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Richard Turton/Richard C. Bailie/Wallace B. Whiting/Joseph A. Shaeiwitz

Analysis, Synthesis, and Design of Chemical Processes

Third Edition

Prentice Hall International Series in the Physical and Chemical Engineering Sciences

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Preface

This book represents the culmination of many years of teaching experience in the senior design course at West Virginia University (WVU) and University of Nevada, Reno. Although the program at WVU has evolved over the past 30 years and is still evolving, it is fair to say that the current program has gelled over the past 20 years as a concerted effort by the authors to integrate design throughout the undergraduate curriculum in chemical engineering.

We view design as the focal point of chemical engineering practice. Far more than the development of a set of specifications for a new chemical plant, design is the creative activity through which engineers continuously improve the operations of facilities to create products that enhance the quality of life. Whether developing the grassroots plant, proposing and guiding process modifications, or troubleshooting and implementing operational strategies for existing equipment, engineering design requires a broad spectrum of knowledge and intellectual skills to be able to analyze the big picture and the minute details and, most important, to know when to concentrate on each.

Our vehicle for helping students develop and hone their design skills is process design rather than plant design, covering synthesis of the entire chemical process through topics relating to the preliminary sizing of equipment, flowsheet optimization, economic evaluation of projects, and the operation of chemical processes. The purpose of this text is to assist chemical engineering students in making the transition from solving well-posed problems in a specific subject to integrating all the knowledge that they have gained in their undergraduate education and applying this information to solving open-ended process problems. Many of the nuts-and-bolts issues regarding plant design (for example, what schedule pipe to use for a given stream or what corrosion allowance to use for a vessel in a certain service) are not covered. Although such issues are clearly important to the practicing engineer, several excellent handbooks and textbooks are available to address such problems, and these are cited in the text where applicable.

In the third edition, we have rearranged some of the material from previous editions, added a new chapter on batch processing and a section on optimization of batch processes, and supplied new problems for all of the quantitative chapters. We continue to emphasize the importance of understanding, analyzing, and synthesizing chemical processes and process flow diagrams. To this end, we have expanded Appendix B to include an additional seven preliminary designs of chemical processes. The CAPCOST program for preliminary evaluation of fixed capital investment and profitability analysis has been expanded to include more equipment. Finally, the chapters on outcomes assessment, written and oral communications, and a written report case study have been moved to the CD accompanying the text.

The arrangement of chapters into the six sections of the book is similar to that adopted in the second edition. These sections are as follows.

Section 1—Conceptualization and Analysis of Chemical Processes
Section 2—Engineering Economic Analysis of Chemical Processes
Section 3—Synthesis and Optimization of Chemical Processes
Section 4—Analysis of Process Performance
Section 5—The Impact of Chemical Engineering Design on Society
Section 6— Interpersonal and Communication Skills

In Section 1, the student is introduced first to the principal diagrams that are used to describe a chemical process. Next, the evolution and generation of different process configurations are covered. Key concepts used in evaluating batch processes are included in the new Chapter 3, and the chapter on product design has been moved to Chapter 4. Finally, the analysis of existing processes is covered.

In Section 2, the information needed to assess the economic feasibility of a process is covered. This includes the estimation of fixed capital investment and manufacturing costs, the concepts of the time value of money and financial calculations, and finally the combination of these costs into profitability measures for the process.

Section 3 covers the synthesis of a chemical process. The minimum information required to simulate a process is given, as are the basics of using a process simulator. The choice of the appropriate thermodynamic model to use in a simulation is covered, and the choice of separation operations is covered. In addition, process optimization (including an introduction to optimization of batch processes) and heat integration techniques are covered in this section.

In Section 4, the analysis of the performance of existing processes and equipment is covered. The material in Section 4 is substantially different from that found in most textbooks. We consider equipment that is already built and operating and analyze how the operation can be changed, how an operating problem may be solved, and how to analyze what has occurred in the process to cause an observed change.

In Section 5, the impact of chemical engineering design on society is covered. The role of the professional engineer in society is addressed. Separate chapters addressing ethics and professionalism, health, safety, and the environment, and green engineering are included.

In Section 6, the interpersonal skills required by the engineer to function as part of a team and to communicate both orally and in written form are covered (both in the text and on the CD). An entire chapter (on the CD) is devoted to addressing some of the common mistakes that students make in written reports.

