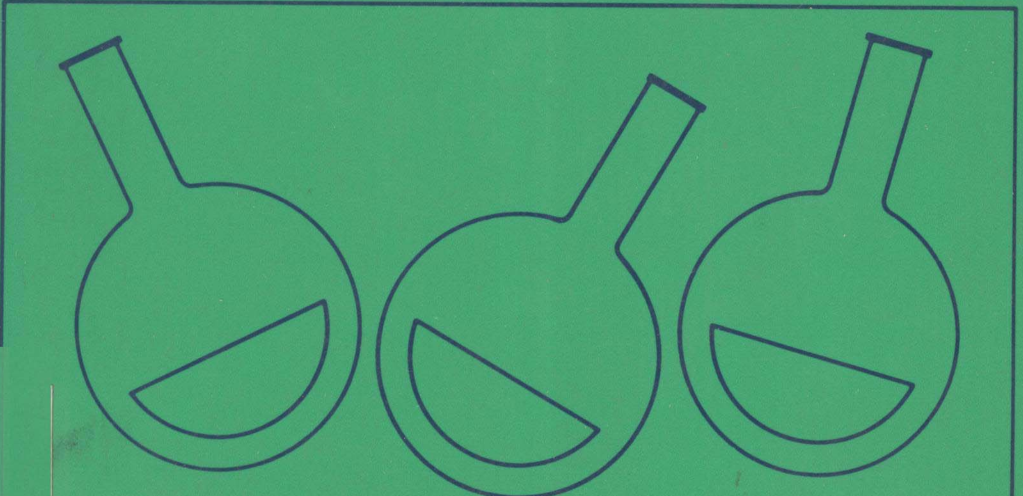
ELEMENTARY CHEMICAL ENGINEERING

MAX PETERS

SECOND EDITION



INTERNATIONAL STUDENT EDITION

ELEMENTARY CHEMICAL ENGINEERING

Second Edition

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INTERNATIONAL STUDENT EDITION

McGRAW-HILL BOOK COMPANY

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INTERNATIONAL STUDENT EDITION

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General engineering factors and constants*

Length		Mass	
1 inch	2.54 centimeters	1 pound†	16.0 ounces
1 foot	30.48 centimeters	1 pound†	453.6 grams
1 yard	91.44 centimeters	1 pound†	7000 grains
1 meter	100.00 centimeters	1 ton (short)	2000 pounds†
1 meter	39.37 inches	1 kilogram	1000 grams
1 micron	10^{-6} meter	1 kilogram	2.205 pounds†
1 mile	5280 ft		
1 kilometer	0.6214 mile	†Avoirdupois	

Volume

1 cubic inch	16.39 cubic centimeters
1 liter	61.03 cubic inches
1 liter	1.057 quarts
1 cubic foot	28.32 liters
1 cubic foot	1728 cubic inches
1 cubic foot	7.481 U.S. gallons
1 U.S. gallon	4.0 quarts
1 U.S. gallon	3.785 liters
1 U.S. bushel	1.244 cubic feet

Density

1 gram per cubic centimeter	62.43 pounds per cubic foot
1 gram per cubic centimeter	8.345 pounds per U.S. gallon
1 gram mole of an ideal gas at 0 C and 760 mmHg is equivalent to 22.414 liters	
1 pound mole of an ideal gas at 0 C and 760 mmHg is equivalent to 359.0 cubic feet	
Density of dry air at 0 C and 760 mmHg	1.293 grams per liter = 0.0807 pound per cubic foot
Density of mercury	13.6 grams per cubic centimeter (at -2 C)

Pressure

1 pound per square inch	2.04 inches of mercury
1 pound per square inch	51.71 millimeters of mercury
1 pound per square inch	2.31 feet of water
1 atmosphere	760 millimeters of mercury
1 atmosphere	2116.2 pounds per square foot
1 atmosphere	33.93 feet of water
1 atmosphere	29.92 inches of mercury
1 atmosphere	14.7 pounds per square inch
1 atmosphere	101.325 kilopascals

Temperature scales

Degrees fahrenheit (F)	1.8 (degrees C) + 32
Degrees celsius (C)	(degrees F − 32)/1.8
Kelvin (K)	degrees C + 273.15
Degrees rankine (R)	degrees F + 459.7

* See also Tables A-6 and A-7 in App. A for SI conversion factors and more exact conversion factors.

