Chemical Engineering for Chemists

Richard G. Griskey

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About the Author

RICHARD G. GRISKEY, Institute Professor Emeritus of Chemistry and Chemical Engineering at Stevens Institute of Technology since 1992, was born in Pittsburgh, Pennsylvania. He received his B.S. in chemical engineering from Carnegie-Mellon University in 1951. He served in the U.S. Army Combat Engineers from 1951 to 1953 (19 months in the Far East during the Korean War). He was then awarded an M.S. and a Ph.D. from Carnegie-Mellon.

Griskey has served as a professor and administrator at many institutions, including the University of Cincinnati, Virginia Polytechnic Institute and State University, the University of Denver, New Jersey Institute of Technology, the University of Wisconsin—Milwaukee, the University of Alabama—Huntsville, Stevens Institute of Technology, and Vanderbilt University. Griskey has held every academic rank (including distinguished professor); he has been a department chair, dean of engineering, provost, and executive vice-president.

Griskey is a fellow of the American Institute of Chemical Engineers (AIChE), the American Society of Mechanical Engineers, and the American Institute of Chemists. He received an Exceptional Achievement Award from the American Chemical Society (Division of Industrial and Engineering Chemistry, Inc.) and has been nominated five times for AIChE's Alan P. Colburn Award (awarded annually to authors of technical papers). He is a member of Sigma Xi and Tau Beta Pi. He has written more than 200 publications, several monographs, and three textbooks. He is listed in *Who's Who in America* and *Who's Who in Engineering*.

Griskey has held visiting professorships at the University of São Paulo in Brazil, Monash University in Australia, and the Institut du Pétrole in Algeria and has been an invited lecturer for the Royal Society of Chemistry in England. In 1971, the National Academy of Science appointed him senior visiting scientist to Poland.

Griskey has full-time industrial experience with Gulf Oil Research, DuPont, and Celanese. Consulting experience includes Hoechst-Celanese, Phillips Petroleum, Monsanto, 3M, ICI, Hewlett-Packard, American Cyanamid, and Litton Industries.

Preface

The impact of chemistry on the world is immense. Its importance is realized in basic chemical and petroleum industries, as well as in high-technology areas such as energy, environmental, biochemical, biomedical, and advanced materials, which are rapidly shaping the future. Yet although it is obvious that chemistry is a necessary ingredient in our world, it has been less clear in academic circles what skills are needed by scientists and engineers employed in the chemical industry and government to be successful professional practitioners.

To better understand the problem of educational needs, let us first consider chemistry to be a continuum that ranges from theoretical science to the application of chemical principles in technology. A simplistic view of a professional's responsibility within the continuum would be that a chemist takes care of theory and a chemical engineer handles application. Unfortunately, this is not how the industrial world works: Individual chemists and chemical engineers often find themselves at various places in the continuum. Chemists' responsibilities many times include applications, and chemical engineers find that they require a sound knowledge of basic chemistry. Hence, it is apparent that the practicing chemical professional in industry and government requires a broad range of chemical knowledge.

Academic training of chemical engineers already acknowledges the need for a broad chemical education because it mandates that undergraduate students take significant course work in analytical, organic, and physical chemistry, all, incidentally, usually taught by the chemistry department at colleges and universities. Degree accreditation, which is a joint effort by the American Institute of Chemical Engineers (AIChE) and the Accreditation Board for Engineering and Technology (ABET), is not granted unless the chemistry requirements are met. Actually, the total credits of chemistry required by the chemical engineering degree far exceed the number normally required for a chemistry minor in most liberal arts programs. The additional applied chemistry courses, such as thermodynamics and kinetics, that are taken by the engineering students make it even more evident that the holder of a baccalaureate in chemical engineering has an exceptionally strong chemistry background.

The inverse, that the academic training of chemists requires a significant number of courses in chemical engineering, is not the case except in certain countries in continental Europe. The lack of engineering courses causes problems for the chemist when he or she ends up in an applications area of the chemistry continuum.

However, the problem can be alleviated by providing chemical professionals with sufficient chemical engineering background, knowledge, and wherewithal that enable them to realize their full potential.

THE APPROACH OF THIS BOOK

Chemists already have a theoretical grounding in many topics that engineers are trained to apply, so the approach of this book is to start with what chemists know and add relevant principles to them. I do not seek to teach a new approach to a skill that chemists already possess. Chemists, for example, learn stoichiometry and certain aspects of thermodynamics, chemical equilibrium, and chemical reaction kinetics. I have chosen to concentrate on new principles and move them from the theoretical to the semiempirical to the empirical approaches needed to use them.

