CHEMICAL
ENGINEERING
SERIES

PROCESS ANALYSIS AND DESIGN FOR CHEMICAL ENGINEERS

PROCESS ANALYSIS AND DESIGN FOR CHEMICAL ENGINEERS

William Resnick
Wolfson Professor of Chemical Engineering
Israel Institute of Technology

McGraw-Hill Book Company

New York St. Louis San Francisco Auckland Bogotá Hamburg
Johannesburg London Madrid Mexico Montreal New Delhi
Panama Paris São Paulo Singapore Sydney Tokyo Toronto

This book was set in Times Roman.
The editors were Julienne V. Brown and Susan Hazlett;
the production supervisor was Leroy A. Young.
The drawings were done by ANCO/Boston.
Fairfield Graphics was printer and binder.

PROCESS ANALYSIS AND DESIGN FOR CHEMICAL ENGINEERS

1234567890 FGFG 89876543210

Library of Congress Cataloging in Publication Data

Resnick, William, date
Process analysis and design for chemical engineers.

(McGraw-Hill series in chemical engineering)
Bibliography: p.
Includes index.
1. Chemical processes. I. Title.
TP155.R47 660.2 80-10678
ISBN 0-07-051887-4

BUILDING THE LITERATURE OF A PROFESSION

Fifteen prominent chemical engineers first met in New York more than 50 years ago to plan a continuing literature for their rapidly growing profession. From industry came such pioneer practitioners as Leo H. Baekeland, Arthur D. Little, Charles L. Reese, John V. N. Dorr, M. C. Whitaker, and R. S. McBride. From the universities came such eminent educators as William H. Walker, Alfred H. White, D. D. Jackson, J. H. James, Warren K. Lewis, and Harry A. Curtis. H. C. Parmelee, then editor of *Chemical and Metallurgical Engineering*, served as chairman and was joined subsequently by S. D. Kirkpatrick as consulting editor.

After several meetings, this committee submitted its report to the McGraw-Hill Book Company in September 1925. In the report were detailed specifications for a correlated series of more than a dozen texts and reference books which have since become the McGraw-Hill Series in Chemical Engineering and which became the cornerstone of the chemical engineering curriculum.

From this beginning there has evolved a series of texts surpassing by far the scope and longevity envisioned by the founding Editorial Board. The McGraw-Hill Series in Chemical Engineering stands as a unique historical record of the development of chemical engineering education and practice. In the series one finds the milestones of the subject's evolution: industrial chemistry, stoichiometry, unit operations and processes, thermodynamics, kinetics, and transfer operations.

Chemical engineering is a dynamic profession, and its literature continues to evolve. McGraw-Hill and its consulting editors remain committed to a publishing policy that will serve, and indeed lead, the needs of the chemical engineering profession during the years to come.