General engineering conversion factors and constants* (*Continued*)

Power

1 kilowatt	737.56 foot-pounds force per second
1 kilowatt	56.87 Btu per minute
1 kilowatt	1.341 horsepower
1 horsepower	550 foot-pounds force per second
1 horsepower	0.707 Btu per second
1 horsepower	745.7 watts

Heat, energy, and work equivalents

	cal	Btu	ft · lb	kWh
cal	1	3.97×10^{-3}	3.086	1.162×10^{-6}
Btu	252	1	778.16	2.930×10^{-4}
ft · lb	0.3241	1.285×10^{-3}	1	3.766×10^{-7}
kWh	860,565	3412.8	2.655×10^{6}	1
hp-h	641,615	2545.0	1.980×10^{6}	0.7455
joules	0.239	9.478×10^{-4}	0.7376	2.773×10^{-7}
liter-atm	24.218	9.604×10^{-2}	74.73	2.815×10^{-5}

	hp-h	joules	liter-atm
cal	1.558×10^{-6}	4.1840	4.129×10^{-2}
Btu	3.930×10^{-4}	1055	10.41
ft · lb	5.0505×10^{-7}	1.356	1.338×10^{-2}
kWh	1.341	3.60×10^{6}	35,534.3
hp-h	1	2.685×10^{6}	26,494
joules	3.725×10^{-7}	1	9.869×10^{-3}
liter-atm	3.774×10^{-5}	101.33	1

Constants

e 2.7183

π 3.1416

Gas-law constants:

R 1.987 (cal) (g mol) (K) or (Btu)/(lb mol) (°R)

R 82.06 (cm³) (atm)/(g mol) (K)

R 10.73 (lb in²) (ft³)/(lb mol) (°R)

R 0.730 (atm) (ft³) (lb mol) (°R)

R 1545.0 (lb/ft²) (ft³)/(lb mol) (°R)

R 8.314 (kPa) (m³)/(kg mol) (K) or (J)/(g mol) (K)

R 21.9 (in Hg) (ft³)/(lb mol) (°R)

g_c 32.17 (ft) (lbm)/(s) (s) (lbf)

Analysis of air

By weight: oxygen, 23.2%; nitrogen, 76.8%

By volume: oxygen, 21.0%; nitrogen, 79.0%

Average molecular weight of air on above basis = 28.84 (usually rounded off to 29)

True molecular weight of dry air (including argon) = 28.96

Viscosity

1 centipoise	0.001 kg/(m) (s)
1 centipoise	0.000672 lb (s) (ft)
1 centipoise	2.42 lb/(h) (ft)

* See also Tables A6 and A7 in App. A for SI conversion factors and more exact conversion factors.

ELEMENTARY CHEMICAL ENGINEERING

McGraw-Hill Chemical Engineering Series

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.

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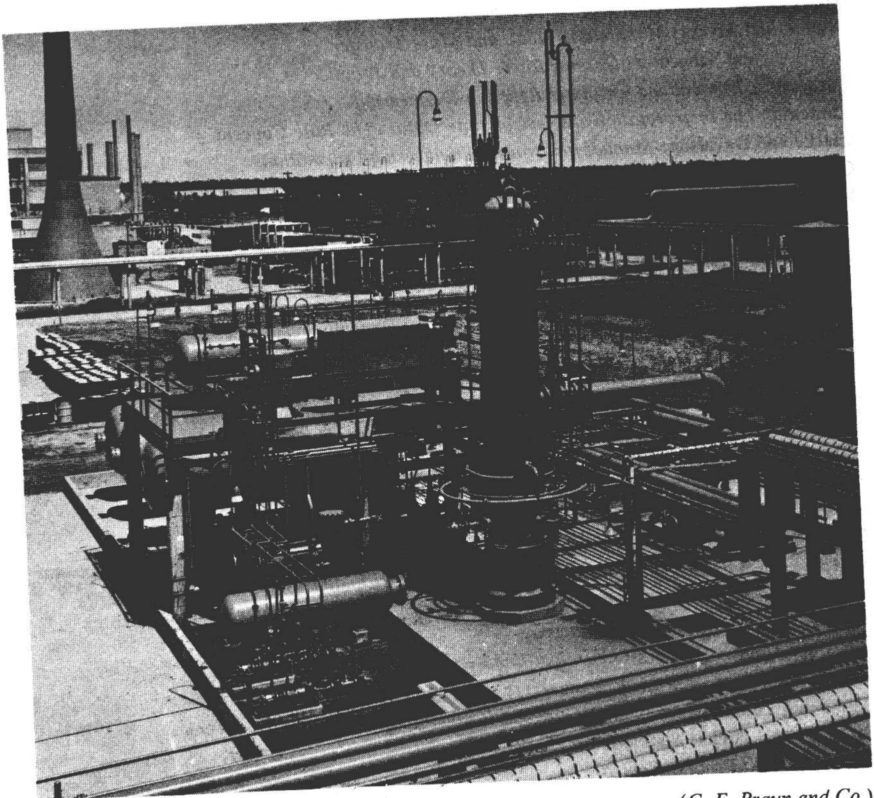

