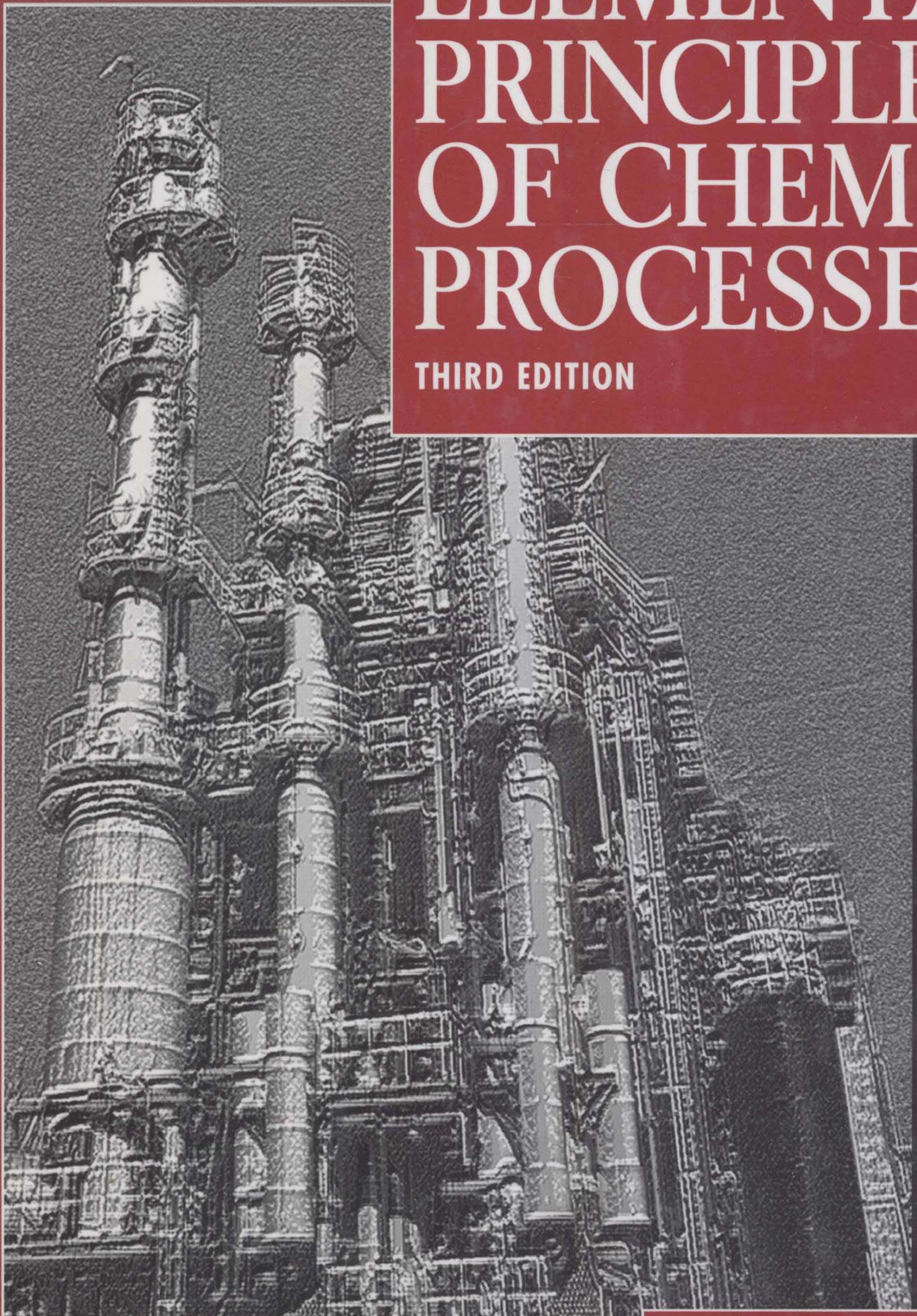
ELEMENTARY PRINCIPLES OF CHEMICAL PROCESSES

THIRD EDITION



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RICHARD M. FELDER
RONALD W. ROUSSEAU