THE SERIES

Bailey and Ollis: *Biochemical Engineering Fundamentals*
Bennett and Myers: *Momentum, Heat, and Mass Transfer*
Beveridge and Schechter: *Optimization: Theory and Practice*
Carberry: *Chemical and Catalytic Reaction Engineering*
Churchill: *The Interpretation and Use of Rate Data—The Rate Concept*
Clarke and Davidson: *Manual for Process Engineering Calculations*
Coughanowr and Koppel: *Process Systems Analysis and Control*
Danckwerts: *Gas Liquid Reactions*
Gates, Katzer, and Schuit: *Chemistry of Catalytic Processes*
Harriott: *Process Control*
Johnson: *Automatic Process Control*
Johnstone and Thring: *Pilot Plants, Models, and Scale-up Methods in Chemical Engineering*
Katz, Cornell, Kobayashi, Poettmann, Vary, Elenbaas, and Weinaug: *Handbook of Natural Gas Engineering*
King: *Separation Processes*
Knudsen and Katz: *Fluid Dynamics and Heat Transfer*
Lapidus: *Digital Computation for Chemical Engineers*
Luyben: *Process Modeling, Simulation, and Control for Chemical Engineers*
McCabe and Smith, J. C.: *Unit Operations of Chemical Engineering*
Mickley, Sherwood, and Reed: *Applied Mathematics in Chemical Engineering*
Nelson: *Petroleum Refinery Engineering*
Perry and Chilton (Editors): *Chemical Engineers' Handbook*
Peters: *Elementary Chemical Engineering*
Peters and Timmerhaus: *Plant Design and Economics for Chemical Engineers*
Ray: *Advanced Process Control*
Reed and Gubbins: *Applied Statistical Mechanics*
Reid, Prausnitz, and Sherwood: *The Properties of Gases and Liquids*
Resnick: *Process Analysis and Design for Chemical Engineers*
Satterfield: *Heterogeneous Catalysis in Practice*
Sherwood, Pigford, and Wilke: *Mass Transfer*
Slattery: *Momentum, Energy, and Mass Transfer in Continua*
Smith, B. D.: *Design of Equilibrium Stage Processes*
Smith, J. M.: *Chemical Engineering Kinetics*
Smith, J. M., and Van Ness: *Introduction to Chemical Engineering Thermodynamics*
Thompson and Ceckler: *Introduction to Chemical Engineering*
Treybal: *Mass Transfer Operations*
Van Winkle: *Distillation*
Volk: *Applied Statistics for Engineers*
Walas: *Reaction Kinetics for Chemical Engineers*
Wei, Russell, and Swartzlander: *The Structure of the Chemical Processing Industries*
Whitwell and Toner: *Conservation of Mass and Energy*

PREFACE

Significant changes have taken place in chemical engineering education during the past two decades. The dominant factor in most university chemical engineering departments is the study of engineering sciences, and only limited time is available for the application of this theoretical and fundamental material to the practical problems of chemical processing. In their classroom work students of chemical engineering are usually presented with reasonably well-defined situations and problems. In addition, they usually are expected to deal with only one aspect of a problem at a time,, e.g., the calculation of a distillation column for a given separation, the volume of a reactor required for a reaction of specified kinetics, or the power required to pump a fluid through a defined piping system. The limited time available in the usual curriculum has resulted in a decrease in the study of process design and analysis and of economics and financial evaluations.

As a result of these factors, the young graduate frequently finds it difficult to acclimatize to the industrial environment. In practice, the engineer will deal with poorly defined situations in which the problems to be solved will not be precisely stated, in which the data available will be incomplete and probably inaccurate, in which the decisions made with regard to one factor can reflect through an entire processing system, and in which the economic considerations will have an importance that may not have been sufficiently stressed in the student's classroom exposure.

This book attempts to help the chemical engineering student and the practicing engineer sharpen their skills and apply them to the problem of analyzing a number of the factors that can affect the design, operation, and commercial success of chemical processing systems.

In the first two chapters some of the characteristics of the chemical industry are detailed, and the role of the chemical engineer in this dynamic industry is briefly presented. Some of the factors involved in the generation and screening of alternatives are considered, along with the roles of analysis and synthesis in design.

One of the shocks young chemical engineers receive as they enter upon their industrial careers comes from the realization that for practically any process or compound with which they must contend either there are very few or no physical and thermodynamic data available or there is an abundance of conflicting data. Chapter 3 is therefore devoted to methods of estimating data. These methods can also be used to interpolate and extrapolate with existing data and to serve as a guide in the evaluation of their reliability.

Several chapters are devoted to the analysis of reaction equilibrium, to nonreacting process analysis, to chemical kinetics, and to reactor design and analysis. Although no attempt is made to cover chemical engineering thermodynamics and chemical reactor design exhaustively, the presentation is sufficiently broad to show, with little or no need for recourse to other sources, how these fundamental tools can be and are used in the analysis of processing systems.

