David M. Himmelblau / James B. Riggs

Basic Principles and Calculations in Chemical Engineering

Seventh Edition

Prentice Hall International Series
in the Physical and Chemical
Engineering Sciences

SEVENTH EDITION

BASIC PRINCIPLES AND CALCULATIONS IN CHEMICAL ENGINEERING

David M. Himmelblau
University of Texas

James B. Riggs
Texas Tech University

PRENTICE HALL
Professional Technical Reference
Upper Saddle River, New Jersey 07458
www.phptr.com

Library of Congress Cataloging-in-Publication Data

Himmelblau, David Mautner
Basic principles and calculations in chemical engineering.-— 7th ed. /
David M. Himmelblau and James B. Riggs.
p. cm.
ISBN 0-13-140634-5
1. Chemical engineering--Tables. I. Riggs, James B. II. Title.
TP151 .H5 2004
660'.2--dc22

2003016672

Publisher: Bernard Goodwin
Editorial/production supervision: Patty Donovan (Pine Tree Composition, Inc.)
Cover design director: Jerry Votta
Art director: Gail Cocker-Bogusz
Manufacturing manager: Maura Zaldivar
Marketing manager: Dan DePasquale
Editorial assistant: Michelle Vincenti
Full-service production manager: Anne R. Garcia

Publishing as Prentice Hall Professional Technical Reference
Upper Saddle River, NJ 07458

The publisher offers excellent discounts on this book when ordered in quantity for bulk purchases or special sales.
For more information, please contact:

U.S. Corporate and Government Sales
1–800–382–3419
corpsales@pearsontechgroup.com

For sales outside of the U.S., please contact:

International Sales
1–317–581–3793
international@pearsontechgroup.com

Printed in the United States of America
Second printing

ISBN: 0-13-140634-5

Pearson Education Ltd., London
Pearson Education Australia Pty, Limited, Sydney
Pearson Education Singapore, Pte. Ltd.
Pearson Education North Asia Ltd., Hong Kong
Pearson Education Canada, Ltd., Toronto
Pearson Educación de Mexico, S.A. de C.V.
Pearson Education–Japan, Tokyo
Pearson Education Malaysia, Pte. Ltd.

CONVERSION FACTORS

Instructions: To convert a given set of units to a desired set, such as $in.^3$ to m^3, proceed as follows. Locate the given set of units in the row in the left hand column of a table. Locate the desired set of units in the column heading in the top row of the table. You thus identify a box that has the desired ratio of units. To carry out the conversion, multiply the given set of units by the number in the box. For example, $(14.3\ in.^3)\ (1.639 \times 10^{-5}\ m^3/1\ in.^3) = 2.34 \times 10^{-4}\ m^3$.

VOLUME EQUIVALENTS

	$in.^3$	ft^3	U.S. gal	liters	m^3
$in.^3$	1	5.787×10^{-4}	4.329×10^{-3}	1.639×10^{-2}	1.639×10^{-5}
ft^3	1.728×10^{3}	1	7.481	28.32	2.832×10^{-2}
U.S. gal	2.31×10^{2}	0.1337	1	3.785	3.785×10^{-3}
liters	61.03	3.531×10^{-2}	0.2642	1	1.000×10^{-3}
m^3	6.102×10^{4}	35.31	264.2	1000	1

MASS EQUIVALENTS

	avoir oz	pounds	grains	grams
avoir oz	1	6.25×10^{-2}	4.375×10^{2}	28.35
pounds	16	1	7×10^{3}	4.536×10^{2}
grains	2.286×10^{-3}	1.429×10^{-4}	1	6.48×10^{-2}
grams	3.527×10^{-2}	2.20×10^{-3}	15.432	1

LINEAR MEASURE EQUIVALENTS

	meter	inch	foot	mile
meter	1	39.37	3.2808	6.214×10^{-4}
inch	2.54×10^{-2}	1	8.333×10^{-2}	1.58×10^{-5}
foot	0.3048	12	1	1.8939×10^{-4}
mile	1.61×10^{3}	6.336×10^{4}	5280	1

POWER EQUIVALENTS

	hp	kW	$(ft)(lb_f)/s$	Btu/s	J/s
hp	1	0.7457	550	0.7068	7.457×10^{2}
kW	1.341	1	737.56	0.9478	1.000×10^{3}
$(ft)(lb_f)/s$	1.818×10^{-3}	1.356×10^{-3}	1	1.285×10^{-3}	1.356
Btu/s	1.415	1.055	778.16	1	1.055×10^{3}
J/s	1.341×10^{-3}	1.000×10^{-3}	0.7376	9.478×10^{-4}	1