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ELEMENTARY PRINCIPLES OF CHEMICAL PROCESSES

Third Edition

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About the Authors

Richard M. Felder is Hoechst Celanese Professor Emeritus of Chemical Engineering at North Carolina State University. He received the B.Ch.E. degree from the City College of New York and the Ph.D. in chemical engineering from Princeton University, and he worked for the Atomic Energy Research Establishment (Harwell, England) and Brookhaven National Laboratory before joining the North Carolina State faculty. He has authored or coauthored over 200 papers on chemical process engineering and engineering education and presented hundreds of seminars, workshops, and short courses in both categories to industrial and research institutions and universities throughout the United States and abroad. Since 1991 he has codirected the National Effective Teaching Institute under the auspices of the American Society for Engineering Education. He is a member of the Publication Board of *Chemical Engineering Education* and since 1988 has written the "Random Thoughts" column for that journal. His honors include the R.J. Reynolds Award for Excellence in Teaching, Research, and Extension, the AT&T Foundation Award for Excellence in Engineering Education, the Chemical Manufacturers Association National Catalyst Award, the ASEE Chester F. Carlson Award for Innovation in Engineering Education, the ASEE Chemical Engineering Division Lifetime Achievement Award for Pedagogical Scholarship, and a number of national and regional awards for his publications on engineering education including the 1988, 1989, 1996, and 2003 ASEE William J. Wickenden Award for the outstanding paper in the *Journal of Engineering Education.* Many of his publications can be found at <*http://www.ncsu.edu/effective_teaching*>.

Ronald W. Rousseau holds the Cecil J. "Pete" Silas Endowed Chair and also chairs the School of Chemical & Biomolecular Engineering at the Georgia Institute of Technology. He is an executive editor of *Chemical Engineering Science*, a member of the Publication Board of *Chemical Engineering Education*, and a topic editor for *Crystal Growth and Design*; he has been a member of the advisory boards of the Wiley Series in Chemical Engineering and of *Separations Technology*, a consulting editor for the *AIChE Journal*, and an associate editor of the *Journal of Crystal Growth.* He was the editor of the *Handbook of Separation Process Technology* (Wiley, 1987). In addition to his commitment to undergraduate education, he has been an active researcher in the field of separation science and technology. Among the many topics his work has addressed, recent attention has focused on the fundamentals of crystal nucleation and growth and the applications of crystallization science and technology. His contributions to the field of chemical separations technology were recognized through the Clarence G. Gerhold Award of the Separations Division of the American Institute of Chemical Engineers (AIChE). He is a Fellow of both AIChE and the American Association for the Advancement of Science. He is a graduate of Louisiana State University and an elected member of the LSU Engineering Hall of Distinction. He has served as chair of the Council for Chemical Research, member of the Board of Directors of AIChE, and chair of the AIChE Publication Committee.

Drs. Felder and Rousseau were joint recipients of the 2002 Warren K. Lewis Award for Contributions to Chemical Engineering Education from the American Institute of Chemical Engineers.

Preface to the Third Edition
2005 Edition
with Integrated Media and Study Tools

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 and transport phenomena, kinetics and reactor design, and process dynamics and control. 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 the 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. In the first chapter we survey fields that recent chemical engineering graduates have entered, from traditional industrial chemistry and petroleum engineering to materials engineering, environmental science and technology, biomedical, biochemical, and genetic engineering, information technology, law, and medicine, and we describe the variety of research, design, and production problems engineers typically confront. In the rest of the book we systematically develop the structure of elementary process analysis: definitions, measurement, and calculation of process variables; conservation laws and thermodynamic relations 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 and improve 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 heat capacity—we introduce them as quantities whose values are required to determine process variables or to perform material and 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.

FEATURES

Industrial Process Case Studies

An important feature of the book is a set of industrial process case studies that 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 4). In each study, the students are asked to produce a flowchart of a moderately complex process from a given description, to perform material and energy balance calculations on the process, and to answer questions that require consideration of 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 course content that will help them obtain the required solutions. The case study thus provides both motivation for learning the text material and a feeling for the contextual significance of this material.

SI Units

SI units are used widely but not exclusively throughout the text, and extensive SI data tables, including steam tables, are contained in the appendices.

Interactive Chemical Process Principles CD

The *Interactive Chemical Processes Principles* CD in the book contains:

- instructional tutorials,
- a learning style assessment tool,
- physical property lookup tables with an embedded routine for calculating sensible heats,
- *Visual Encyclopedia of Chemical Engineering Equipment,*
- E-Z Solve.

(See pages xiv-xvi for a more detailed description.)

Computational Software (E-Z Solve)

E-Z Solve

Computer programming is not covered explicitly, but problems that lend themselves to computer-aided solution are given after each chapter. An exceptionally robust and user-friendly equation-solving program (E-Z Solve) included on the Interactive Chemical Process Principles CD makes it possible for students to analyze relatively large processes without having to spend excessive time on algebraic and numerical calculations.

