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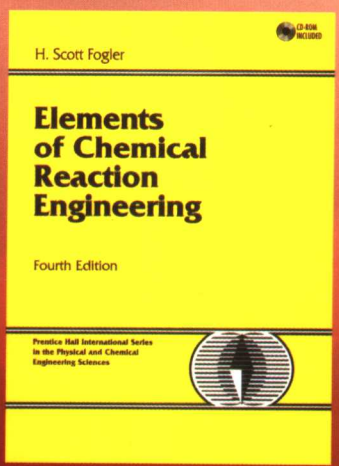
Elements of Chemical Reaction Engineering

Fourth Edition

化学反应工程原理

第四版（英文影印版）

[美] H.斯科特·福格勒 著
(H.Scott Fogler)



化学工业出版社

Pearson Education

附光盘

国外著名教材

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推荐序（一）

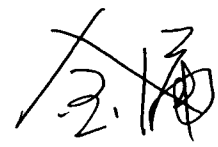
化学工程教育中化学反应工程知识的传授占有核心地位。首先是由于化学反应工程学在工程实践中发挥着重要作用，反应器设计的优劣决定着工程建设的成败；其次，化学反应工程学融会贯通了“物质传递与转化”、“能量传递与转化”、“信息集成与优化”等基础知识，用于考察、解释和解决工程中的实际问题。因此，无论是挑战自己的认知能力还是增强实践技能，化学反应工程都值得学生精心钻研，这时一本好的教科书，将起着事半功倍的作用。

本书是美国密歇根大学 Fogler 教授的知名著作，据统计全球 95 所大学中有 41% 的学校选作教材（Mazen Shalabi, et al. Current Trends in Chemical Reaction Engineering Education. Chemical Engineering Education, 1996, 30 (2): 146)。全书从基本概念、基础理论入手，由浅入深逐步展开，解释了化学反应工程学的主要内涵，应用理论推演、结合工程实践导出问题的解析规律和数学模拟过程，对提高学生分析问题和解决问题的能力有很大帮助。

本书共分 14 章：第 1 章摩尔平衡；第 2 章转化率和反应器尺寸；第 3 章速率方程和化学计量学；第 4 章等温反应器设计；第 5 章反应速率数据收集和分析；第 6 章复合反应；第 7 章反应机制、途径、生化反应与生化反应器；第 8 章稳态非等温反应器设计；第 9 章非稳态非等温反应器设计；第 10 章催化和催化反应器；第 11 章外扩散对非均相反应过程的影响；第 12 章扩散与反应；第 13 章化学反应器中的停留时间分布；第 14 章非理想反应器模型。本书文字精炼、逻辑清晰，通过各种工业应用举例开拓了学生的视野；具有大量推理证明、因果判断、设计求解等不同类型且难度渐进的习题，有助于锻炼学生的创造性思维能力。

本书第四版在保持原有知识框架的基础上不断丰富与深化，特别是生化反应器、反应器模型等方面有显著加强，所提供的光盘给出了从大量分子模拟、反应扩散方程、偏微分方程求解反应工程实际问题的程序，便于增强学生动手演练的能力。这些都体现了世界反应工程发展的前沿，会成为全国高校本科生与研究生的重要教学读本，并可作为相关专业人士的重要参考书。

中国工程院院士、清华大学化学工程系教授



2006 年 7 月

推荐序（二）

应化学工业出版社之约，为即将影印出版的 H. Scott Fogler 教授所著《Elements of Chemical Reaction Engineering》（第四版）写几句话，希望能对选购或选用此书的读者有所帮助。

Fogler 教授的这本教材是值得你用心去读的书。读后便会发现，作者为之倾注的心血融会在文字间。好书皆产自于优秀的作者，这可以用生物遗传学原理加以解释。执教于密歇根大学（the University of Michigan）42 年的 Fogler 教授倡导用评判的眼光去发现问题，用创造性的思维去解决问题。2006 年 7 月，Fogler 教授在密歇根大学的同事，Phillip E. Savage 教授到天津大学讲学，与之交谈后了解到，Fogler 教授依然活跃在课堂上，讲授研究生的化学反应工程课程。反映 Fogler 教授教学理念和教学水平的著作是根据他的研究生讲座内容编写的《Strategies for Creative Problem Solving》一书，中译本名为《创造性问题求解的策略》，该书荣获 1996 年美国工程教育学会（American Society for Engineering Education，ASEE）授予的梅里安-威利（Meriam-Wiley）杰出作者奖。此外，Fogler 教授还在 1971 年至今的三十余年里先后获得近三十项教学奖励，1984 年和 2003 年分别荣获维尼玛（Ame and Catherine Vennema）和舒劳（Arthur F. Thurnau）教授称号。

