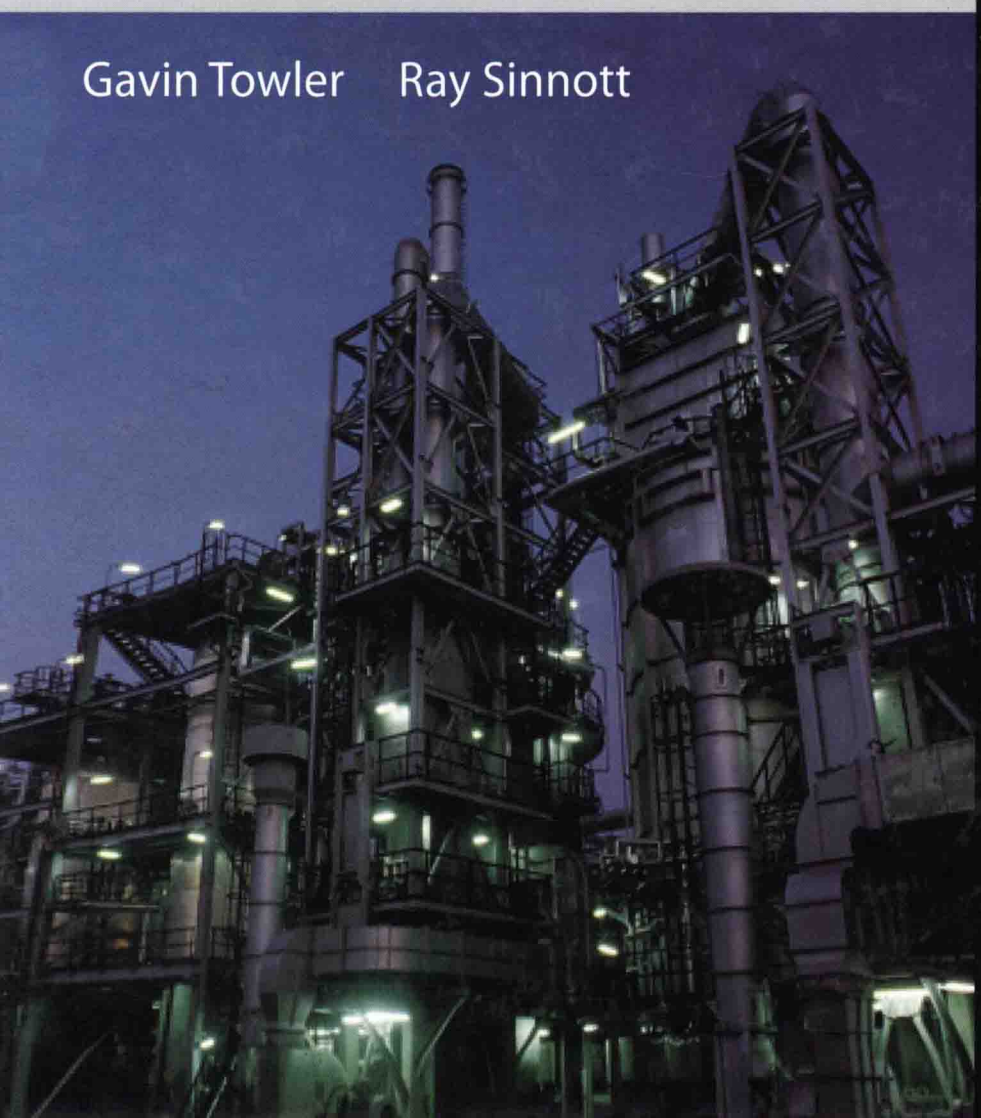
CHEMICAL ENGINEERING DESIGN

Principles, Practice and Economics of Plant and Process Design

Second Editon

Gavin Towler Ray Sinnott



B H

Chemical Engineering Design

Principles, Practice and Economics of Plant and Process Design

Second Edition

Gavin Towler
Ray Sinnott

ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Butterworth-Heinemann is an imprint of Elsevier

Butterworth-Heinemann is an imprint of Elsevier
The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK
225 Wyman Street, Waltham, MA 02451, USA

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

Library of Congress Cataloging-in-Publication Data

Towler, Gavin P.
Chemical engineering design : principles, practice, and economics of plant and process design / Gavin Towler, Ray Sinnott. – 2nd ed.
p. cm.
ISBN 978-0-08-096659-5 (hardback)
1. Chemical engineering. I. Sinnott, R. K. II. Title.