Website

Updates to the text and additional resources to support its use may be found at
<*http://www.ncsu.edu/felder-public/EPCP.html*>

- **Errata listing**—any errors found in the text will be listed on the website.
- **Illustrative course Web site**—A home page from the material and energy balance course at N.C. State University containing links to the course syllabus, policies and procedures, class handouts, study guides for exams, and old exams.
- **Handouts for students**—Tips on maintaining confidence, taking tests, and identifying and taking advantage of learning resources on campus.
- **Index of Learning Styles**—A self-scoring instrument that allows students (and instructors) to determine their learning style preferences. After taking the test, users can obtain information about the strengths of their learning styles and suggestions for how to get more out of their courses. (Also on the CD inside the text)
- **"Stoichiometry Without Tears'**—An article from *Chemical Engineering Education* offering suggestions for teaching the stoichiometry course.

Resources on the publisher's website

Visit the website at <*http://www.wiley.com/college/felder*> to access various resources. Some resources are password-protected, and available only to instructors using this text in their course. Visit the Instructor Companion Site portion of this website to register for a password.

ACKNOWLEDGMENTS

We acknowledge with gratitude the contributions of colleagues and students who have helped us since we began work on the first edition. Our thanks go to Dick Seagrave and the late Professors John Stevens and David Marsland, who read the original manuscript and offered many helpful suggestions for its improvement; our first department head, the late Jim Ferrell, who gave us invaluable encouragement when we brashly (and some might say, foolishly) launched into the book as young assistant professors; and our colleagues around the world who helped us prepare the case studies and suggested improvements in the three successive editions. We raise our glasses to the students in the Fall 1973 offering of CHE 205 at N.C. State, who had the bad luck to get the first draft as a course text. We're sorry we never managed to get to energy balances with them, and we hope and trust that they eventually learned them somewhere. We also thank the many N.C. State and Georgia Tech students in subsequent years who took the trouble to point out errors in the text, who we know did it out of a sense of professional responsibility and not just to collect the quarters. We thank Rebecca and Sandra for many years of unfailing encouragement and support, and last and most of all, we thank Magnificent Mary Wade, who uncomplainingly and with great good humor typed revision after revision of the first edition, until the authors, unable to stand any more, declared the book done.

Notes to Instructors

Suggestions for chapter coverage

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 semester-long courses in which most students have traditional first-year engineering backgrounds will cover most of the first nine chapters, possibly augmented with one case study. A one-quarter course should cover Chapters 1 through 6. Students who have been exposed to dimensional analysis and elementary data correlation can skip or skim Chapter 2, and students whose freshman chemistry courses provided a detailed coverage of process variable definitions and the systematic use of units to describe and analyze chemical processes may omit Chapter 3. The time gained as a result of these omissions may be used to cover additional sections in Chapters 4 through 9, to add Chapter 10 on computer-aided balances or Chapter 11 on transient balances, or to cover appended material on numerical analysis.

Teaching and promoting a systematic approach to process analysis

We have consistently found that the key to student success in the stoichiometry course is approaching the problems systematically: drawing and labeling flow charts, counting degrees of freedom to make sure that problems are solvable, and formulating solution plans before doing any calculations. We have also found that students are remarkably resistant to this process, preferring to launch directly into writing equations in the hope that sooner or later a solution will emerge. The students who make the transition to the systematic approach generally do well, while those who continue to resist it frequently fail.

Homework problems and assignment schedules

In our experience, the only way students learn to use this approach is by repeatedly practicing it. Hundreds of chapter-end problems in the text are structured to provide this practice. Representative assignment schedules are given in the Instructor Companion Site at <*http://www.wiley.com/college/felder*>, and there is enough duplication of problem types for the schedules to be varied considerably from one course offering to another.