化学反应工程学科分支的创立迄今恰好半个世纪，始创于 1986 年的《Elements of Chemical Reaction Engineering》教材也已历经了整整 20 年。目前，在美国有四分之三的化学工程专业培养计划中使用了此教材；而在世界范围内，其使用量同样处于主导地位。国内在 20 世纪 80 年代初，有了自己编写的系统讲述化学反应工程的教材，从此诞生了本土化的教科书和规范化的中文专业术语，不能不说是可喜可贺的进步。近年来，随着中国高等教育的国际化，迫切需要我们直接掌握源自国外的知识内容和教学方法，反应工程这门课也不例外。2001 年教育部在其下发的《关于加强高等学校本科教学工作提高教学质量的若干意见》中明确提出，要积极推动使用英语等外语进行教学。化学工业出版社积极配合国内的教学要求，及时出版两本英文化学反应工程原版教材，为广大读者做了件好事。

《Elements of Chemical Reaction Engineering》（第四版）在内容的含量、组织编排、讲授方式以及计算机应用等方面与众不同，突出表现在以下三点。

1. 注重传授知识的方法

作者特别强调，要让读者通过理解而非机械地记忆掌握反应工程的基础理论。书中将涵盖的内容形象地描绘成有六根支柱的殿堂，系统、全面地揭示了各部分的关系，从而构建起完整的化学反应工程概念。

书中鼓励读者开发评判式的学习（critical thinking）和创造性的思维（creative thinking）技巧，摒弃盲目地接受和一味地继承。书中大量的习题、附录中开放式的问题（open-ended problems）以及附赠光盘中的相关内容（problem solving）有助于

这方面能力的提高。

2. 注重信息量和知识更新

本书及配套光盘适用于本科生和研究生的教学。对于不同层次人才的培养，可选择不同的章节。光盘中提供了三种课程的授课内容，以供教师参考。

书中广泛的内容、丰富的文字、精美的图表和看似随意的编排，处处体现了作者的匠心。内容涉及化学计量关系和反应动力学、理想和非理想反应器、反应器中的停留时间分布、等温和变温操作的反应器、定态和非定态操作的反应器以及催化和非催化过程分析等。为了便于读者有选择地阅读，作者提供了学习顺序和学习方案，清晰地列出了14个章节的关系及研究生和本科生课程的授课内容。此外，每页的左侧均留有提示栏，注释出关键性的问题或相关知识或补充说明。光盘中除配有文字内容之外，还有图片、录音和影像等媒体资料。章节则采用了利于拓展内容的编撰方式，成为本书的独特之处。

第四版还在原书和光盘的基础上丰富了内容。增加了例题和习题的数量，便于读者掌握基本概念和萌生创造性的思维；补充了生物反应工程的内容，包括酶催化动力学、细胞生长及组织工程等；增加了微反应器、膜反应器等学术成果；加深了对碰撞理论、过渡态理论、分子动态学及分子化学反应工程理论的讲授。此外，还介绍了许多工程案例及相关的软件计算方法。

3. 提供了现代化的教学手段

本书的一个引人注目的特点是配有内容丰富的光盘和网络课程。实际上，二者的差别在于计算软件的使用及光盘内容在网上的升级。

光盘作为书的独立组成部分，起到凝练书中信息、提供补充资料的双重作用。光盘主要内容包括：以要点总结（summary notes）、网络模块（web modules）、互动模块（interactive computer modules）和问题解答（solved problems）构成的学习资源（learning resources）；以运用附赠的 Polymath 软件求解常微分方程，进而获得以技能训练为目标的生动实例（living example problem）；由实际反应器的媒体资料、典型反应器的设计过程以及书中简化步骤的详细推导等组成的专业参考资料（professional reference shelf）；含附赠软件 Polymath 及介绍商业软件 Aspen Plus 和 Reactor Lab 等在化学反应工程中应用的软件工具箱（software toolbox）。书中对光盘的内容以及书与光盘针对在校学生和工程技术人员建议采用的使用方法做了详细的说明。