Finally, three appendices are included. Appendix A gives a series of cost charts for equipment. This information is embedded in the CAPCOST program for evaluating fixed capital investments and process economics. Appendix B gives the preliminary design information for 11 chemical processes: dimethyl ether, ethylbenzene, styrene, drying oil, maleic anhydride, ethylene oxide, formalin, batch manufacture of amino acids, acrylic acid, acetone, and heptenes production. This information is used in many of the end-of-chapter problems in the book. These processes can also be used as the starting point for more detailed analyses—for example, optimization studies. Other projects, detailed in Appendix C, are included on the CD accompanying this book. The reader (faculty and students) is also referred to our Web site at che.cemr.wvu.edu/publications/projects/, where a variety of design projects for sophomore- through senior-level chemical engineering courses is provided. There is also a link to another Web site that contains environmentally related design projects.

For a one-semester design course, we recommend including the following core:

- Section 1—Chapters 1 through 6
- Section 3—Chapters 11, 12, and 13
- Section 5—Chapters 23 and 24

For programs in which engineering economics is not a prerequisite to the design course, Section 2 (Chapters 7–10) should also be included. If students have previously covered engineering economics, Chapters 14 and 15 covering optimization and pinch technology could be substituted.

For the second term of a two-term sequence, we recommend Chapters 16 through 20 (and Chapters 14 and 15 if not included in the first design course) plus design projects. If time permits, we also recommend Chapter 21 (Regulating Process Conditions) and Chapter 22 (Process Troubleshooting) because these tend to solidify as well as extend the concepts of Chapters 16 through 20, that is, what an entry-level process engineer will encounter in the first few years of employment at a chemical process facility. For an environmental emphasis, Chapter 25 could be substituted for Chapters 21 and 22; however, it is recommended that supplementary material be included.

We have found that the most effective way both to enhance and to examine student progress is through oral presentations in addition to the submission of written reports. During these oral presentations, individual students or a student group defends its results to a faculty panel, much as a graduate student defends a thesis or dissertation.

Because design is at its essence a creative, dynamic, challenging, and iterative activity, we welcome feedback on and encourage experimentation with this design textbook. We hope that students and faculty will find the excitement in teaching and learning engineering design that has sustained us over the years.

Finally, we would like to thank those people who have been instrumental to the successful completion of this book. Many thanks are given to all undergraduate chemical engineering students at West Virginia University over the years, particularly the period 1992–2008. In particular, we would like to thank Joe Stoffa, who was responsible for developing the spreadsheet version of CAPCOST, and Mary Metzger and John Ramsey, who were responsible for collecting and correlating equipment cost information for this edition. We also acknowledge the many faculty who have provided, both formally and informally, feedback about this text. Finally, RT would like to thank his wife Becky for her continued support, love, and patience during the preparation of this third edition.

R.T.
R.C.B.
W.B.W.
J.A.S.

About the Authors

Richard Turton, P.E., has taught the senior design course at West Virginia University for the past 22 years. Prior to this, he spent five years in the design and construction industry. His main interests are in design education, particulate processing, and process modeling.

Richard C. Bailie has more than ten years of experience in process evaluation, pilot plant operation, plant start-up, and industrial consulting. He also ran his own chemical company. He is professor emeritus at WVU, having taught chemical engineering for more than 20 years.

Wallace B. Whiting, P.E., is professor emeritus at University of Nevada, Reno. He has been involved in the practice and teaching of chemical process design for more than 24 years.

Joseph A. Shaeiwitz has been involved in the senior design sequence and unique sophomore- and junior-level integrated design projects at WVU for 20 years. His interests include design education and outcomes assessment.

List of Nomenclature

Symbol	Definition	SI Units
A	Equipment Cost Attribute	
A	Area	m^2
A	Absorption Factor	
A	Annuity Value	\$/time
$A/F, i, n$	Sinking Fund Factor	
$A/P, i, n$	Capital Recovery Factor	
BV	Book Value	\$
C	Equipment Cost	\$
C or c	Molar Concentration	$kmol/m^3$
CA	Corrosion Allowance	m
CBM	Bare Module Cost	\$
COM	Cost of Manufacture	\$/time
cop	Coefficient of Performance	
C_p	Heat Capacity	kJ/kg°C or kJ/kmol°C
CCP	Cumulative Cash Position	\$
CCR	Cumulative Cash Ratio	
D	Diameter	m
D	Amount Allowed for Depreciation	\$
D	Distillate Product Flowrate	kmol/time
d	Yearly Depreciation Allowance	\$/yr
$DCFROR$	Discounted Cash Flow Rate of Return	
DMC	Direct Manufacturing Cost	\$/time
$DPBP$	Discounted Payback Period	years
E	Money Earned	\$
E	Weld Efficiency	
E_{act} or E	Activation Energy	kJ/kmol
$EAOC$	Equivalent Annual Operating Cost	\$/yr
ECC	Equivalent Capitalized Cost	\$

