CHEMICAL ENGINEERING

An Introduction

"Chemical engineering is the field of applied science that employs physical, chemical, and biochemical rate processes for the betterment of humanity." This opening sentence of Chapter 1 is the underlying paradigm of chemical engineering. *Chemical Engineering: An Introduction* is designed to enable the student to explore the activities in which a modern chemical engineer is involved by focusing on mass and energy balances in liquid-phase processes. Applications explored include the design of a feedback level controller, membrane separation, hemodialysis, optimal design of a process with chemical reaction and separation, washout in a bioreactor, kinetic and mass transfer limits in a two-phase reactor, and the use of a membrane reactor to overcome equilibrium limits on conversion. Mathematics is employed as a language at the most elementary level. Professor Morton M. Denn incorporates design meaningfully; the design and analysis problems are realistic in format and scope. Students using this text will appreciate why they need the courses that follow in the core curriculum.

Morton M. Denn is the Albert Einstein Professor of Science and Engineering and Director of the Benjamin Levich Institute for Physico-Chemical Hydrodynamics at the City College of New York, CUNY. Prior to joining CCNY in 1999, he was Professor of Chemical Engineering at the University of California, Berkeley, where he served as Department Chair, as well as Program Leader for Polymers and Head of Materials Chemistry in the Materials Sciences Division of the Lawrence Berkeley National Laboratory. He previously taught chemical engineering at the University of Delaware, where he was the Allan P. Colburn Professor. Professor Denn was Editor of the *AIChE Journal* from 1985 to 1991 and Editor of the *Journal of Rheology* from 1995 to 2005. He is the recipient of a Guggenheim Fellowship; a Fulbright Lectureship; the Professional Progress, William H. Walker, Warren K. Lewis, Institute Lectureship, and Founders Awards of the American Institute of Chemical Engineers; the Chemical Engineering Lectureship of the American Society for Engineering Education; and the Bingham Medal and Distinguished Service Awards of the Society of Rheology. He is a member of the National Academy of Engineering and the American Academy of Arts and Sciences, and he received an honorary DSc from the University of Minnesota. His previous books are *Optimization by Variational Methods*; *Introduction to Chemical Engineering Analysis*, coauthored with T. W. Fraser Russell; *Stability of Reaction and Transport Processes*; *Process Fluid Mechanics*; *Process Modeling*; and *Polymer Melt Processing: Foundations in Fluid Mechanics and Heat Transfer*.

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Preface

"Chemical engineering is the field of applied science that employs physical, chemical, and biochemical rate processes for the betterment of humanity." This opening sentence of Chapter 1 has been the underlying paradigm of chemical engineering for at least a century, through the development of modern chemical and petrochemical, biochemical, and materials processing, and into the twenty-first century as chemical engineers have applied their skills to fundamental problems in pharmaceuticals, medical devices and drug-delivery systems, semiconductor manufacturing, nanoscale technology, renewable energy, environmental control, and so on. The role of the introductory course in chemical engineering is to develop a framework that enables the student to move effortlessly from basic science and mathematics courses into the engineering science and technology courses that form the core of a professional chemical engineering education, as well as to provide the student with a comprehensive overview of the scope and practice of the profession. An effective introductory course should therefore be constructed around the utilization of rate processes in a context that relates to actual practice.

Chemical engineering as an academic discipline has always suffered from the fact that the things that chemical engineers do as professionals are not easily demonstrated in a way that conveys understanding to the general public, or even to engineering students who are just starting to pursue their technical courses. (Every secondary school student can relate to robots, bridges, computers, or heart-lung machines, but how do you easily convey the beauty and societal importance of an optimally designed pharmaceutical process or the exponential cost of improved separation?) The traditional introductory course in chemical engineering has usually been called something like "Material and Energy Balances," and the course has typically focused on flowsheet analysis, overall mass balance and equilibrium calculations, and process applications of thermochemistry. Such courses rarely explore the scope of the truly challenging and interesting problems that occupy today's chemical engineers.

I have taken a very different approach in this text. My goal is to enable the student to explore a broad range of activities in which a modern chemical engineer might be involved, which I do by focusing on liquid-phase processes. Thus, the student addresses such problems as the design of a feedback level controller, membrane separation and hemodialysis, optimal design of a process with chemical reaction and separation, washout in a bioreactor, kinetic and mass transfer limits in a two-phase reactor, and the use of a membrane reactor to overcome equilibrium limits on conversion. Mathematics is employed as a language, but the mathematics is at the most elementary level and serves to reinforce what the student has studied during the first university year; nothing more than a first course in calculus is required, together with some elementary chemistry. Yet we are able to incorporate design meaningfully into the very first course of the chemical engineering curriculum; the design and analysis problems, although simplified, are realistic in format and scope. Few students of my generation and those that followed had any concept of the scope of chemical engineering practice prior to their senior year (and perhaps not even then). Students enrolled in a course using this text will understand what they can expect to do as chemical engineering graduates, and they will appreciate why they need the courses that follow in the core curriculum.

There is more material in the text than can reasonably be covered in one semester. The organization is such that mass and energy balances can be given equal weight in a one-semester course if the instructor so desires. I prefer to emphasize the use of mass balances in order to broaden the scope of meaningful design issues; any negative consequences of deemphasizing thermochemistry in the introductory course, should the instructor choose to do so, are minimal. Much of what once formed the core of the traditional material and energy balances course is now covered in general chemistry, sometimes in a high school setting, and thermodynamics offerings in many chemical engineering departments have become more focused, with more emphasis on chemical thermodynamics than in the past.

Chemical Engineering: An Introduction incorporates material from an earlier textbook, *Introduction to Chemical Engineering Analysis* (1972), which Fraser Russell and I coauthored. I have added a great deal of new material, however, and removed a great deal as well. Much of what remains has been rewritten. Thus, this is not a new edition, but rather a new creation, with an important family resemblance to an earlier generation.

My PhD advisor was the late Rutherford Aris, whose insightful scholarship was matched by his strong commitment to education, which is reflected in his outstanding textbooks and monographs. Aris believed that students learn best when a subject is presented with rigor, and he wrote with a clarity and elegance that made the rigor accessible to everyone. I think that "Gus" would have approved of the approach presented in this textbook, even if his literary standards are unattainable, and I respectfully dedicate *Chemical Engineering: An Introduction* to his memory.

I am grateful to my colleagues at the City College of New York (CCNY), especially Raymond Tu and Alexander Couzis, for their encouragement and their willingness to use the evolving draft in the classroom, and I appreciate the willingness of the CCNY second-year students to work with us. I am, of course, grateful to Fraser Russell for his insights during our long collaboration and for his generosity in permitting me to use some of the fruits of our joint work. Peter Gordon of

Cambridge University Press enthusiastically supported this project, and Kim Dylla graciously permitted us to use her art on the cover. Finally, I am grateful to my colleagues at the Casali Institute of Applied Chemistry of the Hebrew University of Jerusalem, especially Gad Marom and Shlomo Magdassi, and to the Lady Davis Fellowship Trust, for hospitality and support while I was composing the final chapters of the book. My wife Vivienne's hand is hidden, but it is present throughout.

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