TP155.T69 2012
660.068'5–dc23

2011044962

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

For information on all Butterworth-Heinemann publications visit our website at *www.elsevierdirect.com*

Typeset by: diacriTech, Chennai, India

Printed in the United States of America
12 13 14 15 10 9 8 7 6 5 4 3 2 1

Preface to the Second Edition

This book was originally written by Ray Sinnott as Volume 6 of the "Chemical Engineering" series edited by Coulson and Richardson. It was intended to be a standalone design textbook for undergraduate design projects that would supplement the other volumes in the Coulson and Richardson series. In 2008 we published the first edition of *Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design* as an adaptation of Coulson and Richardson Volume 6 for the North American market. Some older sections of the book were updated and references to laws, codes, and standards were changed to an American rather than British basis; however, the general layout and philosophy of the book remained unaltered.

The first edition of this book was widely adopted and I received a great deal of valuable feedback from colleagues on both the strengths and weaknesses of the text in the context of a typical North American undergraduate curriculum. The experiences and frustrations of my students at Northwestern University and comments from coworkers at UOP also helped suggest areas where the book could be improved. The changes that have been made in this second edition are my attempt to make the book more valuable to students and industrial practitioners by incorporating new material to address obvious gaps, while eliminating some material that was dated or repetitive of foundation classes.

The main change that I have made is to rearrange the order in which material is presented to fit better with a typical two-course senior design sequence. The book is now divided into two parts. Part I: Process Design covers the topics that are typically taught in a lecture class. The broad themes of Part I are flowsheet development, economic analysis, safety and environmental impact, and optimization. Part II: Plant Design contains chapters on equipment design and selection that can be used as supplements to a lecture course. These chapters contain step-by-step methods for designing most unit operations, together with many worked examples, and should become essential references for students when they begin working through their design projects or face design problems early in their industrial career.

The coverage of process flowsheet development has been significantly increased in this edition. The introductory chapters on material and energy balances have been deleted and replaced with chapters on flowsheet development and energy recovery, which lead into the discussion of process simulation. The treatment of process economics has also been increased, with new chapters on capital cost estimating and operating costs, as well as a longer discussion of economic analysis and sensitivity analysis. The section on optimization is now presented as a separate chapter at the end of Part I, as most instructors felt that it was more logical to present this topic after introducing economic analysis and the constraints that come from safety and environmental considerations.

Part II begins with an overview of common themes in equipment design. This is followed by the chapter on pressure vessel design, which underpins the design of most process vessels. The following chapters then proceed through reactors, separation processes, solids handling, heat exchange, and hydraulic equipment. My experience has been that students often struggle to make the connection from reaction engineering fundamentals to a realistic mechanical layout of a reactor, so a new chapter on reactor design has been added, with a focus on the practical aspects of reactor specification. The coverage of separation processes has been expanded to include adsorption, membrane

separations, chromatography, and ion exchange. The treatment of solids-handling processes has also been increased and solids-handling operations have been grouped together in a new chapter.

Throughout the book I have attempted to increase the emphasis on batch processing, revamp designs, and design of biological processes, including fermentation and the separations commonly used in product recovery and purification from biochemical processes. Almost every chapter now contains examples of food, pharmaceutical, and biological processes and operations. Many graduating chemical engineers in the United States will find themselves working in established plants where they are more likely to work on revamp projects than new grassroots designs. A general discussion of revamp design is given in Part I and examples of rating calculations for revamps are presented throughout Part II.

Chemical engineers work in a very diverse set of industries and many of these industries have their own design conventions and specialized equipment. I have attempted to include examples and problems from a broad range of process industries, but where space or my lack of expertise in the subject has limited coverage of a particular topic, references to specialized texts are provided.

This book draws on Ray Sinnott's and my experience of the industrial practice of process design, as well as our experience teaching design at the University of Wales Swansea, University of Manchester, and Northwestern University. Since the book is intended to be used in practice and not just as a textbook, our aim has been to describe the tools and methods that are most widely used in industrial process design. We have deliberately avoided describing idealized conceptual methods that have not yet gained wide currency in industry. The reader can find good descriptions of these methods in the research literature and in more academic textbooks.

