
 - steps involved, 191–193
- Stream variables for degree-of-freedom analysis, steady-state processes, 685
- Streptomycin extraction, 160–162
- Subcooled liquid, 416
- Sublimation, 416
- Sublimation curve, 416
- Sublimation pressure, 416
- Substrates, 243
- Subsystems, 269–270
- Sugar recovery process, 284–287
- Sulfur compound vapors, enthalpies of, 870
- Sulfuric acid, mixing, 168–171
- Supercritical fluids, 373
- Supercritical region, 416
- Superheated steam properties, 428–429
- Superheated vapor, 416
- Surroundings, energy balances, 492
- Symbols
- extent of reaction, 198
 - general energy balance, 544
 - used in this book, 129
- Systems
- closed, 108
 - definition, 108
 - energy balances, 492
 - open, 108
 - pseudo steady-state, 109
 - quasi steady-state, 109
 - steady-state, 108–110
 - unsteady-state, 110–111
- Systems of units. *See also* AE system
- of units; Conversion; SI system of units.
 - derived dimensions, 13
 - derived units, 13
 - dimensions, 13
 - fundamental dimensions, 13
 - fundamental units, 13
 - practice problems, 82
 - units, 13
- T**
- Temperature
- absolute scale, 60
 - Celsius (°C) scale, 60
 - conversions, 62–64
 - Fahrenheit (°F) scale, 60
 - kelvin (K) scale, 60
 - measuring, 60
 - practice problems, 94–95
 - Rankine (°R) scale, 60
 - relative scale, 60
 - standard conditions of, 60
- Theoretical air (oxygen), 234
- Theoretical flame. *See* Adiabatic reaction.

- Thermodynamic charts, 885–886
- Thin film deposition, 426–427
- ThOD (theoretical oxygen demand), 245
- Tie components, 175
- TOD (total oxygen demand), 245
- Total system volume, 421
- Transient state. *See* Unsteady-state.
- Triple point, 414
- Two component gas/single-component liquid systems. *See also* Multiphase equilibrium.
- condensation, 441–449
 - dew point, calculating, 437–440
 - practice problems, 476–481
 - saturation, 437–440
 - vaporization, 450–454
- Two component gas/two-component liquid systems. *See also* Multiphase equilibrium.
- azeotropes, 459
 - bubble point, calculating, 462–465
 - dew point, calculating, 462–465
 - ideal solution relations, 455–457
 - K-value (vapor-liquid equilibrium ratio), 460–462
 - practice problems, 481–485
 - Raoult's law, 455–457
 - vapor-liquid equilibria phase diagrams, 457–459
- Two-phase regions, 418
- U**
- U (internal energy), 511–513
- Underspecified, 135
- UNIFAC method, 376
- UNIQUAC method, 376
- Unique solution, 147
- Units, 13. *See also* Conversion; Systems of units.
- Universe, definition, 729
- Unknowns, 126–132
- Unsteady-state processes, definition, 110–111
- Unsteady-state processes, energy balances
- example, 814–816
 - modeling a calcination process, 816–817
 - practice problems, 820–826
- Unsteady-state processes, energy balances without reactions
- closed systems, 533–541
 - open systems, 557–566
- Unsteady-state processes, material balances
- in batch distillation, 810–812
 - oscillating reactions, 812–814
 - overview, 800–804
 - practice problems, 820–826
 - without generation, 804–810
- V**
- Vacuum, 68, 72–73
- Validating results, 36–37
- van der Waals' equation, 25, 368
- Vapor, 413
- Vapor pressure, 415, 877
- Vaporization
- at constant temperature, 417–418
 - definition, 416
 - of metals, 426–427
 - two component gas/single-component liquid systems, 450–454
- Vapor-liquid equilibria phase diagrams, 457–459
- Variables for degree-of-freedom analysis, steady-state processes, 684. *See also* Functions.
- Vendors of commercial simulators, 771
- Virial equations, 369
- Volumetric flow rate, 78, 356
- W**
- Water properties, 427–429
- Watson's equation, 523

- Weight *vs.* mass, 22–23
 - Well-mixed system, 317
 - Wet basis, 234
 - Wet-bulb line, 658–659
 - Wet-bulb temperature, 654–655
 - White oil, 466–467
 - Work (*W*)
 - in a batch process, 732–733
 - electrical, 502
 - in energy balances, 501–507
 - during evaporation of a liquid, 730–731
 - flow, 502–503
 - mechanical, 502, 504–505
 - shaft, 502–503
 - Working in chemical/bioengineering, 4–10
- Y**
- Yield, 204–205
- Z**
- z* factor charts. *See* Compressibility charts.

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