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David M. Himmelblau

# Basic Principles and Calculations in Chemical Engineering 6th Edition

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in the Physical and Chemical
Engineering Sciences

SIXTH EDITION

# BASIC PRINCIPLES AND CALCULATIONS IN CHEMICAL ENGINEERING

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*To Betty (one more time)*

# PREFACE

## PURPOSE OF THE BOOK

This book is intended to serve as an introduction to the principles and techniques used in the field of chemical, petroleum, and environmental engineering. Although the range of subjects deemed to be in the province of "chemical engineering" has broadened over the last decade, the basic principles involved in chemical engineering remain the same. This book lays a foundation of certain information and skills that can be repeatedly employed in subsequent courses as well as in professional life.

A good introductory book to chemical engineering principles and calculations should (1) explain the fundamental concepts in not too stilted language together with generous use of appropriate equations and diagrams; (2) provide sufficient examples with detailed solutions to clearly illustrate (1); (3) present ideas in small packages that are easily identified as part of a larger framework; (4) include tests and answers that enable the reader to evaluate his or her accomplishments; and (5) provide the instructor with a wide selection of problems and questions to evaluate student competence. All of these features have been built into the sixth edition.

I kept in mind four major objectives for a reader in preparing this sixth edition:

1. to **develop systematic problem solving skills,** enhance confidence, and generate careful work habits;
2. to **learn what material balances are,** how to formulate and apply them, and how to solve them;
3. to **learn what energy balances are** and how to apply them;
4. to learn how to **deal with the complexity of big problems.**

In addition to accomplishing these goals, a reader is exposed to background information on units and measurements of **physical properties,** basic laws about the **behavior of gas, liquids, and solids,** and some **basic mathematical tools.** Other objectives that an instructor may want to include in a course, such as programming and communication skills, information about professional activities, developing a professional attitude, establishing personal goals, developing social awareness, and so on must be implemented by the instructor from other sources. Economic feasibility, a major factor in engineering decision making, costing, and optimization have been omitted because of lack of space. To provide an appreciation of what processing equipment really looks like and how it works, in the Supplement on the CD disk are numerous pictures of the equipment described in the worked out problems.

If this book is used as part of a scheduled course, the role of the teacher must be something more than just communicating the subject matter. The job of the teacher is to arouse emotional reactions of feeling good in connection with the content being conveyed. Creating positive feelings so that a student enjoys the subject makes a teacher effective.

## SCOPE AND PARTS OF THE BOOK

The central themes of the book involve (1) learning how to formulate and solve (a) material balances, (b) energy balances, and (c) both simultaneously; (2) developing problem solving skills; and (3) becoming familiar with the use of units, physical properties, and the behavior of gases and liquids.

The chapters in sequence and their general contents are

Chapter 1: Background information
Chapter 2: Problem solving skills and tools
Chapter 3: Material balances
Chapter 4: Gases, liquids, and solids
Chapter 5: Energy balances
Chapter 6: Combined material and energy balances in large-scale problems
Chapter 7: Unsteady state material and energy balances

## GENERAL FEATURES OF THE BOOK

I have selected, arranged, and presented the material in this book with care based on past teaching experience. All sections are divided into Objectives, Looking Ahead (a preview), Main Concepts, Additional Details (text containing nonessential information), Looking Back (a summary of the section), Key Ideas, Key Words, Self-Assessment Tests, Thought Problems, and Discussion Questions. Some other features common to all the chapters are:

- The book is **self-contained** except for some homework problems that deliberately require outside information.
- The presentation is **detailed** enough so that reference to other books can be omitted.
- The **examples are simple** and concrete to make the book teachable and useful for self-instruction.
- The chapters are largely **independent,** providing flexibility in teaching.
- The book has been reviewed for **readability.**
- The examples and homework problems support **good learning principles.**
- **Numerous illustrations** enhance learning.
- **Subheadings** clearly distinguish successive topics.
- **Thought problems and discussion problems** have been included for class discussion.
- A **table of contents** is listed **at the beginning of each chapter** to show the contents of the chapter.
- **Vital words and concepts** are in boldfaced type.
- At the end of each chapter **references** and numerous **supplementary references** are included.
- **Solutions** to about one-quarter of the **problems** in the problem sets are in the Appendix.
- **Data and computer codes** for solving problems have been provided in an accompanying CD.

At the beginning of each section is a **list of objectives** to be achieved by the reader, stated in such a way that attainment can be readily measured. We often present our objectives by such broad, fuzzy statements that neither the student nor the teacher can ascertain whether students have achieved them. (Unfortunately, this situation does not seem to inhibit the testing of students.) Each set of objectives is quite concrete and has a corresponding set of self-assessment questions and problems at the end of the respective section.