Standards and codes of practice are an essential part of engineering and the relevant North American standards are cited. The codes and practices covered by these standards will be applicable to other countries. They will be covered by equivalent national standards in most developed countries, and in some cases the relevant British, European, or international standards have also been cited. Brief summaries of important U.S. and Canadian safety and environmental legislation have been given in the relevant chapters. The design engineer should always refer to the original source references of laws, standards, and codes of practice, as they are updated frequently.

Most industrial process design is carried out using commercial design software. Extensive reference has been made to commercial process and equipment design software throughout the book. Many of the commercial software vendors provide licenses of their software for educational purposes at nominal fees. I strongly believe that students should be introduced to commercial software at as early a stage in their education as possible. The use of academic design and costing software should be discouraged. Academic programs usually lack the quality control and support required by industry, and the student is unlikely to use such software after graduation. All computer-aided design tools must be used with some discretion and engineering judgment on the part of the designer. This judgment mainly comes with experience, but I have tried to provide helpful tips on how to best use computer tools.

Ray wrote in the preface to the first edition of his book: "*The art and practice of design cannot be learned from books. The intuition and judgment necessary to apply theory to practice will come only from practical experience.*" In modifying the book to this new edition I hope that I have made it easier for readers to begin acquiring that experience.

Gavin Towler

How to Use This Book

This book has been written primarily for students on undergraduate courses in chemical engineering and has particular relevance to their senior design projects. It should also be of interest to new graduates working in industry who find they need to broaden their knowledge of unit operations and design. Some of the earlier chapters of the book can also be used in introductory chemical engineering classes and by other disciplines in the chemical and process industries.

PART I: PROCESS DESIGN

Part I has been conceived as an introductory course in process design. The material can be covered in 20 to 30 lecture hours and presentation slides are available to qualified instructors in the supplementary material available at booksite.elsevier.com/towler. Chapter 1 is a general overview of process design and contains an introductory section on product design. Chapters 2 to 6 address the development of a process flowsheet from initial concept to the point where the designer is ready to begin estimating capital costs. Chapter 2 covers the selection of major unit operations and also addresses design for revamps and modification of conventional flowsheets. Chapter 3 introduces utility systems and discusses process energy recovery and heat integration. Chapter 4 provides an introduction to process simulation and shows the reader how to complete process material and energy balances. Chapter 5 covers those elements of process control that must be understood to complete a process flow diagram and identify where pumps and compressors are needed in the flowsheet. The selection of materials of construction can have a significant effect on plant costs, and this topic is addressed in Chapter 6. The elements of process economic analysis are introduced in Chapters 7 to 9. Capital cost estimation is covered in Chapter 7. Operating costs, revenues, and price forecasting are treated in Chapter 8. Chapter 9 concludes the economics section of the book with a brief introduction to corporate finance, a description of economic analysis methods, and a discussion on project selection criteria used in industry. Chapter 10 examines the role of safety considerations in design and introduces the methods used for process hazard analysis. Chapter 11 addresses site design and environmental impact. Part I concludes with a discussion of optimization methods in Chapter 12.

PART II: PLANT DESIGN

Part II contains a more detailed treatment of design methods for common unit operations. Chapter 13 provides an overview of equipment design and is also a guide to the following chapters. Chapter 14 discusses the design of pressure vessels, and provides the necessary background for the reader to be able to design reactors, separators, distillation columns, and other operations that must be designed under pressure vessel codes. Chapter 15 covers the design of mixers and reactors, with an emphasis on the practical mechanical layout of reactors. Chapters 16 and 17 address fluid phase separations. Multistage column separations (distillation, absorption, stripping, and extraction) are described in Chapter 17, while other separation processes, such as adsorption, membrane separation, decanting,

crystallization, precipitation, ion exchange, and chromatography, are covered in Chapter 16. Chapter 18 examines the properties of granular materials and introduces the processes used for storing, conveying, mixing, separating, heating, drying, and altering the particle size distribution of solids. Chapter 19 covers all aspects of the design of heat-transfer equipment, including plate exchangers, air coolers, fired heaters, and direct heat transfer to vessels, as well as design of shell and tube heat exchangers, boilers, and condensers. Chapter 20 addresses the design of plant hydraulics and covers design and selection of pumps, compressors, piping systems, and control valves. The material in Part II can be used to provide supplementary lectures in a design class, or as a supplement to foundation courses in chemical engineering. The chapters have also been written to serve as a guide to selection and design, with extensive worked examples, so that students can dip into individual chapters as they face specific design problems when working on a senior year design project.

