ELEMENTARY PRINCIPLES OF CHEMICAL PROCESSES

RICHARD M. FELDER
RONALD W. ROUSSEAU

ELEMENTARY PRINCIPLES OF CHEMICAL PROCESSES

RICHARD M. FELDER
RONALD W. ROUSSEAU
Department of Chemical Engineering
North Carolina State University
Raleigh, North Carolina

JOHN WILEY & SONS
New York Santa Barbara Chichester
Brisbane Toronto

Library of Congress Cataloging in Publication Data

Felder, Richard M. 1939–
  Elementary principles of chemical processes.

  Includes bibliographical references and indexes.
  1. Chemical processes. I. Rousseau, Ronald W., 1943– II. Title.

TP155.7.F44 660.2'8 77–12043
ISBN 0-471-74330-5

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

PREFACE

An introductory stoichiometry course traditionally plays several important roles in the chemical engineering curriculum. On the most obvious level, it prepares the student to formulate and solve material and energy balances on chemical process systems and lays the foundation for subsequent courses in thermodynamics, unit operations, kinetics, and process dynamics. More fundamentally, it introduces the engineering approach to solving process-related problems: breaking a process down into its components, establishing the relations between known and unknown process variables, assembling the information needed to solve for the unknowns using a combination of experimentation, empiricism, and the application of natural laws, and, finally, putting the pieces together to obtain the desired problem solution.

We have tried in this book to fulfill each of these functions. Moreover, recognizing that the stoichiometry course is often the students' first real encounter with what they think may be their chosen profession, we have attempted to provide in the text a realistic, informative, and positive introduction to the practice of chemical engineering.

We begin the book with a qualitative discussion of the kinds of problems engineers must face in connection with several apparently dissimilar processes and, after a brief introduction to fundamental techniques of engineering calculations, systematically develop the structure of elementary process analysis: what process variables are and how they are expressed, measured, and calculated; laws of nature that govern the performance of processes; and physical properties of process materials that must be determined in order to design a new process or analyze an existing one.

The chemical process constitutes the structural and motivational framework for the presentation of all of the text material. When we bring in concepts from physical chemistry—for example, vapor pressure, solubility, and compressibility—we introduce them as quantities whose values are required to determine process variables or to perform material and/or energy balance calculations on a process. When we discuss computational techniques such as curve fitting, root-finding methods, and numerical integration, we present them on the same need-to-know basis in the context of process analysis.

An important feature of the book is a set of industrial process case studies, which demonstrate the role of single-unit calculations in the analysis of multiple-unit processes. We have designed the case studies to be worked on as term projects by individuals or (preferably) small teams of students, beginning after the students have completed the introductory chapter on material balances (Chapter 5). In each study, the students are asked to produce a flow chart of a moderately complex process from a given description and to perform material and energy balance calculations on the process; in addition, they are called on to answer questions that require them to think about how the overall process is structured and why it might be structured that way.

Knowing the problems associated with the case study, the students tend to be on the lookout for information in the formal course material that will help them obtain the required solutions. The case study thus provides both a motivation for learning the text material and a feeling for the contextual significance of this material; moreover, it introduces the common engineering discipline of starting with a large multifaceted problem and systematically building up the blend of information and technique needed to solve it.

In writing the book we have tried to avoid pedanticism without sacrificing thoroughness or rigor. The writing style is largely informal; all solution techniques are illustrated by examples; and short "Test Yourself" questions of the type used effectively in the self-paced approach to education help focus the students' attention and reinforce the main points in each section. Most of the problems concern real processes and contain realistic data; they are designed to provide practice in all of the methods discussed in the chapters they follow and, in addition, illustrate the range of activities encompassed by chemical engineering, both in the traditional areas of chemical processing and in such fields as environmental science and technology and biomedicine.

The SI system of units is used widely but not exclusively throughout the text, and extensive SI data tables, including steam tables, are contained in appendices. Computer programming is not covered explicitly, but applications of computers in process analysis are discussed, and problems for which computer solutions are appropriate are given.