Student Workbook *New!*

Student Workbook

A new feature of this updated edition is the availability of a supplementary workbook containing detailed outlines of solutions to selected chapter-end problems, with spaces for students to insert equations and numerical solutions. Working through these problems will help students become comfortable with the systematic approach sooner rather than later. We suggest that workbook problems be included in regular homework assignments, but at the very least, instructors should encourage their students to solve the problems on their own. **Problems in the Workbook are designated by an icon in the margin of this text.**

Developing creativity with open-ended problems

In addition to the basic material and energy problems at the end of the chapters, we have provided a variety of open-ended problems that focus on conceptual understanding and creative thinking, both imbedded within chapter-end problems and as separate "Creativity Exercises." We encourage instructors to assign these open-ended problems on a regular basis and perhaps to include similar problems on tests after ample practice has been provided in assignments. The problems can be introduced in a variety of ways: as focal points for in-class brainstorming sessions, as parts of regular or extra-credit homework assignments, or as individual or group projects with rewards (e.g., bonus points on subsequent tests) for the solutions exhibiting the greatest fluency (quantity of solutions). Far more than the algorithmic drills, these exercises convey a sense of the challenging and intellectually stimulating possibilities in a chemical engineering career. Conveying this sense may be the most valuable task that can be accomplished in the introductory chemical engineering course.

Using the case studies

We have discussed in the Preface the motivational aspects of the case studies and the way the studies complement the formal text material. 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 semi-anarchy and then developing cohesiveness as the weeks go by. By the end of the term most students have learned how to divide the labor appropriately and to learn from one another, since they know they are liable to be tested on any part of the project and not just the part for which they were personally 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 added educational benefits to all parties concerned.

Resources for instructors

The Instructor Companion Web Site contains resources for instructors, including illustrative assignment schedules, reproducible copies of figures in the text, and problem solutions. The password-protected site is accessible only to instructors who are using the text for their course. Go to <*http://www.wiley.com/college/felder*> and click on the link to "Instructor Companion Site" to register for a password.

RMF
RWR

Interactive Chemical Process Principles

(CD near front of text)

The CD that accompanies this edition of the text contains a variety of resources for students and instructors collected under the title *Interactive Chemical Process Principles* (ICPP). Some of the components of ICPP are instructional aids for the stoichiometry course, and others are computational and reference tools that should prove useful throughout the chemical engineering curriculum. One or more of the ICPP tools can be effectively applied to almost every example and problem in the book. Icons throughout the book remind students and instructors when the tools on the CD may be helpful.

In this section, we provide an overview of ICPP and some thoughts on how it might be used effectively as an adjunct to the text. We encourage you to read through this outline and then explore the tools for yourself. If you are a student, you will soon be able to recognize when you can use the tools for problem solving; if you are an instructor, you will see when suggestions for using the tools might be helpful in your lecture notes or assignments.

Index of Learning Styles

What is your Learning Style?

Students learn in a variety of ways. For example, some students are concrete and practical. These students appreciate many illustrations, examples, and applications of course material and are uncomfortable with abstract mathematical presentations. Other students are much more comfortable with abstraction and are easily bored by repetitive calculations and examples. Some learn visually, getting much more from pictures and diagrams than they do from words and formulas, while others benefit more from verbal explanations than from visual representations. The list of such differences is endless.

A student's *learning style* is a set of preferences for certain ways of taking in and processing information. The **Index of Learning Styles** (ILS) is an instrument that enables you to assess several of your learning style preferences. We sugggest that the first thing you do when you begin to explore ICPP is to complete the ILS, determine your learning style profile, and then read the accompanying material that suggests study strategies (if you are a student) or teaching strategies (if you are an instructor) that might work effectively for you in the stoichiometry course and in subsequent courses.

Instructional Tutorials

Interactive Tutorials

ICPP contains six interactive tutorials, designed for students to work through after they have progressed to certain points in the text. In each tutorial, process descriptions are given, questions are posed, and students enter answers and receive affirmation or corrective feedback, and then go on to additional questions. Process simulations are also included, so that students may predict how process systems will respond to changes in certain system variables, and then explore the effects of those changes experimentally. The active involvement and immediate feedback implicit in these exercises can significantly reinforce learning.

Once students can successfully work through a tutorial from beginning to end, they may be confident that they have mastered a significant portion of the material covered in that tutorial. If they have repeated trouble with a part of the tutorial, they will be able to identify gaps in their understanding of the course material and get help with them.

The tutorials and the points in the course when they may be completed are as follows:

1. Basic process calculations and process system variables (end of Chapter 3).
2. Material balances on nonreactive single-unit processes (end of Section 4.3).
3. Material balances on reactive multiple-unit processes (end of Chapter 4).
4. Material balances on multiphase systems (end of Chapter 6).
5. Material and energy balances on nonreactive processes (end of Chapter 8).
6. Material and energy balances on reactive processes (end of Chapter 9).