SUPPLEMENTARY MATERIAL

Many of the calculations described in the book can be performed using spreadsheets. Templates of spreadsheet calculations and equipment specification sheets are available in Microsoft Excel format online and can be downloaded from booksite.elsevier.com/Towler. An extensive set of design problems are included in the Appendices, which are also available at booksite.elsevier.com/Towler.

Additional supplementary material, including Microsoft PowerPoint presentations to support most of the chapters and a full solutions manual, are available only to instructors, by registering at the Instructor section on booksite.elsevier.com/Towler.

Acknowledgments

As stated in the preface, after launching the first edition of this book I received a great deal of very valuable feedback from students and colleagues. I have tried to make good use of this feedback in the second edition. Particular thanks are due to John Baldwin, Elizabeth Carter, Dan Crowl, Mario Eden, Mahmoud El-Halwagi, Igor Kourkine, Harold Kung, Justin Notestein, Matthew Realff, Tony Rogers, Warren Seider, and Bill Wilcox, all of whose suggestions I have gratefully incorporated. Many further improvements were suggested during the review phase and I would like to thank Mark James, Barry Johnston, Ken Joung, Yoshiaki Kawajiri, Peg Stine, Ross Taylor, and Andy Zarchy for their thoughtful reviews and input. Rajeev Gautam and Ben Christolini allowed me to pursue this project and make use of UOP's extensive technical resources. As always, many colleagues at UOP, AIChE, and CACHE and students and colleagues at Northwestern have shared their experience and given me new insights into chemical engineering design and education.

Material from the ASME Boiler and Pressure Vessel Code is reproduced with permission of ASME International, Three Park Avenue, New York NY 10016. Material from the API Recommended Practices is reproduced with permission of the American Petroleum Institute, 1220 L Street, NW, Washington, DC 20005. Material from British Standards is reproduced by permission of the British Standards Institution, 389 Chiswick High Road, London, W4 4AL, United Kingdom. Complete copies of the codes and standards can be obtained from these organizations.

I am grateful to Aspen Technology Inc. and Honeywell Inc. for permission to include the screenshots that were generated using their software to illustrate the process simulation and costing examples. The material safety data sheet in Appendix I is reproduced with permission of Fischer Scientific Inc. Aspen Plus®, Aspen Process Economic Analyzer, Aspen Kbase, Aspen ICARUS, and all other AspenTech product names or logos are trademarks or registered trademarks of Aspen Technology Inc. or its subsidiaries in the United States and/or in other countries. All rights reserved.

The supplementary material contains images of processes and equipment from many sources. I would like to thank the following companies for permission to use these images: Alfa-Laval, ANSYS, Aspen Technology, Bete Nozzle, Bos-Hatten Inc., Chemineer, Dresser, Dresser-Rand, Enardo Inc., Honeywell, Komax Inc., Riggins Company, Tyco Flow Control Inc., United Valve Inc., UOP LLC, and The Valve Manufacturer's Association.

Joe Hayton and Michael Joyce led the Elsevier team in developing this book and provided much useful editorial guidance. I would also like to thank Lisa Lamenzo for her excellent work in managing all the stages of production and printing.

The biggest debt that I must acknowledge is to my coauthor, Ray Sinnott. Although Ray was not involved in writing this edition, it is built on the foundation of his earlier work, and his words can be found in every chapter. I hope I have remained true to Ray's philosophy of design and have preserved the strengths of his book. It was necessary for me to remove some older material to make space for new sections in the book and I hope that Ray will forgive these changes. Needless to say, I am entirely responsible for any deficiencies or errors that have been introduced.

My regular job at UOP keeps me very busy and I worked on this book in the evenings and on the weekends, so it would not have been possible without the love and support of my wife, Caroline, and our children Miranda, Jimmy, and Johnathan.

Gavin P. Towler
Inverness, Illinois

Contents