书中的附录部分还提供了可获取反应速率数据的网址。

《Elements of Chemical Reaction Engineering》（第四版）不仅是一本教科书，而且是使从事化学反应工程领域研究和工程实践的技术人员颇有收益的参考书。

天津大学化工学院教授

辛峰

2006 年 8 月

Preface

> The man who has ceased to learn ought not to be allowed to wander around loose in these dangerous days.
>
> M. M. Coady

A. The Audience

This book and interactive CD-ROM is intended for use as both an undergraduate-level and a graduate-level text in chemical reaction engineering. The level will depend on the choice of chapters and CD-ROM *Professional Reference Shelf* (PRS) material to be covered and the type and degree of difficulty of problems assigned.

B. The Goals

B.1. To Develop a Fundamental Understanding of Reaction Engineering

The first goal of this book is to enable the reader to develop a clear understanding of the fundamentals of chemical reaction engineering (CRE). This goal will be achieved by presenting a structure that allows the reader to solve reaction engineering problems **through reasoning** rather than through memorization and recall of numerous equations and the restrictions and conditions under which each equation applies. The algorithms presented in the text for reactor design provide this framework, and the homework problems will give practice at using the algorithms. The conventional home problems at the end of each chapter are designed to reinforce the principles in the chapter. These problems are about equally divided between those that can be solved with a

calculator and those that require a personal computer and a numerical software package such as Polymath, MATLAB, or COMSOL.

To give a reference point as to the level of understanding of CRE required in the profession, a number of reaction engineering problems from the California Board of Registration for Civil and Professional Engineers—Chemical Engineering Examinations (PECEE) are included in the text.[1] Typically, these problems should each require approximately 30 minutes to solve.

Finally, the CD-ROM should greatly facilitate learning the fundamentals of CRE because it includes summary notes of the chapters, added examples, expanded derivations, and self tests. A complete description of these *learning resources* is given in the "The Integration of the Text and the CD-ROM" section in this Preface.

B.2. To Develop Critical Thinking Skills

A second goal is to enhance critical thinking skills. A number of home problems have been included that are designed for this purpose. Socratic questioning is at the heart of critical thinking, and a number of homework problems draw from R. W. Paul's six types of Socratic questions[2] shown in Table P-1.

TABLE P-1. SIX TYPES OF SOCRATIC QUESTIONS

(1) *Questions for clarification:* Why do you say that? How does this relate to our discussion?
"Are you going to include diffusion in your mole balance equations?"
(2) *Questions that probe assumptions:* What could we assume instead? How can you verify or disprove that assumption?
"Why are you neglecting radial diffusion and including only axial diffusion?"
(3) *Questions that probe reasons and evidence:* What would be an example?
"Do you think that diffusion is responsible for the lower conversion?"
(4) *Questions about viewpoints and perspectives:* What would be an alternative?
"With all the bends in the pipe, from an industrial/practical standpoint, do you think diffusion and dispersion will be large enough to affect the conversion?"
(5) *Questions that probe implications and consequences:* What generalizations can you make? What are the consequences of that assumption?
"How would our results be affected if we neglected diffusion?"
(6) *Questions about the question:* What was the point of this question? Why do you think I asked this question?
"Why do you think diffusion is important?"

[1] The permission for use of these problems, which, incidentally, may be obtained from the Documents Section, California Board of Registration for Civil and Professional Engineers—Chemical Engineering, 1004 6th Street, Sacramento, CA 95814, is gratefully acknowledged. (Note: These problems have been copyrighted by the California Board of Registration and may not be reproduced without its permission).

[2] R. W. Paul, *Critical Thinking* (Santa Rosa, Calif.: Foundation for Critical Thinking, 1992).

Scheffer and Rubenfeld[3,4] expand on the practice of critical thinking skills discussed by R. W. Paul by using the activities, statements, and questions shown in Table P-2.