Heat, Energy, or Work Equivalents

	$(ft)(lb_f)$	kWh	(hp)(hr)	Btu	calorie*	joule
$(ft)(lb_f)$	1	3.766×10^{-7}	5.0505×10^{-7}	1.285×10^{-3}	0.3241	1.356
kWh	2.655×10^{6}	1	1.341	3.4128×10^{3}	8.6057×10^{5}	3.6×10^{6}
(hp)(hr)	1.98×10^{6}	0.7455	1	2.545×10^{3}	6.4162×10^{5}	2.6845×10^{6}
Btu	7.7816×10^{2}	2.930×10^{-4}	3.930×10^{-4}	1	2.52×10^{2}	1.055×10^{3}
calorie*	3.086	1.162×10^{-6}	1.558×10^{-6}	3.97×10^{-3}	1	4.184
joule	0.7376	2.773×10^{-7}	3.725×10^{-7}	9.484×10^{-4}	0.2390	1

*The thermochemical calorie = 4.184 J.

Pressure Equivalents

	mm Hg	in. Hg	bar	atm	kPa	psia
mm Hg	1	3.937×10^{-2}	1.333×10^{-3}	1.316×10^{-3}	0.1333	1.934×10^{-2}
in. Hg	25.40	1	3.386×10^{1}	3.342×10^{-2}	3.386	0.4912
bar	750.06	29.53	1	0.9869	100.0	14.51
atm	760.0	29.92	1.013	1	101.3	14.696
kPa	7.502	0.2954	1.000×10^{-2}	9.872×10^{-3}	1	0.1451
psia	51.71	2.036	6.893×10^{-2}	6.805×10^{-2}	6.893	1

Ideal Gas Constant R

1.987 cal/(g mol)(K)
1.987 Btu/(lb mol)(°R)
10.73 (psia)(ft^3)/(lb mol)(°R)
8.314 (kPa)(m^3)/(kg mol)(K) = 8.314 J/(g mol)(K)
82.06 (cm^3)(atm)/(g mol)(K)
0.08206 (L)(atm)/(g mol)(K)
21.9 (in Hg)(ft^3)/(lb mol)(°R)
0.7302 (ft^3)(atm)/(lb mol)(°R)

Miscellaneous Conversion Factors

To convert from	To	Multiply by
angstrom	meter	1.000×10^{-10}
barrel (petroleum)	gal	42
centipoise	(newton)(s)/m^2	1.000×10^{-3}
torr (mm Hg, 0°C)	newton/$meter^2$	1.333×10^{2}
fluid oz	cm^3	29.57

BASIC PRINCIPLES AND CALCULATIONS IN CHEMICAL ENGINEERING

PRENTICE HALL PTR INTERNATIONAL SERIES
IN THE PHYSICAL AND CHEMICAL ENGINEERING SCIENCES

NEAL R. AMUNDSON, SERIES EDITOR, *University of Houston*

ADVISORY EDITORS

ANDREAS ACRIVOS, *Stanford University*
JOHN DAHLER, *University of Minnesota*
H. SCOTT FOGLER, *University of Michigan*
THOMAS J. HANRATTY, *University of Illinois*
JOHN M. PRAUSNITZ, *University of California*
L. E. SCRIVEN, *University of Minnesota*

BALZHISER, SAMUELS, AND ELIASSEN *Chemical Engineering Thermodynamics*
BEQUETTE *Process Control: Modeling, Design, and Simulation*
BEQUETTE *Process Dynamics*
BIEGLER, GROSSMAN, AND WESTERBERG *Systematic Methods of Chemical Process Design*
BROSILOW AND JOSEPH *Techniques of Model-based Control*
CROWL AND LOUVAR *Chemical Process Safety: Fundamentals with Applications, 2nd edition*
CONSTANTINIDES AND MOSTOUFI *Numerical Methods for Chemical Engineers with MATLAB Applications*
CUTLIP AND SHACHAM *Problem Solving in Chemical Engineering with Numerical Methods*
DENN *Process Fluid Mechanics*
ELLIOT AND LIRA *Introductory Chemical Engineering Thermodynamics*
FOGLER *Elements of Chemical Reaction Engineering, 3rd edition*
HIMMELBLAU AND RIGGS *Basic Principles and Calculations in Chemical Engineering, 7th edition*
HINES AND MADDOX *Mass Transfer*
KYLE *Chemical and Process Thermodynamics, 3rd edition*
PRAUSNITZ, LICHTENTHALER, AND DE AZEVEDO *Molecular Thermodynamics of Fluid-Phase Equilibria, 3rd edition*
PRENTICE *Electrochemical Engineering Principles*
SHULER AND KARGI *Bioprocess Engineering, 2nd edition*
STEPHANOPOULOS *Chemical Process Control*
TESTER AND MODELL *Thermodynamics and Its Applications, 3rd edition*
TURTON, BAILIE, WHITING, AND SHAEIWITZ *Analysis, Synthesis, and Design of Chemical Processes, 2nd edition*
WILKES *Fluid Mechanics for Chemical Engineering*