Physical Property Database

Physical Property Database

The physical property database of ICPP contains easily accessed values of molecular weights, specific gravities, phase transition points, critical constants, vapor pressures, heat capacities, and latent heats for many species that duplicate the values found in Appendix B of the text. The values retrieved from the database may be incorporated into process calculations performed using E-Z Solve.

The principal benefit to students is a built-in function for integrating tabulated heat capacities between specified temperature limits. Without this tool, polynomial formulas in Table B.2 of the text must be integrated term-by-term and the initial and final temperatures must be entered as the limits, with tedious calculations being required for the associated arithmetic. With the Physical Property Database tool, the desired species is selected from a pull-down menu, the initial and final temperatures are typed in, and a single click leads to the calculation of the integral. This feature will be most helpful in Chapters 8 and 9 of the text.

Visual Encyclopedia of Chemical Engineering Equipment

Equipment Encyclopedia

Most of the examples and problems in the text refer to items of equipment commonly found in chemical processes, such as reactors, heat exchangers, distillation columns, absorption towers, crystallizers, filters, and centrifuges. In some cases, brief explanations of these equipment items are given; in others, the terms are simply used. *The Visual Encyclopedia of Chemical Engineering Equipment*, created by Dr. Susan Montgomery of the University of Michigan, contains photographs, cutaway diagrams, movies, animations, and explanations of how the different equipment items work. It should be consulted to clarify references to process units in the text and to better understand how the processes described in the chapter-end problems work.

E-Z Solve

E-Z Solve

E-Z Solve is a powerful and user-friendly equation-solving program designed and written by Intellipro, the company that produced ICPP. It can be used to obtain numerical solutions of sets of linear and nonlinear algebraic equations of the types that occur in almost every chapter-end problem in Chapters 4 through 10 of the text, and it can also solve ordinary differential equations of the types that occur in Chapter 11. Examples of applications of E-Z Solve to representative stoichiometry problems are provided on the CD. E-Z Solve is convenient to use whenever a problem calls for solving three or more simultaneous linear algebraic equations or any number of nonlinear algebraic equations and ordinary differential equations.

We have found an interesting phenomenon associated with E-Z Solve, and that is that many students do not use it unless they are initially required to do so, probably because they are worried about the time it will take them to learn how. The result is that the students spend hours slogging through manual solutions of equations that could be solved in minutes with E-Z Solve. Once they have used the tool two or three times, however, they turn to it constantly throughout the remainder of the chemical engineering curriculum.

E-Z Solve more than lives up to its name. Here, for example, are three equations in three unknowns (x_A, x_B, T_{dp}) that arise as part of a problem in Chapter 6.

$$(1)\ x_A = \frac{0.980(760)}{10^{6.84471-\frac{1060.793}{T_{dp}+231.541}}} \qquad (2)\ x_B = \frac{0.020(760)}{10^{6.88555-\frac{1175.817}{T_{dp}+224.867}}} \qquad (3)\ x_A + x_B = 1$$

Solving these equations manually requires trial and error. It would be a long and tedious task if done with a simple calculator, and not too difficult for a spreadsheet. To use E-Z Solve, the following three lines of code would be typed in:

```
xa = 0.980*760/10^(6.84471–1060.793/(Tdp+231.541))
xb = 0.020*760/10^(6.88555–1175.817/(Tdp+224.867))
xa + xb = 1
```

Once the equations are entered, a command to "Solve" would be entered followed by a click on "OK," and the solution for all three variables would immediately appear. The longer and more complex the text problem, the greater the time saving that results from using E-Z Solve to solve the material and energy balance equations and physical property estimation formulas that arise in the course of its solution.

Nomenclature

The variables to be listed will be expressed in SI units for illustrative purposes, but they could equally well be expressed in any dimensionally consistent units.