Chapters 7 to 9 are devoted to economic evaluation, forecasting and prediction, and dealing with uncertainty. No process analysis can be complete or well founded without a well-based economic evaluation, and to be realistic this evaluation requires that projections into the future be made. The chemical engineer should therefore be aware of some of the principles and procedures involved in forecasting and predicting such factors as markets, prices, costs, and productivity. The effects of inflation and how to account for erosion in the purchasing power of currency are also considered. The practicing chemical engineer is always confronted with uncertainty, and some analytical methods and procedures for quantifying and dealing with uncertainty are presented.

In Chapter 10 several of the more formal and systematic procedures for the synthesis of chemical processes are discussed. Some elements of optimization and chemical process simulation are presented, and a computer-aided process synthesizer is described. In Chapter 11 five case studies are presented, and detailed analyses are made so that the reader can see how the various principles are applied and how they work out in practice. Numerous examples are solved throughout the book, and a large number of problems of varying complexity are included. Many of them are open-ended and can provide stimulating challenges to the reader. For the reader's convenience all the references are concentrated at the end of the book.

The book is suitable for a one- or two-semester course for advanced undergraduate or graduate chemical engineers. The recommended sequence of material is that presented in the book although there are a number of appropriate sequences. Another suitable sequence would be Chapters 1, 7, 8, 9, 2, 10, 3, 4, 5, 6, and 11. Depending upon the particular department and curriculum, Chapters 4, 5, and 6 may be treated very lightly if the instructor feels that the students have had sufficient and suitable exposure to this material in their undergraduate studies. Although in our department the course based on this book is accompanied by a separate plant design course, this book can be used in the traditional senior design course with lectures being given as needed in accordance with the progress of the design project.

It is hoped that this book, which is based on notes used in teaching a course in process analysis and design for chemical engineers for a number of years, will be useful in easing the young chemical engineer's transition from the academic world to the world of industrial chemical engineering practice where design decisions must be made. Practicing chemical engineers should find the integrative presentation of a number of chemical engineering tools and their application to process analysis and process design of value in their day-to-day confrontation with practice.

Thanks and acknowledgments are due to many: To my students, from whom I have learned much, but especially to the class of '79, who not only taught me much but also scrutinized the final manuscript for typographical errors and for errors of fact. To P. V. Danckwerts, J. F. Davidson, and K. Østergaard, for their hospitality: major parts of the manuscript were written when I was a visitor at the Shell Department of Chemical Engineering and the Danmarks Tekniske Højskole Instituttet for Kemiteknik. To the Master and Fellows of Churchill College, for the hospitality of their friendly and stimulating college during a sabbatical leave. To my departmental colleagues, and especially to D. Hasson for our many hours of discussion and for his encouragement. To my learned colleague from the Department of Chemistry, A. Halevi for the quotations from our Sages and from even earlier sources that he suggested for the chapters and that are as appropriate and relevant now as they were then.

The typing has been the work of Norma Jacob with an able assist by Talma Shavit. Some of the earliest parts were typed in Cambridge by Miss Margaret Sansom and in Lyngby by my wife.

The debt I owe to my wife cannot be measured. Suffice it to say that I have relied on her for advice, support, and encouragement through all our years of marriage.

William Resnick

LIST OF SYMBOLS

a = van der Waals constant
A = availability of component; course of action; heat-transfer coefficient
b = van der Waals constant
B = availability
c_p = heat capacity at constant pressure
c_p^0 = ideal-gas constant-pressure heat capacity
c_v = heat capacity at constant volume
C = cost
C_i = concentration of component i
D = annual depreciation; product demand
E = activation energy; economic measure of performance; internal energy
f = fraction of market; fugacity; inflation rate
f_f = failure probability density function
f_r = repair-time probability density function
F = annual fixed cost; molar flow rate
$\tilde{F}$ = function
$\overline{F}$ = annual maintenance cost per unit of investment; base case
g = acceleration of gravity; general economy growth rate
G = Gibbs free energy; mass flow rate per unit cross-sectional area
H = enthalpy
i = interest rate
I = investment
k = ratio of heat capacities; reaction rate constant; thermal conductivity
k_f = market-share rate factor
k_F = price-floor decay-rate factor
k_g = economy growth-rate factor
k_i = capacity of ith plant addition