Piaget has argued that human intelligence proceeds in stages from the concrete to the abstract and that one of the big problems in teaching is that the teachers are formal reasoners (using abstraction) while many students are still concrete

thinkers or at best in transition to formal operational thinking. I believe that this is true. Consequently, most topics are initiated with simple illustrations that illustrate the basic ideas. In this book the **topics are presented in order of easy assimilation** rather than in a strictly logical order. The organization is such that easy material is alternated with difficult material in order to give a "breather" after passing over each hump. For example, discussion of unsteady-state balances has been deferred until the final chapter because experience has shown that most students lack the mathematical and engineering maturity to absorb these problems simultaneously with the steady-state balances.

A principle of educational psychology is to reinforce the learning experience by providing detailed guided practice following each new principle. We all have found from experience that there is a vast difference between understanding a principle and in establishing our ability to apply it. For example, can you learn how to play piano from a series of lectures? By the use of numerous detailed **examples** following each brief section of text, it is hoped that straightforward, orderly methods of procedure can be instilled along with some insight into the principles involved. Furthermore, the wide variety of **problems** at the end of each chapter, about one-fourth of which are accompanied by **answers,** offer practice in the application of the principles explained in the chapter.

After all these years a perplexing problem still remains for an author in preparing a new edition, namely, the extent to which SI units should be used. I believe that SI is an important system of measurement that chemical engineers must be able to deal with, but also feel that chemical engineering students in the United States must be familiar with a variety of systems for some years to come. As a compromise, a little more than one-half of the text, examples, and problems and most of the tables employ SI units. For convenience, some of the crucial tables, such as the steam tables, are presented in both American Engineering and SI units.

**Self-assessment tests** have been included to provide readers with questions and answers that assist them in appraising and developing their knowledge about a particular topic. Self-assessment is intended to be an educational experience for a student. The availability of answers to the self-assessment questions together with supplementary reading citations for further study is an inherent characteristic of self assessment. To help the reader think about the concepts and decide whether to study further is one reason for having appraisal questions.

Let me now mention some of the new features of the sixth edition, features that were not present in earlier editions.

## NEW FEATURES IN THE BOOK

For the sixth edition I have added a number of new features (and deleted some old ones) that make both teaching and self-study easier.

In this edition special attention has been devoted to presenting a consistent **sound strategy for solving material balance and energy balance** problems, one that can be used again and again as a framework for solving word problems. All the examples showing how to solve material and energy balances have been reformulated according to this strategy (see Table 3.1). In teaching I ask students to learn the strategy and apply it in all their homework problems and exams. I discourage the use of self-devised heuristic algorithms, or "cookbook" methods, pointing out that they may be successful for one class of problems but fail quite dismally for others. By this means a student is guided into forming generalized patterns of attack in problem solving that can be used successfully in connection with unfamiliar types of problems. The text is designed to acquaint the student with a sufficient number of fundamental concepts so that he or she can (1) continue with his or her training, and (2) start finding solutions to new types of problems on his or her own. It offers practice in finding out what the problem is, defining it, collecting data, analyzing and breaking down information, assembling the basic ideas into patterns, and, in effect, doing everything but testing the solution experimentally.

A major problem in any book is to what extent and in what manner should problems involving the use of computer codes be introduced into the text. If the use of the computer is to be integrated into the classroom successfully, it is wise to start early in the game. The selection of appropriate problems and the illustration of good computer habits, pointing out instances in which computer solutions are not appropriate or efficient as well as instances when they are, are important. What I have observed is a shift in paradigm from teaching programming skills to teaching the use of specialized software (such as Polymath or Matlab) to solve problems. Consequently, no reference to programming is made in the book, but Section 2.1 explains briefly how to use current software packages. Some Fortran programs that solve linear and nonlinear equations, retrieve the properties of water and steam, and of air-water mixtures, calculate the vapor pressures of pure substances, and calculate enthalpy changes from heat capacity equations, can be found on the **CD containing codes in a pocket in the back of the book.** As a result, the portions of the book formerly treating graphical integration, trial and error solutions, lever arm principles, and graphical solution methods have been drastically reduced or entirely eliminated.

Other new features are:

1. **Discussion questions added** at the end of each section. These are open-ended problems requiring collection of information not in the book, and can be used for class discussion, required or optional written reports, group assignments, and so forth.
2. **A section on problem solving has been added** (in Chapter 2). Several techniques of solving open-ended problems are discussed.

3. A section (Section 2.2) has been organized to treat **methods of solving problem with the help of computer software.**
4. **Chapter 5** on energy balances **has been completely revised, reduced in length, and simplified.**
5. **The problems** at the end of each section **have been augmented** to include features of safety, semiconductor processing, and biotechnology.
6. **The chapter on material balances, Chapter 3, has been completely revised** to provide a consistent algebraic approach to the formulation of problems that is carried out in all subsequent chapters.
7. **A summary of key concepts** has been added to the end of each section.
8. **Lists of key words and the page numbers where first introduced** have been added to the end of each section.