We acknowledge with gratitude the many contributions of colleagues and friends who have helped us in the preparation of the book. Proceeding in no particular order, our thanks go to Professors David Marsland, of North Carolina State University, and Richard Seagrave, John Stevens, and George Burnet, of Iowa State University, who read the manuscript and offered many helpful suggestions for its improvement; Russ O'Dell, who worked out solutions and corrected several dozen mistakes in the manuscript after the authors had convinced themselves there were none left; Jim Ferrell, our beloved leader, who gave us much moral and financial support throughout the seemingly unending years in which the book was being written; Bobbie and Tess, for more than we could summarize here; Kenneth Felder, who performed with great diligence the horrible job of proofreading data tables; Ron Jr., David, Brett, Lanie, and Gary for just being there; and Thurman Poston, the engaging engineering editor, who provided us with many broad perspectives, deep insights, and free lunches. We also thank students who served as guinea pigs during the formative stages of the book's development, and we sincerely apologize for all those problems they involuntarily and painfully debugged for us; in particular, we raise our glasses to the Lost Generation of Fall 1973, who had the miserable fortune to get the first draft as a course text.

We are especially indebted to Dr. James Fair of the Monsanto Company, Mr. Norman Kaplan, of the U.S. Environmental Protection Agency, and Dr. Ray E. Harrison, of Westvaco, Inc., who reviewed draft copies of the case studies and suggested changes to bring the process descriptions closer in line with industrial practice. In some cases we chose to retain deviations from practice for pedagogical reasons; any such deviations should be attributed to us and not the reviewers.

Last, and most of all, we thank Magnificent Mary Wade, who uncomplainingly and with great good humor typed revision after revision, until the authors, unable to stand any more, declared the book done.

Richard M. Felder
Ronald W. Rousseau

TO THE INSTRUCTOR

The organization of this text has been planned to provide enough flexibility to accommodate classes with diverse backgrounds within the scope of a one-semester or two-quarter course. We anticipate that classes starting with a minimal background in engineering analysis will cover the first 10 chapters and one case study. Classes of students who have been exposed to dimensional analysis in freshman courses can skip or skim Chapter Two; classes whose freshman chemistry courses cover the systematic use of units to describe and analyze reactive systems may omit portions of Chapter Three, and classes that get a thorough coverage of temperature and fluid pressure measurement and unit conversion in freshman physics may proceed rapidly through these sections of Chapter Three. Similarly, classes in schools whose freshman engineering courses provide a good exposure to elementary data correlation and curve fitting may choose to omit Chapter Four. The time gained as a result of these omissions may be used to cover additional optional sections in Parts 1 to 3, including Chapter Eleven on unsteady-state systems, or to cover appended material on computer applications, or to work through an additional case study. Covering all of Chapters Two to Four should, in any event, take no more than six lecture hours. A one-quarter course should cover Chapters One through Seven.

In our presentation of material balance procedures we place greater emphasis on algebraic solution techniques and less on such devices as tie elements than do most authors. We have adopted this approach for several reasons. The algebraic technique is perfectly general, applying to processes both with tie elements and without them, and is better adapted to computer-aided balancing; when tie elements are stressed, we find that students tend to use them as crutches, and when (as in most real industrial processes) there is no tie element, the students often tend to flounder unless they are accustomed to the algebraic approach.

Furthermore, we believe that much of the calculational efficiency attributed to the use of tie elements is illusory. If students are accustomed to labeling unknown variables on a flow chart, *and if they are grounded in the principle that balances that involve the fewest unknowns should be taken first*, they can solve most material balance problems as quickly without explicitly using the concept of a tie element as they could using this concept; they are also in a much better position to analyze truly complex processes for which the shortcuts useful for simple processes are generally inapplicable.

We have discussed in the Preface the motivational aspects of the case studies and the way the studies complement the formal text material and vice versa. An additional benefit occurs if the assignments are made to groups, an approach we regularly use in our classes. We invariably see the groups starting out in a state of semianarchy, with each group member doing much the same thing as every other member, and then developing coherence as the weeks go by. By the end of the term the students have learned how to divide the labor appropriately and to learn from each other (since they know that they are liable to be tested on any part of the problem, not just the part for which they were responsible). This is the part of the course the students usually say they enjoyed most. We have also found that periodic conferences between the groups and the instructor to discuss the case studies provide educational benefits to all parties concerned.