TABLE P-2. CRITICAL THINKING SKILLS[2,3]

Analyzing: separating or breaking a whole into parts to discover their nature, function, and relationships "I studied it piece by piece." "I sorted things out."
Applying Standards: judging according to established personal, professional, or social rules or criteria "I judged it according to...."
Discriminating: recognizing differences and similarities among things or situations and distinguishing carefully as to category or rank "I rank ordered the various...." "I grouped things together."
Information Seeking: searching for evidence, facts, or knowledge by identifying relevant sources and gathering objective, subjective, historical, and current data from those sources "I knew I needed to look up/study...." "I kept searching for data."
Logical Reasoning: drawing inferences or conclusions that are supported in or justified by evidence "I deduced from the information that...." "My rationale for the conclusion was...."
Predicting: envisioning a plan and its consequences "I envisioned the outcome would be...." "I was prepared for...."
Transforming Knowledge: changing or converting the condition, nature, form, or function of concepts among contexts "I improved on the basics by...." "I wondered if that would fit the situation of ...."

I have found the best way to develop and practice critical thinking skills is to use Tables P-1 and P-2 to help students write a question on any assigned homework problem and then to explain why the question involves critical thinking.

More information on critical thinking can be found on the CD-ROM in the section on *Problem Solving*.

B.3. To Develop Creative Thinking Skills

The third goal of this book is to help develop creative thinking skills. This goal will be achieved by using a number of problems that are open-ended to various degrees. Here the students can practice their creative skills by exploring the example problems as outlined at the beginning of the home problems of each

[3] Courtesy of B. K. Scheffer and M. G. Rubenfeld, "A Consensus Statement on Critical Thinking in Nursing," *Journal of Nursing Education, 39*, 352–9 (2000).

[4] Courtesy of B. K. Scheffer and M. G. Rubenfeld, "Critical Thinking: What Is It and How Do We Teach It?" *Current Issues in Nursing* (2001).

chapter and by making up and solving an original problem. Problem P4-1 gives some guidelines for developing original problems. A number of techniques that can aid the students in practicing and enhancing their creativity can be found in Fogler and LeBlanc[5] and in the *Thoughts on Problem Solving* section on the CD-ROM and on the web site *www.engin.umich.edu/~cre*. We will use these techniques, such as Osborn's checklist and de Bono's lateral thinking (which involves considering other people's views and responding to random stimulation) to answer add-on questions such as those in Table P-3.

TABLE P-3. PRACTICING CREATIVE THINKING

(1) Brainstorm ideas to ask another question or suggest another calculation that can be made for this homework problem.
(2) Brainstorm ways you could work this homework problem incorrectly.
(3) Brainstorm ways to make this problem easier or more difficult or more exciting.
(4) Brainstorm a list of things you learned from working this homework problem and what you think the point of the problem is.
(5) Brainstorm the reasons why your calculations overpredicted the conversion that was measured when the reactor was put on stream. Assume you made no numerical errors on your calculations.
(6) "What if..." questions: The "What if..." questions are particularly effective when used with the *Living Example Problems* where one varies the parameters to explore the problem and to carry out a sensitivity analysis. For example, *what if someone suggested that you should double the catalyst particle diameter, what would you say?*

One of the major goals at the undergraduate level is to bring students to the point where they can solve complex reaction problems, such as multiple reactions with heat effects, and then ask "What if..." questions and look for optimum operating conditions. One problem whose solution exemplifies this goal is the Manufacture of Styrene, Problem P8-26. This problem is particularly interesting because two reactions are endothermic and one is exothermic.

(1) Ethylbenzene → Styrene + Hydrogen: *Endothermic*
(2) Ethylbenzene → Benzene + Ethylene: *Endothermic*
(3) Ethylbenzene + Hydrogen → Toluene + Methane: *Exothermic*

To summarize Section B, it is the author's experience that both critical and creative thinking skills can be enhanced by using Tables P-1, P-2, and P-3 to extend any of the homework problems at the end of every chapter.