(*C. F. Braun and Co.*)

The chemical engineer understands the complete plant including the physical processes and the chemical changes.

$$\underset{\text{Dollars}}{\$} + \underset{\text{Chlorine}}{Cl_2} + \underset{\text{Ethylene}}{CH_2{=}CH_2} \longrightarrow \left\{\begin{array}{l}\text{Stoichiometry}\\ \text{Equipment}\\ \text{Unit Operations}\\ \text{Chemical Technology}\\ \text{Design and Economics}\\ \text{Production}\end{array}\right\}$$

$$\longrightarrow \underset{\text{Ethylene dichloride}}{CH_2ClCH_2Cl} + \underset{\text{Dollars}}{\$}$$

Dedicated to
LAURNELL STEPHENS PETERS

PREFACE

Modern industrial methods require the services of large numbers of technically trained specialists such as chemists, physicists, electrical engineers, mechanical engineers, engineering technologists, economists, or technical salespersons. These specialists cannot do an effective job unless they have a general knowledge and understanding of many subjects outside their own field. This is particularly true with reference to chemical engineering, a basic knowledge of which is necessary in almost all types of industrial work.

In this book, the principles of chemical engineering are presented in a form that will be easily understood by readers with no previous training in the field. The essential purpose has been to present a unified picture of chemical engineering, with emphasis upon the development, applications, and interrelationships of the basic principles.

The subjects of economics, distillation, flow of fluids, and the rest are not unrelated: they are part of the overall process and, as such, constitute the practical science of chemical engineering. Hence, a composite picture of chemical engineering is presented in the introductory chapters of this book, and the concept of the complete chemical plant and the various principles involved are discussed. This gives the reader an opportunity to become acquainted with the entire profession, and the need for understanding the various principles becomes immediately apparent.

Later chapters deal with stoichiometry, typical equipment, unit operations, chemical technology, economics, and plant design. Each chapter gives clearly and briefly the essential, basic information on the particular subject.

The book is organized to permit its use as a text in a general chemical engineering course for nonmajors, as well as an introductory text for persons majoring in the field. The entire text can be covered in a two-semester three-hour course, and it should be possible to treat most of it more briefly but adequately in a one-semester course. The book can be used as a reference in a short course on chemical engineering for non-chemical engineers, and it should also be of value to practicing chemists, industrial supervisors or executives, technical salespersons, engineers, and engineering technologists.

The author has used the first edition of this book successfully as the text for the introductory first-semester freshman-level course for chemical engineers. For this two-hour course, emphasis was placed on all of Chaps. 2 (Technical Introduction), 3 (Chemical Engineering Stoichiometry), 4 (Industrial Chemical Engineering Equipment), 5 (Fluid Flow), 13 (Chemical Technology), and 14 (Chemical Engineering Economics and Plant Design), with partial coverage of Chaps. 6 (Heat Transfer), 7 (Evaporation), and 8 (Distillation). This coverage was sufficient to show the general field of chemical engineering to the students and allow a presentation that was relatively quantitative. Senior chemical engineering students volunteered to serve as teaching assistant–counselors for the course, grading the homework problems and serving as friend and counselor for the individual freshmen on a person-to-person basis. The seniors enjoyed this activity and always volunteered in sufficient numbers so that each senior would grade and work with only about six to eight freshmen.

A large amount of previous technical training is not required for an understanding of the material as presented. A good mathematical background with some calculus will permit the reader to obtain a grasp of the material rapidly; however, the method of presentation will enable even the reader with no advanced mathematical training to understand much of the subject matter. In some sections, where the mathematics involved would be above the level of many readers, simplified derivations of the mathematical relationships of physical variables have been presented. The fundamental derivations of these relationships using more advanced mathematics have been presented in App. B. References to the chemical engineering literature have been included to show where additional information may be obtained.

Many illustrative examples have been used throughout the text. The author has found this to be one of the best means for conveying to the reader the applicability of theoretical reasoning to actual cases and for showing the importance of clear designation and use of units. Problems have been given at the end of individual chapters to illustrate the information presented in the chapter and to give the reader a chance to test the understanding of the material. Some of the problems are designed to require computer solution for those who wish to try out their skills in computer programming. Answers have been given in App. D, permitting the reader to determine immediately if he or she has attacked the problems correctly.