k_L = learning-rate factor
k_M = price-margin decay-rate factor
k_0 = frequency factor
K = capitalized cost; reaction equilibrium constant
L = length
m = exponent in cost-capacity equation
M = molecular weight
n = number; number of interest periods; number of years; moles
N = number of moles
N_i = rate of change of number of moles of component i
NPW = net present worth
O = objective function
p = probability
P = parachor; pressure; present value; principal
$\bar{P}$ = production capacity
P_i = vapor pressure of component i
$\bar{P}_i$ = partial pressure of component i
P_F = price floor
P_M = price margin
P_v = vapor pressure
Q = heat; production rate
Q_d = design production rate
r = annular thickness
r_i = rate of formation of i per unit reactant volume
r_i' = rate of formation of i per unit reactor volume
r_i'' = rate of formation of i per unit interfacial area
R = gas constant; reflux ratio; region of available technology; reliability; uniform cash flow
$\dot{R}$ = uniform-cash-flow rate
$\mathscr{R}$ = reaction rate as moles per unit time per unit mass of catalyst
s = sensitivity
S = cross-sectional area; entropy; future value; interfacial area; state of nature
t = time
$\bar{t}$ = average residence time
t_r = reaction time
T = absolute temperature; number of trials; tax rate
T_c = temperature of coolant stream
u = velocity
U = unavailability; utility
v = specific volume; unit variable cost; volumetric feed rate

V = annual sales volume; variable; volume
W = catalyst weight; work
W_l = lost work
W_{rev} = reversible work
W_u = useful work
x = mole fraction (general or in liquids)
X = fractional conversion; task constraints
$X_i \cup X_j$ = union of sets X_i and X_j
$X_i \subset X_j$ = set X_i is contained in set X_j
$X_i \cap X_j$ = intersection of sets X_i and X_j
y = mole fraction in gases
z = elevation above a datum
Z = compressibility factor
α = pessimism-optimism index; stoichiometric coefficient
γ = fugacity coefficient
λ = mean failure rate
μ = dynamic viscosity; mean repair rate
ρ = density
ρ_b = bulk density
σ = standard deviation; surface tension
ϕ = instantaneous fractional yield
Φ = overall fractional yield

Subscripts

b = boiling
c = critical condition
f = final condition; formation
l = liquid
0 = initial condition
o = overhead product
r = reduced conditions
v = vapor, vaporization

Superscripts

b = bottom product
L = liquid
$^\circ$ = standard conditions
V = vapor phase

CONTENTS

CHAPTER
ONE

THE CHEMICAL INDUSTRY

Behold, as the clay is in the potter's hand, so are you in my hand.

Jeremiah, 18: 6

The products of the chemical industry, the raw materials it uses, and the markets it serves cover a range so diverse that the chemical industry defies a straightforward description. In this chapter we shall attempt to characterize the chemical industry, to indicate its diversity, and to point out not only its economic significance but also its importance in our day-to-day lives. The role played by the chemical engineer in this industry will also be described.

1-1 WHAT IS THE CHEMICAL INDUSTRY?

Because of the diversity of its products, raw materials, and markets, the chemical industry is one of the most difficult industries in the world to define. Even the definition of the chemical industry or of its products differs somewhat from country to country and in some cases even between different groups within the same country. A descriptive definition is possible, however, by defining the chemical process industries as those industries in which processes of a chemical nature predominate or which are closely related to such industries.

Production of chemicals as well as the production of certain raw materials used by the chemical industry are thus considered to be part of the chemical process industries. This latter category would include, for example, the production and purification of refinery gases and preparation of naphtha feedstocks for