To Betty for the 7th time

DMH

To Brenda, Michelle, J. Michael, and Matt

JBR

About Prentice Hall Professional Technical Reference

With origins reaching back to the industry's first computer science publishing program in the 1960s, and formally launched as its own imprint in 1986, Prentice Hall Professional Technical Reference (PH PTR) has developed into the leading provider of technical books in the world today. Our editors now publish over 200 books annually, authored by leaders in the fields of computing, engineering, and business.

Our roots are firmly planted in the soil that gave rise to the technical revolution. Our bookshelf contains many of the industry's computing and engineering classics: Kernighan and Ritchie's *C Programming Language*, Nemeth's *UNIX System Adminstration Handbook*, Horstmann's *Core Java*, and Johnson's *High-Speed Digital Design*.

PH PTR acknowledges its auspicious beginnings while it looks to the future for inspiration. We continue to evolve and break new ground in publishing by providing today's professionals with tomorrow's solutions.

PREFACE

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.

Our Motivation for Writing This Book

Far too many chemical engineering textbooks have become difficult, dry, and demoralizing for their readers. With this book, we have maintained a conversational style and detailed explanation of principles both in the text and examples to provide a readable yet comprehensive text. We have strived to maintain a suitable balance between understanding and developing skills. Our vision is to avoid comments (from a student about a different text) such as: "My text is useless, well not really, I use it to kill roaches in my room."

Piaget has argued that human intelligence proceeds in stages from the concrete to the abstract and that one of the biggest 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. We believe that there is considerable truth in this viewpoint. Consequently, we initiate most topics with simple examples that illustrate the basic ideas. In this book the topics are presented

in order of assimilation. We start with easy material followed by more difficult material to give readers a "breather" before passing over each hump.

Assumed Prerequisites

The level of the book is directed to the first course in chemical engineering, which usually occurs in a student's sophomore year. We have assumed that you as a reader to have completed the second part of calculus and started organic chemistry. Familiarity with hand-held calculators is essential, but computer programming is not. Familiarity with PC software would be helpful, but is not critical.

Intended Audience

We believe that the main category of individuals who will use this book will be students of chemical engineering. However, the book is well designed for courses for nonchemical engineers as well as independent study, long-distance learning, and review for licensing examinations through its self-assessment features.

Our Objectives

This book is not an introduction to chemical engineering as a profession. We have focused instead on five general objectives in writing this book:

1. To introduce you to the principles and calculation techniques used in chemical engineering.
2. To acquaint you with what material and energy balances are, and how to formulate and solve them.
3. To assist you in learning efficient and consistent methods of problem solving so that you can effectively solve problems you will encounter after leaving school.
4. To offer practice in defining problems, collecting data, analyzing the data and breaking it down into basic patterns, and selecting pertinent information for application.
5. To review certain principles of applied physical chemistry.

In addition to focusing on the five above objectives, we expose you to background information on units and measurements of physical properties; basic laws about the behavior of gases, liquids, and solids; and some basic mathematical tools. Other ob-

jectives 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 from other sources. Economic feasibility, a major factor in engineering decision making, costing, and optimization, have been omitted because of lack of space.

We have not focused on using process simulation software to analyze and solve problems even though it is very good in exploring and handling "what if" questions as well as removing some of the drudgery in solving problems because

1. the pedagogy is too closely aligned to cookbook-style problem solving;
2. learning how to use the software with ease takes some time; and
3. development of a problem-solving strategy is taken out of the hands of the user by the software programmers. The software provides too much guidance for neophytes.

Organization and Scope of this Book

The major portion of the book comprises four parts:

Part 1. Background information (Chapters 1–5)
Part 2. Material balances (Chapters 6–12)
Part 3. Behavior of gases, liquids, and solids (Chapters 13–20)
Part 4. Energy balances (Chapters 21–29)

In addition, on the accompanying CD, Chapter 30 treats the degrees of freedom, Chapter 31 process simulators, and Chapter 32 unsteady state material and energy balances.