The study of chemical engineering can be a fascinating experience. However, there is no quick and easy method for becoming proficient in this field. The reader who expects to obtain the maximum benefit from this book must be prepared to make a sincere and concentrated effort to understand the text material and the problems. If the elementary principles are clearly understood, the applications and advanced treatment will be easy to grasp.

The same style and form of presentation used in the first edition have been retained for the second edition, with changes relating primarily to the introduction of SI units and to the updating of discussions of process data. The author repeats his thanks from the first edition to numerous individuals for their critical perusal of the material and for their many helpful suggestions. The author here extends his thanks to his students who have made suggestions for improvements after using the book and to his many colleagues and peers, such as Klaus D. Timmerhaus and Ronald E. West of the University of Colorado, James R. Fair of the University of Texas, and Joseph E. Nowrey and J. E. Ekhaml of Trident Technical College, who have provided useful input for preparing the second edition.

Max S. Peters

ELEMENTARY CHEMICAL ENGINEERING

CONTENTS

CHAPTER

ONE

CHEMICAL ENGINEERS AND THEIR PROFESSION

Chemical engineering is a science and an art dealing with the relationships of physical and chemical changes. This profession came into existence toward the end of the nineteenth century when the need for technical workers with a combined training in physics, chemistry, and mechanical engineering became apparent. Since that time, the profession of chemical engineering has increased in stature, until it now stands as an integral and essential part of our modern industrial society.

The chemical engineer must have a wide variety of talents. One must understand how and why a given process works, be able to design, set up, and operate equipment to carry out the process, and have the ability to determine the profits obtainable by carrying out the particular process. One must have the theoretical understanding of a physicist combined with the practical attitude of a mechanic or a loan agency. In addition, the chemical engineer is in constant contact with workers of widely varying levels of intelligence and must have the ability to maintain friendly and effective relations with all these persons.

The fundamental working tools of the chemical engineer are the basic laws of chemistry and physics, a logical mind, and an aptitude for the practical application of mathematics, including computer applications. The use of these tools permits the various principles to come to life as finished chemical plants or such simple final products as a cake of soap, a can of paint, or the plastic handle of a toothbrush.

An example of the application of the principles can be found in the final step involved in the production of nitric acid. Nitric acid is formed when nitrogen dioxide reacts with water. This reaction gives off heat, which must be removed if the process is to continue efficiently. One method for removing the heat is to pass cold water through the inside of a tube immersed in the hot nitric acid. The heat passes through the wall of the tube into the cold water and is thereby removed from the system. By applying basic principles, the chemical engineer can determine what length of tube must be immersed in the nitric acid to ensure adequate removal of the heat, the best diameter of the tube, the flow of water necessary, and even the best material for making the tube. These same principles can be used to find how fast a hot ingot of iron will cool or how much heat should be supplied to a room to maintain a constant temperature.

The chemical engineer is trained to take chemical and physical processes from small-scale operation to large-scale operation. The chemist in the research laboratory may find a new method for producing a certain chemical. In the laboratory, the chemist probably carried out the process in glass beakers and transferred the products from one container to another by hand. When the chemical engineer takes over this process to develop it for large-scale operation, many things must be considered which were of no importance to the chemist. A glass beaker may have been suitable for the laboratory work since it was only the chemical reaction that was of importance. However, the chemical engineer must attempt to use for the container a material which has good heat-transfer and corrosion-resistance qualities while being cheap, easily fabricated, and not easily broken. The rate of the reaction must also be considered as well as effects of changes in temperature or pressure. Practical methods for transfer of the material from one container to another must be found for the large-scale operation, since it is ordinarily too expensive to transfer materials by hand. In the practice of chemical engineering, then, it is necessary to understand the basic principles of chemistry as well as the economics and principles involved in physical processes.

There are many different types of work for which chemical engineers are fitted. Some of these are plant and equipment design, plant operation and supervision, technical sales, consulting work, basic and applied research, market development, and teaching.

THE TECHNIQUES OF CHEMICAL ENGINEERING

The chemical engineer must use fundamental working tools to transform the theoretical principles into practical results. A number of different techniques have been developed for accomplishing this transformation. One of the basic techniques is the use of generalized mathematical expressions for indicating the relationships between physical variables. These expressions are merely shorthand indications showing how the different variables are interrelated. This last statement may appear to be obvious; however, many prospective chemical engineers have fallen by the wayside because they could never attach the true physical significance to a mathematical expression.

Consider the simple example of the pythagorean theorem, which is familiar to all high school mathematics students. This theorem states that the square of the length of the hypotenuse of a right triangle equals the sum of the squares of the length of the two triangle legs. Mathematically, this may be expressed as

$$h^2 = a^2 + b^2$$