a, b, c, d	Either arbitrary constants or coefficients of a polynomial expression for heat capacity, such as those listed in Appendix B.2.
C_p [kJ/(mol·K)], C_v [kJ/(mol·K)]	Heat capacities at constant pressure and constant volume, respectively.
E_k(kJ), $\dot{E}_k$(kJ/s)	Kinetic energy, rate of kinetic energy transport by a flowing stream.
E_p(kJ), $\dot{E}_p$(kJ/s)	Potential energy, rate of potential energy transport by a flowing stream.
g(m/s^2)	Gravitational acceleration constant, equal to 9.8066 m/s^2 or 32.174 ft/s^2 at sea level.
H (kJ), $\dot{H}$(kJ/s), $\hat{H}$(kJ/mol)	Enthalpy of a system (H), rate of transport of enthalpy by a process stream ($\dot{H}$), specific enthalpy ($\hat{H}$), all determined relative to a specified reference state.
m, M (kg), $\dot{m}$(kg/s)	Mass (m or M) or mass flow rate ($\dot{m}$) of a process stream or stream component.
n(mol), $\dot{n}$(mol/s)	Number of moles (n) or molar flow rate ($\dot{n}$) of a process stream or stream component.
p_A(N/m^2)	Partial pressure of species A in a mixture of gaseous species, $= y_A P$.
$p_A^*(T)$(N/m^2)	Vapor pressure of species A at temperature T.
P (N/m^2)	Total pressure of a system. Unless specifically told otherwise, assume that P is absolute pressure and not gauge pressure.
P_c(K)	Critical pressure. Values of this property are listed in Table B.1.
Q (kJ), $\dot{Q}$(kJ/s)	Total heat transferred to or from a system (Q), rate of heat transfer to or from a system ($\dot{Q}$). Q is defined to be positive if heat is transferred to the system.
R [kJ/(mol·K)]	Gas constant, given in different units on the inside back cover of the text.

SCMH, SCLH, SCFH	Abbreviations for standard cubic meters per hour [m^3(STP)/h], standard liters per hour [L(STP)/h], and standard cubic feet per hour [ft^3(STP)/h], respectively: the volumetric flow rate of a gas stream if the stream were brought from its actual temperature and pressure to standard temperature and pressure (0°C and 1 atm).
SG	Specific gravity, or ratio of the density of a species to the density of a reference species. The abbreviation is always used for liquids and solids in this text and usually refers to species for which specific gravities are listed in Table B.1.
t(s)	Time
T(K)	Temperature
T_{mp}, T_{bp}, T_c(K)	Melting point temperature, boiling point temperature, and critical temperature, respectively. Values of these properties are listed in Table B.1.
U(kJ), $\dot{U}$(kJ/s), $\hat{U}$(kJ/mol)	Internal energy of a system (U), rate of transport of internal energy by a process stream ($\dot{U}$), specific internal energy ($\hat{U}$), all relative to a specified reference state.
V(m^3), $\dot{V}$, $\dot{v}$ (m^3/s), $\hat{V}$(m^3/mol)	Volume (V) of a fluid or process unit, volumetric flow rate ($\dot{V}$ or $\dot{v}$) of a process stream, specific volume ($\hat{V}$) of a process material.
W(kJ), $\dot{W}_s$(kJ/s)	Work transferred to or from a system (W), rate of transfer of shaft work to or from a continuous process system ($\dot{W}_s$). W is defined to be positive (in this text) if work is transferred from a system to its surroundings.
x, y, z	Mass fraction or mole fraction of a species in a mixture. (Subscripts are usually used to identify the species.) In liquid-vapor systems, x usually denotes fraction in the liquid and y denotes fraction in the vapor. z may also denote the compressibility factor of a gas.

Greek letters

Δ	In batch (closed) systems, ΔX denotes the difference $X_{\text{final}} - X_{\text{initial}}$, where X is any system property. In continuous (open) systems, $\Delta\dot{X}$ denotes the difference $\dot{X}_{\text{output}} - \dot{X}_{\text{input}}$.
$\Delta\hat{H}_c$, $\Delta\hat{H}_f$(kJ/mol)	Heats of combustion and formation, respectively. Values of these properties at 25°C and 1 atmosphere are listed in Table B.1.
$\Delta\hat{H}_m$, $\Delta\hat{H}_v$(kJ/mol)	Heats of melting (fusion) and vaporization, respectively. Values of these properties at the

	normal melting and boiling points are listed in Table B.1.
ν_A	Stoichiometric coefficient of species A in a chemical reaction, defined to be positive for products, negative for reactants. For $N_2 + 3H_2 \rightarrow 2NH_3$, $\nu_{N_2} = -1$, $\nu_{H_2} = -3$, $\nu_{NH_3} = 2$.
ξ(mol)	Extent of reaction. If n_{A0}(mol) of reactive species A is initially present in a reactor and n_A(mol) is present some time later, then the extent of reaction at that time is $\xi = (n_{A0} - n_A)/\nu_A$, where ν_A is the stoichiometric coefficient of A in the reaction (see preceding definition). The value of ξ is the same regardless of which reactant or product is chosen as species A.
$\dot{\xi}$(mol/s)	Extent of reaction for a continuous process at steady state. If $\dot{n}_{A0}$(mol/s) of reactive species A enters the reactor and $\dot{n}_A$(mol/s) exits, then the extent of reaction is $\dot{\xi} = (\dot{n}_{A0} - \dot{n}_A)/\nu_A$, where ν_A is the stoichiometric coefficient of A in the reaction. The value of $\dot{\xi}$ is the same regardless of which reactant or product is chosen as species A.
ρ(kg/m^3)	Density.