To provide high-quality software to aid readers in solving problems, in addition to the specialized codes that accompanied the fifth edition, in this sixth edition you will find on the CD in the back of the book two new significant additions:

1. Polymath, self-documented widely used software that runs on PCs, can solve linear and nonlinear equations and regression problems, and carry out matrix operations.
2. A database supplied by Professor Yaws of Lamar University, Beaumont, Texas that contains retrievable physical properties (such as vapor pressures, and heat capacities and enthalpies) for 700 compounds.

With these tools, execution of the solution phase of any problem becomes easily managed.

## SUGGESTIONS TO THE READER AS TO HOW TO USE THIS BOOK

How should you study using this book? Read the objectives before and after studying each section. Read the text, and when you get to an example, cover up the solution and try to solve the stated problem. Some people, those who learn by reading concrete examples, should look at the examples first, and then read the text. Memorization is minimal in achieving the stated objectives, but practice in problem solving is essential, hence, after reading a section, solve some of the problems at the end of the chapter listed under that section number. 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 the systematic and general steps listed in Table 3.1. 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 to practice solving problems. Finally, when you are confident that you have achieved the stated objectives for a section, complete the self-assessment test at the end of the section (the answers are in the Appendix).

## SUGGESTIONS FOR A COURSE

This book can be used in a variety of learning environments besides the traditional lectures, such as self-paced instruction, group study or discussion groups, and individual study. More topics have been included in the text than can be covered in one semester, so that an instructor has some choice as to pace of instruction and topics to include. In a lecture course for students with a background of having completed only freshman courses, Chapters 1, 3, 4, and 5 form the basis of an ample course. For more experienced students, if computer flow sheeting programs are available, perhaps Chapter 1 can be skimmed and Chapters 2 and 6 included. Chapter 7 will probably take at least one week (and probably two weeks) if you want to include it as well.

## ACKNOWLEDGMENTS

I am indebted to many of my former teachers, colleagues, and students who directly or indirectly helped me in preparing this book, and in particular the present edition of it. Special thanks go to Kim Mathews and Carrie Anderson for preparing a number of new homework problems and putting the manuscript in its final form. Professor Donald Woods was most helpful in providing information about sound techniques of problem solving. I also want to thank Professor C. L. Yaws for his kindness in making available the physical properties database that is on the CD in the back of this 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 for me to list them all by name. However, I do wish to express my appreciation for their kind assistance. Any further comments and suggestions for improvement of the book would be gratefully received.

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# CONTENTS

# INTRODUCTION TO CHEMICAL ENGINEERING CALCULATIONS

1



What do chemical engineers do? Although their backgrounds and professional skills are similar, chemical engineers work in a wide variety of industries, in addition to chemicals and petroleum, such as:

| | |
|---|---|
| Biotechnology | Lime and cement |
| Consulting | Man-made fibers |
| Drugs and pharmaceuticals | Metallurgical and metal products |
| Fats and oils | Paints, varnishes, and pigments |
| Fertilizer and agricultural chemicals | Pesticides and herbicides |
| Foods and beverages | Plastic materials and synthetic resins |
| Government | Solid state materials |

Chemical engineers focus on design, operation, control, troubleshooting, research, management, and even politics—the latter because of environmental and economic concerns. This book is not an introduction to chemical engineering as a profession. Instead, it is an introduction to the types of calculations made by chemical engineers in their everyday work. For you to learn how to appreciate and treat the problems that will arise in modern technology, and especially in the technology of the future, it is necessary to learn certain basic principles and practice their application. This text describes how to make material and energy balances, and illustrates their application in a wide variety of ways.

We begin the book by reviewing in Chapter 1 certain background informa-

tion. You have already encountered most of these concepts in your basic chemistry and physics courses. Why, then, the need for a review? First, from experience we have found it necessary to restate these familiar basic concepts in a somewhat more precise and clearer fashion; second, you will need practice to develop your ability to analyze and work engineering problems. If, because of an incomplete background, when encountering new material, instead of focusing on it, you flounder over little gaps in your skills or knowledge, you will find the path rough going. To read and understand the principles discussed in this chapter is relatively easy; to apply them to different unfamiliar situations is not. An engineer becomes competent in his or her profession by mastering the techniques developed by ones predecessors—thereafter comes the time to pioneer new ones.

The chapter begins with a discussion of units, dimensions, and conversion factors, and then goes on to review some terms you should already by acquainted with, including:

**(1)** Mole and mole fraction
**(2)** Density and specific gravity
**(3)** Measures of concentration
**(4)** Temperature
**(5)** Pressure

Finally, we review the principles of stoichiometry.

## 1.1 UNITS AND DIMENSIONS

***Your objectives in studying this section are to be able to:***

1. Add, subtract, multiply, and divide units associated with numbers.
2. Specify the basic and derived units in the SI and American Engineering systems for mass, length, volume, density, and time, and their equivalences.
3. Convert one set of units in a function or equation into another equivalent set for mass, length, area, volume, time, energy, and force.