C. The Structure

The strategy behind the presentation of material is to build continually on a few basic ideas in chemical reaction engineering to solve a wide variety of problems. These ideas, referred to as the *Pillars of Chemical Reaction Engineering*,

[5] H. S. Fogler and S. E. LeBlanc, *Strategies for Creative Problem Solving* (Upper Saddle River, N.J.: Prentice Hall, 1995).

are the foundation on which different applications rest. The pillars holding up the application of chemical reaction engineering are shown in Figure P-1.

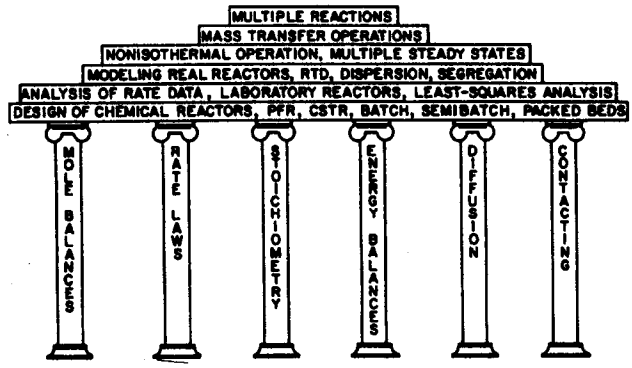


Figure P-1 Pillars of Chemical Reaction Engineering.

From these Pillars we construct our CRE algorithm:

Mole balance + Rate laws + Stoichiometry + Energy balance + Combine

With a few restrictions, the contents of this book can be studied in virtually any order after students have mastered the first four chapters. A flow diagram showing the possible paths can be seen in Figure P-2.

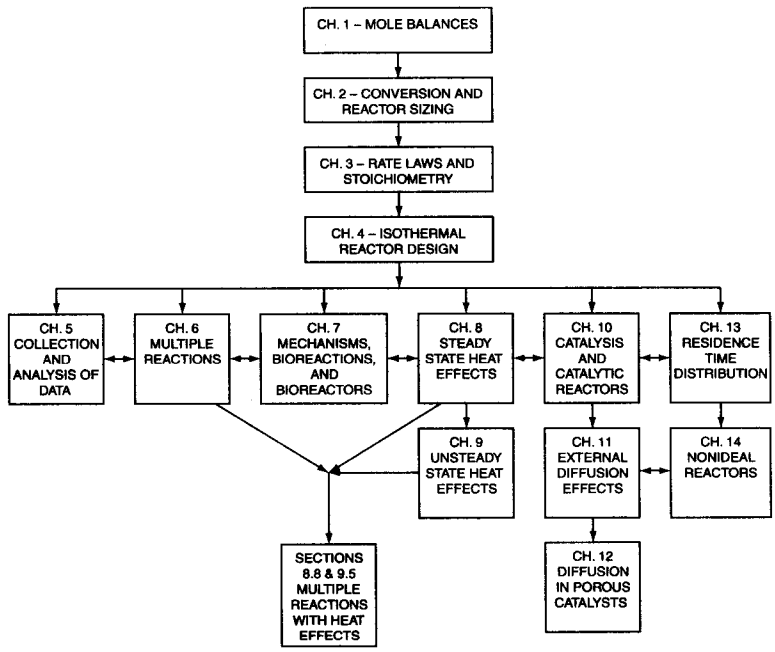


Figure P-2 Sequences for studying the text.

Table P-4 shows examples of topics that can be covered in a graduate course and an undergraduate course. In a four-hour undergraduate course at the University of Michigan, approximately eight chapters are covered in the following order: Chapters 1, 2, 3, 4, and 6; Sections 5.1–5.3; and Chapters 7, 8, and parts of Chapter 10.