R.M.F.
R.W.R.

ELEMENTARY PRINCIPLES OF CHEMICAL PROCESSES

CONTENTS

2 MATERIAL BALANCES

CHAPTER FIVE

CHAPTER SIX

CHAPTER SEVEN

3 ENERGY BALANCES

CHAPTER EIGHT

Part 1
ENGINEERING PROBLEM ANALYSIS

Chapter One
WHAT CHEMICAL ENGINEERS SOMETIMES DO FOR A LIVING

Since you bought this book you are probably thinking of spending the next 3 years learning to be a chemical engineer and then going to work as one for the next 40; even so, it is a fairly safe bet that, like most people in your position, you have only a limited idea of what chemical engineering is. A logical way for us to begin this book might therefore be with a definition of chemical engineering, but, unfortunately, no universally accepted definition has ever been formulated. Instead, we will cite some examples of problems that recent chemical engineering graduates have been called on to solve. You might ponder these examples to see if any of them seem to present the sort of intellectual challenge you can see yourself taking on and enjoying.

EXAMPLE 1

A chemist in your company's research and development division has discovered that if he mixes two reactants in a certain proportion at an elevated temperature, he obtains a product more valuable than both reactants put together. The company contemplates manufacturing the product using a process based on this reaction. At this point the matter becomes an engineering problem or, more precisely, hundreds of engineering problems.

(a) What should the reaction be carried out in? A long pipe? A large tank? Several smaller tanks? An extremely large test tube? How large? Made of what? Does it have to be heated? If so, how much and how? With an electrical heater inside or outside the reactor? By passing a hot fluid through a heating coil in the reactor? By heating the reactants before they get into the reactor? Does the reaction supply its own heat, so that heating is needed only for startup? If so, can it "run away" with itself, and possibly explode. Should control measures be introduced to prevent this? What kind?

(b) Where should the reactants be obtained? Buy them, or make them? In what proportions should they be fed to the reactor?

(c) Should the reactor effluent, which contains the product and unconsumed reactants, be sold as is, or should the product be separated from the reactants and the latter be sent back to the reactor? If separation is desirable, how can it be accomplished? Heat the mixture and draw off and condense the vapor, which will be richer in the more volatile substances than the original mixture? Add another substance that absorbs the product and is immiscible with the reactants, and then separate the two phases mechanically? If all of the process materials are gases at the reaction temperature, can the mixture be cooled to a temperature at which the product condenses but the reactants do not, or vice versa, or if they are liquids can the mixture be cooled to a temperature at which the product crystallizes? If one of these alternatives is chosen, what kind of equipment is needed? What size? What materials? What are the heating or cooling requirements? Are controls needed to keep the operation of the process within rigid limits? What kind of controls? Should they be manual or automatic?

(d) How should the reactant and product streams be moved to and from the reactor and any heating, cooling, and separation equipment involved in the process? By gravity from a raised feed tank? With pumps, or blowers, or compressors, or conveyor belts? What kinds? How big? In pipes made of what?

(e) Is enough known about the reaction system to be able to answer all of these questions, or should additional laboratory studies be carried out? What studies? Can the laboratory data be used directly to design the industrial plant, or should a smaller pilot plant be constructed first to make sure? How much smaller?

(f) What can possibly go wrong with the process, and what can be done if and when it does?

(g) Are there waste products that result from the process? In what quantities? Are they potentially harmful if released untreated into the environment? If so, in what way? What should be done to reduce pollution hazards? Chemical treatment of the wastes? Dump liquid and solid wastes into containers, seal and cart out to sea? Disperse gases in the atmosphere with a high stack? Precipitate solids electrostatically from gas exhausts?

(h) How much of the process should be automated, and how should it be done?

(i) How much does all of this cost? How much can the product be sold for, and to whom? How much money will the process net each year? Is it enough to make it worthwhile? If so, where should the plant be built?