I have selected my approach based on my past experience gained from teaching chemical engineering to chemists. Some people might argue that chemists should take all of the chemical engineering courses they have not had, but I believe that chemists already have a strong background in many of the topics covered in introductory chemical engineering courses. I did not always believe this. While at the University of Denver in the late 1960s, I initiated and taught a graduate course titled "Chemical Engineering for Scientists". One part of the course called for me to teach the students how to do mass balances. I handed out a set of homework problems of the sort that are typical in an engineering course, requiring them to be done by the next class.

At the next meeting, I collected the homework and began to go over the problems. As I did so, the students in the class wore perplexed expressions that changed to surprise when I obtained the correct answer. Sensing that something was out of order, I asked the group what was wrong. Their collective response was, "We've never seen anyone do a mass balance that way." I asked one of them to work the problem at the board, upon which *I* looked perplexed and surprised when the student got the correct answer.

The obvious lesson I learned is that chemists, as do scientists and engineers, thoroughly understand basic mass balances and do not have to learn stoichiometry. Similarly, other topics such as chemical equilibrium are understood in much the same way. Therefore, this text, while it touches on these subjects, will do so only as a brief review and exposure to the chemical engineering approach.

HOW THIS TEXT CAN HELP YOU

The selection of topics used in this book was derived from my experience working with chemists in industry, from my teaching and research activities, and, last but not least, from my interactions with more than 4000 professionals who have taken my three-day course, Chemical Engineering and Process Fundamentals for Chemists, sponsored by the American Chemical Society. The last experience has been especially useful in shaping the text and has provided insight as to how powerful chemical engineering knowledge can be in enhancing one's career. A few examples reported by some of the course alumni will demonstrate this point:

- One individual who came to the class was the supervisor of a large number of professionals (half were chemists and half engineers). The engineers, the supervisor said, were using the supervisor's lack of process knowledge to their advantage, using engineering jargon during meetings and generally making things difficult. After taking the course, the supervisor was able to understand what the engineers were discussing and was, in fact, able to ask more perceptive and applicable questions and to control meetings with more authority. Understanding engineering basics leveled the playing field.
- Another class attendee was a researcher who had large amounts of interesting data that had defied interpretation. A knowledge of how to apply dimensionless groups of numbers to data from different scales of operations (a technique commonly used by chemical engineers) gave this individual the means to both comprehend the significance of the data and the ability to write three refereed journal articles.
- A third person was transferred to a pilot plant group after taking the course. This individual said that the understanding of chemical engineering basics (i.e., heat transfer and reactor design) made it possible to perform on a level orders of magnitude above the precourse level.

There is general concensus among course attendees that they were able to handle a wide range of process situations and problems. Furthermore, everyone agreed that technical communication and jargon problems disappeared.

HOW TO USE THIS BOOK

Each chapter contains examples of problems and their complete solutions, the complexity of which should not be a problem to any chemist, scientist, or engineer who has had calculus. (Most of the problems require more algebra than calculus.) And finally, references and further reading sources are provided at the end of each chapter.

I suggest that you read Chapters 1 through 6 in order because each subsequent chapter builds on the concepts of the previous one. Working through the solved examples in each chapter is extremely helpful. Above all, try to develop a physical sense of the meaning of the materials.

Finally, this text is just a start, not an end. There is a Chinese proverb that says, "A journey of a thousand miles begins with a single step." It is my hope that this text will provide many steps along the journey toward an understanding of chemical engineering principles and applications, a journey that will bring you to an even higher level of professional competence.

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Introduction to Chemical Engineering Principles

INTERFACE BETWEEN CHEMISTRY AND CHEMICAL ENGINEERING

Chemistry and chemical engineering, though taught as separate disciplines, are parts of the fabric that is chemical science and technology. Although they are closely related, chemistry and chemical engineering do differ.

Chemistry came first in the cultures of many nations from the earliest times. Chemical engineering came later when the large, complex production during the Industrial Revolution (18th and 19th centuries) demanded skills beyond those offered by chemistry or traditional engineering education. Fluids, previously transported on a small scale in buckets or flasks, needed to be moved by piping and pumps. Heat could no longer be supplied by throwing another log on the fire. Industrial production needed the help of an engineer.

At first, a mechanical engineer seemed to have the knowledge to make large-scale processes possible. But mechanical engineering could not provide the technology needed because it was divorced from chemistry. Mechanical engineers worked with mass. The mole was a foreign concept to them, and molecular weight was as close as they came to chemistry. There was a chasm between chemists and mechanical engineers.

The chemical industry needed engineers familiar with chemistry and production, so chemical engineering was born. At first, chemical engineering was a branch of chemistry, just as organic, physical, inorganic, and analytical chemistry were established. During the Industrial Revolution, however, chemistry was undergoing a major change, developing into a science in which it was necessary to know the whys as much as the hows. Chemistry moved toward elucidating fundamentals and away from applications.