TABLE P-4. UNDERGRADUATE/GRADUATE COVERAGE OF CRE

Undergraduate Material/Course	*Graduate Material/Course*
Mole Balances (Ch. 1) Smog in Los Angeles Basin (PRS Ch. 1) Reactor Staging (Ch. 2) Hippopotamus Stomach (PRS Ch. 2) Rate Laws (Ch. 3) Stoichiometry (Ch.3) Reactors (Ch. 4): Batch, PFR, CSTR, PBR, Semibatch, Membrane Data Analysis: Regression (Ch. 5) Multiple Reactions (Ch. 6) Blood Coagulation (SN Ch. 6) Bioreaction Engineering (Ch. 7) Steady-State Heat Effects (Ch. 8): PFR and CSTR with and without a Heat Exchanger Multiple Steady States Unsteady-State Heat Effects (Ch. 9) Reactor Safety Catalysis (Ch. 10)	Short Review (Ch. 1–4, 6, 8) Collision Theory (PRS Ch. 3) Transition State Theory (PRS Ch. 3) Molecular Dynamics (PRS Ch. 3) Aerosol Reactors (PRS Ch. 4) Multiple Reactions (Ch. 6): Fed Membrane Reactors Bioreactions and reactors (Ch. 7, PRS 7.3, 7.4, 7.5) Polymerization (PRS Ch. 7) Co- and Counter Current Heat Exchange (Ch. 8) Radial and Axial Gradients in a PFR COMSOL (Ch. 8) Reactor Stability and Safety (Ch. 8, 9, PRS 9.3) Runaway Reactions (PRS Ch. 8) Catalyst Deactivation (Ch. 10) Residence Time Distribution (Ch. 13) Models of Real Reactors (Ch. 14) Applications (PRS): Multiphase Reactors, CVD Reactors, Bioreactors

The reader will observe that although metric units are used primarily in this text (e.g., kmol/m^3, J/mol), a variety of other units are also employed (e.g., lb/ft^3). This is intentional! We believe that whereas most papers published today use the metric system, a significant amount of reaction engineering data exists in the older literature in English units. Because engineers will be faced with extracting information and reaction rate data from older literature as well as the current literature, they should be equally at ease with both English and metric units.

The notes in the margins are meant to serve two purposes. First, they act as guides or as commentary as one reads through the material. Second, they identify key equations and relationships that are used to solve chemical reaction engineering problems.

D. The Components of the CD-ROM

The interactive CD-ROM is a novel and unique part of this book. The main purposes of the CD-ROM are to serve as an enrichment resource and as a professional reference shelf. The home page for the CD-ROM and the CRE web site (*www.engin.umich.edu/~cre/fogler&gurmen*) is shown in Figure P-3.

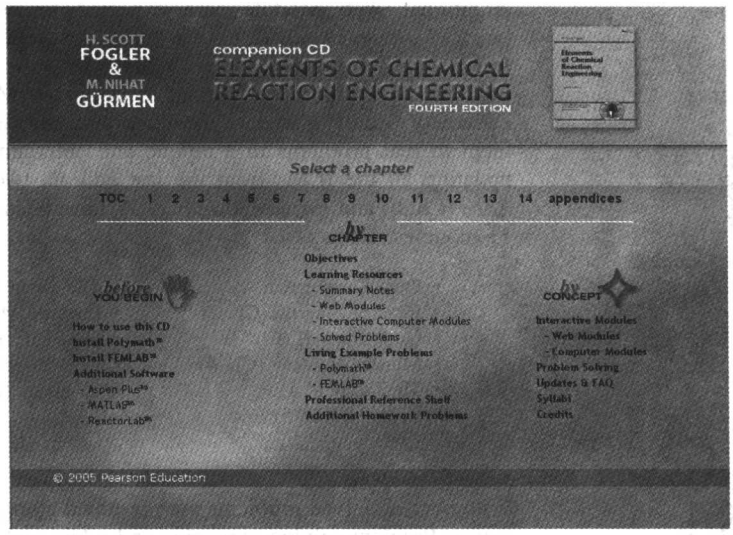
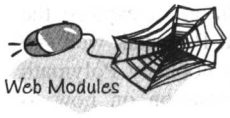


Figure P-3 Screen shot of the home page of the CD-ROM.

The objectives of the CD-ROM are threefold: (1) to facilitate the learning of CRE by interactively addressing the *Felder/Solomon Inventory of Learning Styles*[6] in the Summary Notes, the additional examples, the Interactive Computing Modules (ICMs), and the Web Modules; (2) to provide additional technical material for the professional reference shelf; (3) to provide other tutorial information, examples, derivations, and self tests, such as additional thoughts on problem solving, the use of computational software in chemical reaction engineering, and representative course structures. The following components are listed at the end of most chapters and can be accessed from each chapter in the CD-ROM.

