CHEMICAL ENGINEERING DESIGN AND ANALYSIS
Second Edition

This textbook puts design at the center of introducing students to the course in mass and energy balances in chemical engineering. Employers and accreditations increasingly stress the importance of design in the engineering curriculum, and design-driven analysis will motivate students to dig deeply into the key concepts of the field.

The Second Edition has been completely revised and updated. It introduces the central steps in design, and three methods of analysis: mathematical modeling, graphical methods, and dimensional analysis. Students learn how to apply engineering skills—such as simplification of calculations through assumptions and approximations; verification of calculations; identification of significant figures; application of spreadsheets; graphical analysis (standard, semi-log, and log–log); and the use of data maps—in the contexts of contemporary chemical processes such as the hydrogen economy, petrochemical and biochemical processes, polymers, semiconductors, and pharmaceuticals.

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Chemical Engineering Design and Analysis

An Introduction

Second Edition

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To Deborah and Maxwell
T. Michael Duncan

To Karen, Jennifer, Jonathan, Charlotte, and Martin
Jeffrey A. Reimer
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Preface

The teaching of introductory chemical engineering traditionally begins with analysis. Our contention is that design is the essential prerequisite to analysis – and that, in fact, beginning the study of chemical engineering with design is more motivating and engaging to students. We originally developed this textbook to demonstrate that design – the quintessential skill for chemical engineers – can be taught at the first-year or second-year level. This new edition, refined and reorganized following many semesters of classroom use at Cornell University and the University of California at Berkeley, continues to adhere to that paradigm.

Why is the central theme of this textbook process design substantiated by analysis? Design is a key skill in the chemical engineering curriculum. Employers and accreditation boards increasingly stress design training, yet design is typically postponed until a capstone course in the final semester. One design experience at the end of a four-year program is not enough and we, along with other educators, believe that design is an experience that must grow with the student’s development. This textbook, we believe, succeeds in providing students with that experience.

THE APPROACH OF THIS TEXT

The choice of textbook for a course, and in particular the first course in the chemical engineering discipline, is a vexing one. Instructors who teach mass and energy balance often feel as though the weight of the whole discipline is resting on their choice; that is, that they must convey a comprehensive set of deep and abiding truths, teach the skill set that will launch a career, and deploy the most modern methods from educational psychology and teaching practice.

Traditional mass and energy balance textbooks represent this approach well. Indeed, these books are so powerful and comprehensive that the independent learner can engage with them in the absence of a professor or classroom; they are a self-study course in print, open to anyone willing to invest the time. Dedicated and brilliant authors prepare traditional comprehensive texts, and many dedicated teachers use them effectively.

We chose to create a different type of textbook – namely a conversational narrative that focuses on design. “To create what never has been,” to quote Theodore von Kármán, is a thrill at all stages of preparation in the discipline, and a delight at all ability levels. As such, we focus our narratives less on comprehensive coverage of topics typical of the traditional Mass And Energy Balance course. We believe that the notion of learning being governed by coverage of topics is a legacy of the twentieth century and has not been substantiated by contemporary educational psychology. Comprehensive coverage of topics further complicates instruction in the introductory course because the number of
Preface

topics encompassed by chemical engineering continues to grow substantially. We offer something special with our textbook – namely that the concepts of algebra and calculus, the visual display of information, and dimensional analysis are timeless themes that are the perfect platform for a book that is neither an encyclopedia nor a list of current industrial/academic topics.

FEATURES OF THIS TEXT

A story-telling approach. We intend this textbook to be read, not studied. We are storytellers, and the student will find this book to be a collection of stories crafted to show the reader how to design chemical processes. The end-of-chapter exercises afford practice at the design skills introduced in the stories. These exercises have been time-tested by students at our institutions. As is true for most designs, the exercises are often without a unique solution (as is true for most designs), and indeed are best worked with fellow students engaged in the process of discussing, posing, correcting, and re-posing ideas.

The essential tools to create new designs. If design is to be a full partner in a foundational course, then it is appropriate to ask what tools are necessary for students to create new designs. Here is where we deviate significantly from other “mass and energy balance” textbooks: we demonstrate three different skills for students to employ in design:

- Like our peer texts, we rely heavily on algebra and macroscopic mathematical models for mass, energy, and asset conservation.
- Unlike others, we affirm that the visual display of information is in its own right a design tool for systems whose behavior is well described phenomenologically, e.g. systems described by thermodynamic phase diagrams.
- Finally, we augment algebra and graphs with dimensional analysis for those systems that elude a fundamental basis. This topic is often relegated to later courses in the curriculum and is so heavily contextualized in those specific topics that its general applicability is lost; Chapter 5 rectifies this omission.