Other Symbols

$\dot{}$ (e.g., $\dot{m}$)	Flow rate, such as mass flow rate.
$\hat{}$ (e.g., $\hat{U}$)	Specific property, such as specific internal energy.
( )	Parentheses are used to express functional dependence, as in $p^*(T)$ to denote a vapor pressure that depends on temperature, and also to enclose units of variables, as in m(g) to denote a mass expressed in grams. The intended use can usually be easily seen in context.

Glossary of Chemical Process Terms

Equipment Encyclopedia

Absorption A process in which a gas mixture contacts a liquid solvent and a component (or several components) of the gas dissolves in the liquid. In an *absorption column* or *absorption tower* (or simply *absorber*), the solvent enters the top of a column, flows down, and emerges at the bottom, and the gas enters at the bottom, flows up (contacting the liquid), and leaves at the top.

Adiabatic A term applied to a process in which no heat is transferred between the process system and its surroundings.

Equipment Encyclopedia

Adsorption A process in which a gas or liquid mixture contacts a solid (the *adsorbent*) and a mixture component (the *adsorbate*) adheres to the surface of the solid.

Barometer A device that measures atmospheric pressure.

Equipment Encyclopedia

Boiler A process unit in which tubes pass through a combustion furnace. *Boiler feedwater* is fed into the tubes, and heat transferred from the hot combustion products through the tube walls converts the feedwater to steam.

Boiling point (at a given pressure) For a pure species, the temperature at which the liquid and vapor can coexist in equilibrium at the given pressure. When applied to the heating of a mixture of liquids exposed to a gas at the given pressure, the temperature at which the mixture begins to boil.

Bottoms product The product that leaves the bottom of a distillation column. The bottoms product is relatively rich in the less volatile components of the feed to the column.

Bubble point (of a mixture of liquids at a given pressure) The temperature at which the first vapor bubble appears when the mixture is heated.

Calibration (of a process variable measurement instrument) A procedure in which an instrument is used to measure several independently known process variable values, and a *calibration curve* of known variable values versus the corresponding instrument readings is plotted. Once the instrument has been calibrated, readings obtained with it can be converted to equivalent process variable values directly from the calibration curve.

Equipment Encyclopedia

Catalyst A substance that significantly increases the rate of a chemical reaction, although it is neither a reactant nor a product.

Compressibility factor $z = PV/nRT$ for a gas. If $z = 1$, then $PV = nRT$ (the ideal gas equation of state) and the gas is said to *behave ideally.*

Equipment Encyclopedia

Compressor A device that raises the pressure of a gas.

Condensation A process in which an entering gas is cooled and/or compressed, causing one or more of the gas components to liquefy. Uncondensed gases and liquid *condensate* leave the condenser as separate streams.

Critical pressure, P_c The highest pressure at which distinct vapor and liquid phases can coexist for a species.

Critical temperature, T_c The highest temperature at which distinct vapor and liquid phases can coexist for a species. The critical temperature and pressure, collectively referred to as the *critical constants,* are listed for various species in Table B.1.

Equipment Encyclopedia

Crystallization A process in which a liquid solution is cooled, or solvent is evaporated, to an extent that solid crystals of solute form. The crystals in the *slurry* (suspension of solids in a liquid) leaving the crystallizer may subsequently be separated from the liquid in a filter or centrifuge.

Decanter A device in which two liquid phases or liquid and solid phases separate by gravity.

Degrees of freedom When applied to a general process, the difference between the number of unknown process variables and the number of equations relating those variables; the number of unknown variables for which values must be specified before the remaining values can be calculated. When applied to a system at equilibrium, the number of intensive system variables for which values must be specified before the remaining values can be calculated. The degrees of freedom in the second sense is determined using the Gibbs Phase Rule.

Dew point (of a gas mixture) The temperature at which the first liquid droplet appears when the mixture is cooled at constant pressure.