Today chemistry continues to move toward fundamentals, and this development puts chemists at a disadvantage in dealing with industrial processes. The physical chemistry course is an example of chemistry's concentration on fundamentals. Less than 20 years ago, it included treatment of the laws of thermodynamics, solution behavior, phase equilibrium, chemical kinetics, and diffusion phenomena, all applicable to designing and operating industrial processes. In many universities today, however, physical chemistry is dedicated mainly to statistical and quantum mechanics. Applied chemistry is now taught mainly in the engineering curriculum.

WHAT'S IN THIS BOOK

We're in another revolution now. New materials, new industries, and changing economics demand engineering skills from chemists, scientists, and researchers uneducated in engineering. With the proliferation of small technical companies, many classically trained scientists wear the hats not only of the discoverer of a new material, but also of the manager in charge of producing it commercially.

If you're reading this book, you've realized you need some practical engineering skills. This chapter summarizes the principal areas in chemical engineering that will enable you to understand and work successfully in a chemical plant, pilot plant, product development group, or scale-up project.

It is divided into chapters that concentrate on applied thermodynamics, fluid flow, heat transfer, mass transfer, chemical engineering kinetics, process design and control, and engineering economics. Each chapter presents a discussion of fundamentals with a large number of examples and their solutions. The approach should give you a firm grasp of basic principles and the ability to solve practical problems.

MASS BALANCES

An initial course in chemical engineering usually covers mass balances, familiar to chemists as stoichiometry. A mass balance represents nothing more than the Law of Mass Conservation, i.e., what goes into a system must come out or accumulate. On an industrial scale, mass is balanced across entire processes. It is one of the first tasks an engineer undertakes in designing or optimizing a process.

To obtain a mass balance, apply the following systematic approach:

1. Make a schematic flow diagram of the process, showing all process streams flowing into and out of the system, being sure to include recycled and side streams.
2. Note all of the physical and chemical changes taking place, and list all available data about the streams, including flow rates, temperatures, and pressures.
3. Choose a basis for the mass balance calculation (moles or mass) and a time period over which the balance will be calculated.
4. Select the process segment of interest and circle it to establish the streams entering and leaving. This circle is called the ***boundary***. Process streams that do not cut the boundary, including recycled flows, are not considered in the mass balance calculations.
5. Develop equations that describe relationships between entering and exiting streams and enable you to calculate the mass balances across the schematic.

You may need to develop several independent equations, one for each unknown variable. Sometimes in complex systems, many components are interrelated, greatly reducing the number of independent equations.

6. To solve the mass balance, track a compound or compounds through the chosen process segment. If a chemical reaction occurs, track an element or a radical.

Solutions for mass balance problems cannot be generalized and are handled by understanding the process. Because of the lack of generalization possible, this book does not devote a chapter to mass balancing. Instead, the mass balances shown in Examples 1.1 and 1.2 will get you started, and special situations in mass balancing will be noted in chapter examples hereafter.

Example 1.1 demonstrates the principle of mass balance, the interaction of input, output, and accumulation.

Example 1.2 illustrates several important mass balance techniques. The first technique shows how to track specific components through a process, rather than characterizing the overall mass flow. The second technique shows how to define the boundary for a mass balance; only those process streams within the boundary are considered in the mass balance calculations. Furthermore, we'll see that you can define as many boundaries as you need to solve the balance of a given situation.

EXAMPLE 1.1. MASS BALANCE ACROSS A STORAGE TANK

A half-full 60,000-gallon gasoline storage tank is filled from five sources in one day. These sources supply 8,000, 7,000, 5,000, 13,000, and 19,000 gallons, respectively. During the day, 57,000 gallons of gasoline are withdrawn. What is the final volume of gasoline in the tank?

The mass balance is solved by following the six steps previously described. The schematic for the first step is a sketch of a tank showing five input and one output streams. No chemical changes take place, only changes in flow. The mass balance is in gallons and the time interval is one day.

The law of conservation is

$$\Sigma m_{\text{input}} = \Sigma m_{\text{output}} + \Sigma m_{\text{accumulation}}$$

for which m is the mass or moles. (When there is no accumulation of flow, the system is operating under *steady-state* conditions. The accumulation here represents unsteady-state conditions.) The basis for this calculation is mass. To convert the units in gallons to mass, we apply

$$m = V\rho$$

where V is volume and ρ is the density of gasoline in weight per unit volume. The mass balance can then be stated:

$$\rho_{\text{input}}\Sigma V_{\text{input}} = \rho_{\text{output}}\Sigma V_{\text{output}} + \rho_{\text{accumulation}}\Sigma V_{\text{accumulation}}$$

If

$$\rho_{\text{input}} = \rho_{\text{output}} = \rho_{\text{accumulation}}$$

then,

$$\Sigma V_{\text{input}} = \Sigma V_{\text{output}} + \Sigma V_{\text{accumulation}}$$