The denouement of our textbook engages all three approaches to design and analyze systems that vary with time.

“Context, concepts, defining question” introduction for each section, which establishes for the student a framework for thinking about chemical engineering

An abundance of design-oriented exercises. A key feature of our textbook is the exercises; 359 exercises in total, including 71 open-ended design exercises. Every exercise has been assigned at least once in our courses at Cornell University and the University of California at Berkeley. The wording, the just-in-time delivery of concepts, and the solutions have been crafted so students can practice design skills and then deploy them in situations completely unfamiliar to them.

ORGANIZATION OF THIS TEXT

The coverage of such a vast array of topics suggests that students need to have been exposed to many chemical engineering topics prior to using this book. On the contrary, we chose to eschew an encyclopedic presentation of chemical engineering information: our textbook organizes skills in a “just-in-time” fashion, where each skill is presented to answer a pending design question.
Preface

After a brief overview of contemporary chemical engineering in Chapter 1, we introduce concepts and methods of qualitative process design in Chapter 2. We then demonstrate three quantitative methods to analyze design options. Chapter 3 introduces mathematical modeling with mass and energy balances, including techniques for informal mass balances, essential for quickly assessing a design change. We further improve this traditional topic by introducing a third tool essential for process design: process economics, which is mathematical modeling based on the conservation of assets. Chapter 4 demonstrates graphical modeling for quantitative process analysis and design; graphical representations of mass and energy balances. Chapter 5 introduces dimensional analysis and dynamic scaling for process design scale-up from pilot plant to commercial process or scale-down from bench scale to microchemical process. Chapter 6 applies mathematical modeling, graphical modeling, and dynamic scaling to transient-state processes.

TOOLS FOR THE INSTRUCTOR

Our online resources include:

- A solutions manual providing detailed solutions for every exercise in our textbook
- Alternative designs (with relative pros and cons)
- A list of common errors
- Additional exercises, similar to the ones in the textbook, which will be posted regularly, together with detailed solutions
- Design projects
- Grading rubrics, which will be posted for:
  - The design exercises published in the second edition
  - The additional design exercises that we will be regularly adding online
- PowerPoint presentations for exercises suitable for in-class team solutions
- Suggestions for abbreviated syllabi
- Lectures in PowerPoint or in Word, with different contexts to support the concepts of many textbook sections. Please contact us for any of this supplementary material.

We have had success in adopting this text for the Mass and Energy Balance course taught in the 14-week semester system. At various times, and with various stages of preparation, we have chosen to amplify some material. For example, well-prepared students can successfully use Chapter 6 for the organizing topics, with back-reflection to earlier chapters when steady-state design is to be considered. We have also used this text in a course that emphasizes Chapters 2 and 3 for a large fraction of the semester, an especially effective approach when students have minimal chemistry, physics, and mathematics backgrounds. Finally, we have discovered in conversations with colleagues around the world, as well as thoughtful reviews provided of a draft of this text, that the introductory chemical engineering course is often used to introduce chemical thermodynamics. This text does not serve that need well, though we have had considerable success with Chapter 4 as preparation for a chemical engineering thermodynamics course without having to parse exercises into constructs “ideal” and “real.” Data drive our description of phase behavior, graphs represent those data well, and graphs can be used to conduct design, including McCabe–Thiele type analyses.

We hope you enjoy reading our book and we welcome your feedback. We are pleased to regularly post new exercises and resources onto our website.
Acknowledgements

We are grateful to the hundreds of Cornell University and University of California at Berkeley students in the past two decades for their patience and critical comments in preparing this textbook. We have been fortunate to work with dozens of dedicated teaching assistants who also improved the text and paid particular attention to the exercises and solutions. During this time we benefited from the steadfast support of Cornell University and the University of California at Berkeley and the freedom to teach and learn alongside our students.

Several textbooks influenced this work. Two fine textbooks on design – Process Synthesis by Dale Rudd, Gary Powers, and Jeffrey Siirola, and Process Modeling by Morton Denn – inspired us and spawned the material on process design (Chapter 2), mathematical modeling (Chapter 3), and transient process (Chapter 6).

Mass and energy balances, introduced in Chapter 3 as examples of mathematical modeling, is a mature topic in chemical engineering. We are grateful to the authors of three excellent textbooks – Richard Felder and Ronald Rousseau, Elementary Principles of Chemical Processes, William Luyben and Leonard Wenzel, Chemical Process Analysis: Mass and Energy Balances, and Gintaras Reklaitis, Introduction to Material and Energy Balances – for permission to adapt and reprint examples and exercises.