Equipment Encyclopedia

Distillation A process in which a mixture of two or more species is fed to a vertical column that contains either a series of vertically spaced horizontal plates, or solid packing through which fluid can flow. Liquid mixtures of the feed components flow down the column and vapor mixtures flow up. Interphase contact, partial condensation of the vapor, and partial vaporization of the liquid all take place throughout the column. The vapor flowing up the column becomes progressively richer in the more volatile components of the feed, and the liquid flowing down becomes richer in the less volatile components. The vapor leaving the top of the column is condensed: part of the condensate is taken off as the *overhead product* and the rest is recycled to the reactor as *reflux,* becoming the liquid stream that flows down the column. The liquid leaving the bottom of the column is partially vaporized: the vapor is recycled to the reactor as *boilup,* becoming the vapor stream that flows up the column, and the residual liquid is taken off as the *bottoms product.*

Equipment Encyclopedia

Drying A process in which a wet solid is heated or contacted with a hot gas stream, causing some or all of the liquid wetting the solid to evaporate. The vapor and the gas it evaporates into emerge as one outlet stream, and the solid and remaining residual liquid emerge as a second outlet stream.

Enthalpy (kJ) Property of a system defined as $H = U + PV$, where $U =$ internal energy, $P =$ absolute pressure, and $V =$ volume of the system.

Equipment Encyclopedia

Evaporation (vaporization) A process in which a pure liquid, liquid mixture, or solvent in a solution is vaporized.

Equipment Encyclopedia

Extraction (liquid extraction) A process in which a liquid mixture of two species (the *solute* and the *feed carrier*) is contacted in a mixer with a third liquid (the *solvent*) that is immiscible or nearly immiscible with the feed carrier. When the liquids are contacted, solute transfers from the feed carrier to the solvent. The combined mixture is then allowed to settle into two phases that are then separated by gravity in a decanter.

Equipment Encyclopedia

Filtration A process in which a *slurry* of solid particles suspended in a liquid passes through a porous medium. Most of the liquid passes through the medium (e.g., a filter) to form the *filtrate,* and the solids and some entrained liquid are retained on the filter to form the *filter cake.* Filtration may also be used to separate solids or liquids from gases.

Equipment Encyclopedia

Flash vaporization A process in which a liquid feed at a high pressure is suddenly exposed to a lower pressure, causing some vaporization to occur. The vapor product is rich in the more volatile components of the feed and the residual liquid is rich in the less volatile components.

Flue gas See *stack gas.*

Heat Energy transferred between a system and its surroundings as a consequence of a temperature difference. Heat always flows from a higher temperature to a lower one.

Equipment Encyclopedia

Heat exchanger A process unit through which two fluid streams at different temperatures flow on opposite sides of a metal barrier. Heat is transferred from the stream at the higher temperature through the barrier to the other stream.

Internal energy (U) The total energy possessed by the individual molecules in a system (as opposed to the kinetic and potential energies of the system as a whole). U is a strong function of temperature, phase, and molecular structure, and a weak function of pressure (it is independent of pressure for ideal gases). Its absolute value cannot be determined, so it is always expressed relative to a reference state at which it is defined to be zero.

Equipment Encyclopedia

Membrane A thin solid or liquid film through which one or more species in a process stream can permeate.

Overhead product The product that leaves the top of a distillation column. The overhead product is relatively rich in the most volatile components of the feed to the column.

Equipment Encyclopedia

Pump A device used to propel a liquid or slurry from one location to another, usually through a pipe or tube.

Equipment Encyclopedia

Scrubber An absorption column designed to remove an undesirable component from a gas stream.

Equipment Encyclopedia

Settler See *decanter.*

Shaft work All work transferred between a continuous system and its surroundings other than that done by or on the process fluid at the system entrance and exit.

Stack gas The gaseous products exiting from a combustion furnace.

Equipment Encyclopedia

Stripping A process in which a liquid containing a dissolved gas flows down a column and a gas (*stripping gas*) flows up the column at conditions such that the dissolved gas comes out of solution and is carried off with the stripping gas.

Vapor pressure The pressure at which pure liquid A can coexist with its vapor at a given temperature. In this text, vapor pressures can be determined from tabulated data (e.g., Tables B.3 and B.5–B.7 for water), the Antoine equation (Table B.4), or the Cox chart (Figure 6.1-4).

Volume percent (% v/v) For liquid mixtures, the percentage of the total volume occupied by a particular component; for ideal gases, the same as mole percent. For nonideal gases, the volume percent has no meaningful physical significance.

Work Energy transferred between a system and its surroundings as a consequence of motion against a restraining force, electricity or radiation, or any other driving force except a temperature difference.