- **Learning Resources**
  The Learning Resources give an overview of the material in each chapter and provide extra explanations, examples, and applications to reinforce the basic concepts of chemical reaction engineering. The learning resources on the CD-ROM include the following:

1. *Summary Notes*
   The Summary Notes give an overview of each chapter and provide on-demand additional examples, derivations, and audio comments as well as self tests to assess each reader's understanding of the material.

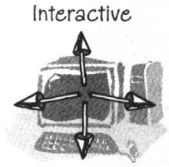


2. *Web Modules*
   The Web Modules, which apply key concepts to both standard and nonstandard reaction engineering problems (e.g., the use of wetlands to degrade toxic chemicals, cobra bites), can be loaded directly from the CD-ROM.

[6] *http://www.ncsu.edu/felder-public/ILSdir/styles.htm*

Additional Web Modules are expected to be added to the web site (*www.engin.umich.edu/~cre*) over the next several years.

3. *Interactive Computer Modules* (ICMs)



Students have found the Interactive Computer Modules to be both fun and extremely useful to review the important chapter concepts and then apply them to real problems in a unique and entertaining fashion. In addition to updating all the ICMs from the last edition, two new modules, *The Great Race* (Ch. 6) and *Enzyme Man* (Ch. 7), have been added. The complete set of 11 modules follows:

- Quiz Show I (Ch. 1)
- Reactor Staging (Ch. 2)
- Quiz Show II (Ch. 3)
- Murder Mystery (Ch. 4)
- Tic Tac (Ch. 4)
- Ecology (Ch. 5)
- The Great Race (Ch. 6)
- Enzyme Man (Ch. 7)
- Heat Effects I (Ch. 8)
- Heat Effects II (Ch. 8)
- Catalysis (Ch. 10)

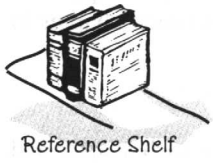
4. *Solved Problems*

A number of solved problems are presented along with problem-solving heuristics. Problem-solving strategies and additional worked example problems are available in the *Problem Solving* section of the CD-ROM.

- **Living Example Problems**

A copy of Polymath is provided on the CD-ROM for the students to use to solve the homework problems. The example problems that use an ODE solver (e.g., Polymath) are referred to as "living example problems" because students can load the Polymath program directly onto their own computers in order to study the problem. Students are encouraged to change parameter values and to "play with" the key variables and assumptions. Using the Living Example Problems to explore the problem and asking "What if..." questions provide students with the opportunity to practice critical and creative thinking skills.

- **Professional Reference Shelf**



This section of the CD-ROM contains

1. Material that was in previous editions (e.g., polymerization, slurry reactors, and chemical vapor disposition reactors) that has been omitted from the printed version of the fourth edition
2. New topics such as *collision and transition state theory, aerosol reactors, DFT,* and *runaway reactions*, which are commonly found in graduate courses
3. Material that is important to the practicing engineer, such as details of the industrial reactor design for the oxidation of SO_2 and design of spherical reactors and other material that is typically not included in the majority of chemical reaction engineering courses

- **Software Toolbox on the CD-ROM**

Polymath. The Polymath software includes an ordinary differential equation (ODE) solver, a nonlinear equation solver, and nonlinear regression. As with previous editions, Polymath is included with this edition to explore the example problems and to solve the home problems. A special Polymath web site (*www.polymath-software.com/fogler*) has been set up for this book by Polymath authors Cutlip and Shacham. This web site provides information on how to obtain an updated version of Polymath at a discount.

*COMSOL.** The COMSOL Multiphysics (referred to throughout the book as COMSOL) software includes a partial differential equation solver. This edition includes a specially prepared version of COMSOL on its own CD-ROM. With COMSOL the students can view both axial and radial temperature and concentration profiles. Five of the COMSOL modules are:

- Isothermal operation
- Adiabatic operation
- Heat effects with constant heat exchange fluid temperature
- Heat effects with variable heat exchanger temperature
- Dispersion with Reaction using the Danckwerts Boundary Conditions (two cases)

As with the Polymath programs, the input parameters can be varied to learn how they change the temperature and concentration profiles.