A series of appendices follow that include, in addition to tables and charts of physical properties, miscellaneous information you will find useful. Look at the Table of Contents for details.

In the CD that accompanies this book you will find several valuable tools:

1. Polymath: Software that solves equations, and can be used without reading any instructions.
2. Software to retrieve physical property data for over 740 compounds.
3. A Supplementary Problems Workbook containing 100 problems with complete detailed solutions, and another 100 problems with answers.
4. Descriptions of process equipment, and animations that illustrate the functions of the equipment.

5. Problem-solving suggestions including check lists to help you diagnose and overcome problem-solving difficulties you may experience.

To provide an appreciation of what processing equipment really looks like and how it works, in the files on the CD disk in the worked-out problems are numerous pictures of the equipment along with an explanation of their function and operation.

Problem Sets

We have included several categories of problems in the books to assist in self-study.

1. Self-assessment tests with answers (in Appendix A) follow each section.
2. Thought and discussion problems follow the self-assessment tests. Thought problems require reflection more than calculation. Discussion problems, which can be used as the basis of research, papers, and class discussions, pertain to broader issues and are more open ended.
3. Homework-type problems are listed at the end of each chapter, one-third of which have answers (in Appendix N). Each of the problems is rated 1 to 3 (using asterisks) to indicate the degree of difficulty, with 3 being the most difficult.
4. The CD contains more than 100 worked-out examples and another 100 problems with answers keyed to sections in the chapters in the text.

All of the examples and problems are designed to build your problem-solving skills.

Miscellaneous Useful Features in this Book

To make the book more usable and friendly, we have incorporated a number of beneficial features:

1. A list of contents at the beginning of each chapter.
2. A list of instructional objectives at the beginning of each chapter.
3. Important terms appear in **boldface** type.
4. A glossary has been placed at the end of each chapter.
5. Supplementary references that you can use to get additional information are listed at the end of each chapter.
6. Web sites containing information and links are listed at the end of each chapter.

7. The examples are simple and concrete so that the book is both teachable and useful for self instruction.
8. The chapter topics are independent but linked through a few principles.
9. The examples demonstrate a proven problem-solving strategy.

New Features in the Seventh Edition

The seventh edition is a completely rewritten and revised version of *Basic Principles and Calculations in Chemical Engineering*. Instead of five long chapters, the book is now comprised of 32 short chapters, each typically corresponding to one class session in a schedule of three meetings a week. New features include:

1. A consistent, sound strategy for solving material balance and energy balance problems, one can be used again and again as a framework for solving word problems, which is explained in Chapter 7. All of the examples in this book showing how to solve material and energy balances have been formulated according to this strategy.
2. The examples and problems in each chapter have been augmented to include expanded areas of importance to chemical engineers such as safety, semiconductor processing, and biotechnology.
3. The chapters on material balances have been revised to offer practice in finding out what the problem is, defining it, collecting data to be used in the problem, analyzing the information pertaining to the problem in order to relate it to what you know about similar problems, and, in effect, doing everything but testing the solution experimentally.
4. The extent of reaction has been added to the tools used to solve problems involving chemical reactions.
5. The degree of freedom analysis in solving problems has been emphasized and simplified.
6. A glossary has been added to each chapter.

On the CD that accompanies this book is

7. A new version of Polymath, a self-documented, widely used software package that runs on PCs and can solve linear, nonlinear, and differential equations as well as regression problems.
8. A new physical properties database that contains retrievable physical properties (such as vapor pressures and heat capacities and enthalpies for 740 compounds plus the steam tables).

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. Special thanks go to Chris Bailor for getting the manuscript to its final form, and to H. R. Heichelheim and Dale Slaback for their reviews of the manuscript. We also want to thank Professor C. L. Yaws for his kindness in making available the physical properties database that is the basis of the physical properties packages in 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 to list them by name. However, we do wish to express our appreciation for their kind assistance. Any further comments and suggestions for improvement of the book would be appreciated.

David M. Himmelblau
Austin, Texas

James B. Riggs
Lubbock, Texas

READ ME

Welcome to our book *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. **Don't neglect to use them.**

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 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 provided in Appendix N for about a third of them.
7. Thought and discussion problems that involve more reflection and consideration than the problem sets cited in #6 above.
8. An appendix 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 does not require any training to use.
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 check lists to diagnose and overcome problem-solving difficulties that you experience.

12. In the pocket in the back of the book is a set of steam tables (properties of water) both in SI and American Engineering units.

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 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.