f_q	Quantity Factors for Trays	
F	Future Value	\$
F	Molar Flowrate	kmol/s
F	Equipment Module Cost Factor	
F	Correction for Multipass Heat Exchangers	
F	Future Value	\$
F_d	Drag Force	N/m^2 or kPa
f	Friction Factor	
f	Rate of Inflation	
$F/A, i, n$	Uniform Series Compound Amount Factor	
FCI	Fixed Capital Investment	\$
$F/P, i, n$	Single Payment Compound Amount Factor	
FMC	Fixed Manufacturing Costs	\$/time
F_{Lang}	Lang Factor	
G	Gas Flowrate	kg/s, kmol/s
GE	General Expenses	\$/time
h	Individual Heat Transfer Coefficient	W/m^{2}K
H	Enthalpy or Specific Enthalpy	kJ or kJ/kg
H	Height	m
I	Cost Index	
i	Compound Interest	
i'	Effective Interest Rate Including Inflation	
$INPV$	Incremental Net Present Value	\$
$IPBP$	Incremental Payback Period	years
k	Thermal Conductivity	W/m K
k_o	Preexponential Factor for Reaction Rate Constant	Depends on molecularity of reaction
K_p	Equilibrium Constant	Depends on reaction stoichiometry
k_{reac} or k_i	Reaction Rate Constant	Depends on molecularity of reaction
L	Lean Stream Flowrate	kg/s
L	Liquid Flowrate	kg/s or kmol/s
$\dot{m}$	Flowrate	kg/s
m	Partition Coefficient (y/x)	
n	Life of Equipment	years
n	Years of Investment	years
n	Number of Batches	
n_c	Number of Campaigns	
N	Number of Streams	
N	Number of Trays, Stages, or Shells	
N	Molar Flowrate	kmol/s
$NPSH$	Net Positive Suction Head	m of liquid
NPV	Net Present Value	\$

N_{toG}	Number of Transfer Units	
OBJ, OF	Objective Function	usually \$ or \$/time
p	Price	\$
P	Dimensionless Temperature Approach	
P	Pressure	bar or kPa
P	Present Value	\$
P^*	Vapor Pressure	bar or kPa
P/A, i, n	Uniform Series Present Worth Factor	
PBP	Payback Period	year
PC	Project Cost	\$
P/F, i, n	Single Payment Present Worth Factor	
PVR	Present Value Ratio	
P(x)	Probability Density Function of x	
Q or q	Rate of Heat Transfer	W or MJ/h
Q	Quantity	
r	Reaction Rate	kmol/m^3 or kmol/kg cat s
r	Rate of Production	kg/h
R	Gas Constant	kJ/kmol K
R	Ratio of Heat Capabilities	
R	Residual Funds Needed	\$
R	Reflux Ratio	
Re	Reynolds Number	
R	Rich Stream Flowrate	kg/s
Rand	Random Number	
ROROI	Rate of Return on Investment	
ROROII	Rate of Return on Incremental Investment	
S	Salvage Value	\$
S	Maximum Allowable Working Pressure	bar
S	Salt Concentration Factor	
S	Sensitivity	
SF	Stream Factor	
t	Thickness of Wall	m
t	Time	s, min, h, yr
T	Total Time for a Batch	s, min, h, yr
T	Temperature	K, R, °C, or °F
u	Flow Velocity	m/s
U	Overall Heat Transfer Coefficient	W/m^{2}K
V	Volume	m^3
V	Vapor Flow Rate	kmol/h
v_{react}	Specific Volume of Reactor	m^3/kg of product
v_p	Velocity	m/s
$\dot{v}$	Volumetric Flowrate	m^3/s
W	Weight	kg

W	Total Moles of a Component	kmol
W or WS	Work	kJ/kg
WC	Working Capital	$
X	Conversion	
X	Base-Case Ratio	
x	Mole or Mass Fraction	
y	Mole or Mass Fraction	
YOC	Yearly Operating Cost	$/yr
YS	Yearly Cash Flow (Savings)	$/yr
z	Distance	m

Greek Symbols

α	Multiplication Cost Factor	
α	Relative Volatility	
ε	Void Fraction	
ε	Pump Efficiency	
ϕ	Fugacity Coefficient	
γ	Activity Coefficient	
η	Selectivity	
λ	Heat of Vaporization	kJ/kg
μ	Viscosity	kg/m s
ξ	Selectivity	
ρ	Density	kg/m^3
θ	Rates of Species Concentration to that of Limiting Reactant	s\
Θ	Cycle Time	s
τ	Space Time	s

Subscripts

1	Base Time
2	Desired Time
a	Required Attribute
ACT	Actual
Aux	Auxiliary Buildings
b	Base Attribute
BM	Bare Module
$clean$	Cleaning
$Cont$	Contingency
$cycle$	Cycle
d	Without Depreciation
D, d	Demand
E	Contractor Engineering Expenses
eff	Effective Interest
eq	Equivalent