Instructions are included on how to use not only the software packages of Polymath, MATLAB, and COMSOL, but also on how to apply ASPEN PLUS to solve CRE problems. Tutorials with detailed screen shots are provided for Polymath and COMSOL.

- **Other CD-ROM Resources**
  FAQs. The Frequently Asked Questions (FAQs) are a compilation of questions collected over the years from undergraduate students taking reaction engineering.

  Problem Solving. In this section, both critical thinking and creative thinking are discussed along with what to do if you get "stuck" on a problem.

  Visual Encyclopedia of Equipment. This section was developed by Dr. Susan Montgomery at the University of Michigan. Here a wealth of photographs and descriptions of real and ideal reactors are given. The students with visual, active, sensing, and intuitive learning styles of the Felder/Solomon Index will particularly benefit from this section.

  Reactor Lab. Developed by Professor Richard Herz at the University of California at San Diego, this interactive tool will allow students not only to test their comprehension of CRE material but also to explore different situations and combinations of reaction orders and types of reactions.

Green engineering

Green Engineering Home Problems. Green engineering problems for virtually every chapter have been developed by Professor Robert Hesketh at Rowan University and Professor Martin Abraham at the University of Toledo and can be found at *www.rowan.edu/greenengineering*. These problems also accompany the book by David Allen and David Shonnard, *Green Chemical Engineering: Environmentally Conscious Design of Chemical Processes* (Prentice Hall, 2002).

E. The Integration of the Text and the CD-ROM

E.1. The University Student

There are a number of ways one can use the CD-ROM in conjunction with the text. The CD-ROM provides enrichment resources for the reader in the form of

* The name *FEMLAB* was changed to *COMSOL Multiphysics* on July 1, 2005.

interactive tutorials. Pathways on how to use the materials to learn chemical reaction engineering are shown in Figure P-4. The keys to the CRE learning flow sheets include primary resources and enrichment resources:

In developing a fundamental understanding of the material, students may wish to use only the primary resources without using the CD-ROM (i.e., using only the boxes shown in Figure P-4), or they may use a few or all of the interactive tutorials in the CD-ROM (i.e., the circles shown in Figure P-4). However, to practice the skills that enhance critical and creative thinking, students are strongly encouraged to use the *Living Example Problems* and vary the model parameters to ask and answer "What if..." questions.

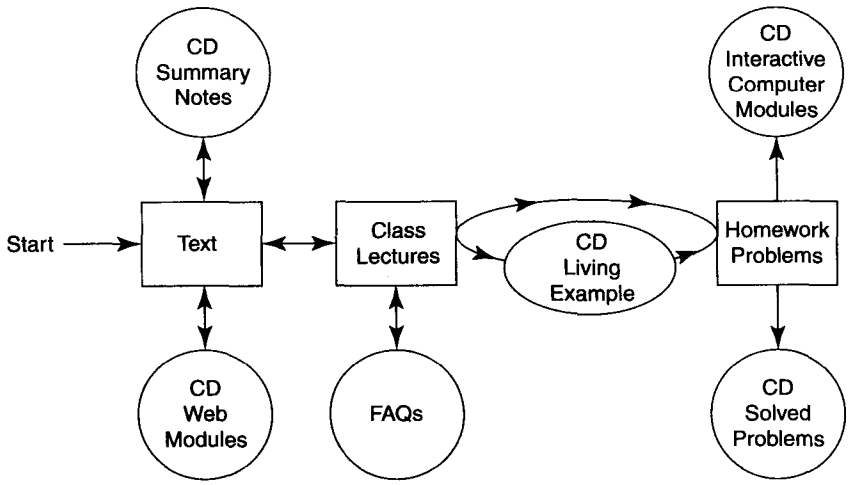


Figure P-4 A Student Pathway to Integrate the Class, the Text, and the CD.

Note that even though the author recommends studying the Living Example Problems before working home problems, they may be bypassed, as is the case with all the enrichment resources, if time is short. However, class testing of the enrichment resources reveals that they not only greatly aid in learning the material but also serve to motivate students through the novel use of CRE principles.

E.2. For the Practicing Engineer

A figure similar to Figure P-4 for the practicing engineer is given in the CD-ROM Appendix.