FLUID FLOW FOR THE PRACTICING CHEMICAL ENGINEER

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To
my mother and father
who have unconditionally loved and supported me throughout my life
(J.P.A.)

To
Cecil K. Watson
a friend who has contributed mightily
to basketball and the youth of America
(L.T.)

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NOTE

Additional Problems for each chapter are available for all readers at www.wiley.com. Follow links for this title.

The above Problems may be used for training and/or homework purposes. Solutions to these Problems plus 10 exams with solutions (5 for each year or semester) are available to those who adopt the text for instructional purposes. A PowerPoint presentation covering all chapters is also available. Visit www.wiley.com for details; follow links for this title.

PREFACE

Persons attempting to find a motive in this narrative will be prosecuted;
Persons attempting to find a moral in it will be banished;
Persons attempting to find a plot in it will be shot
By order of the Author, Mark Twain (Samuel Langhorne Clemens, 1835–1910),
Adventures of Huckleberry Finn

It is becoming more and more apparent that engineering education must provide courses that will include material the engineering student will need and use both professionally and socially later in life. It is no secret that the teaching of Unit Operations—fluid flow, heat transfer, and mass transfer—is now required in any chemical engineering curriculum and is generally accepted as one of the key courses in applied engineering. In addition, this course, or its equivalent, is now slowly and justifiably finding its way into other engineering curricula.

Chemical engineering has traditionally been defined as a synthesis of chemistry, physics and mathematics, tempered with a concern for the dollar sign and applied in the service of humanity. During the 120 years (since 1888) that the profession has been in existence as a separate branch of engineering, humanity's needs have changed tremendously and so has chemical engineering. Thus it is that today, this changing profession faces a challenge and an opportunity to put to better use the advances that have occurred since its birth.

The teaching of Unit Operations at the undergraduate level has remained relatively static since the publication of several early to mid-1900 texts. At this time, however, these and some of the more recent texts in this field are considered by many to be too advanced and of questionable value for the undergraduate engineering student. The present text is the first of three texts to treat the three aforementioned unit operations—fluid flow, heat transfer, and mass transfer. This initial treatise has been written in order to offer the reader the fundamentals of fluid flow with appropriate practical applications, and to possibly serve as an introduction to the specialized and more sophisticated texts in this area.

It is no secret that the teaching of both stoichiometry (material and energy balances) and the three unit operations, including fluid flow, has been a major factor

in the success of chemical engineers and chemical engineering since the early 1900s. The authors believe that the approach presented here is a logical step in the continual evolution of this subject that has come to be defined as a unit operation. This "new" treatment of fluid flow is offered in the belief that it will be more effective in training engineers for successful careers in and/or out of the chemical process industry.

The present book has primarily evolved from notes, illustrative examples, problems and exams prepared by the authors for a required three semester fluid flow course given to chemical engineering students at Manhattan College. The course is also offered as an elective to other engineering disciplines in the school and has occasionally been attended by students outside the Department. It is assumed the student has already taken basic college physics and chemistry, and should have as a minimum background in mathematics courses through differential equations.

The course at Manhattan roughly places equal emphasis on principles and applications. However, depending on the needs and desires of the lecturer, either area may be emphasized, and the material in this text is presented in a manner to permit this. Further, no engineering tool is complete without information on how to use it. By the same token, no engineering text is complete without illustrative examples that serve the important purpose of demonstrating the use of the procedures, equations, tables, graphs, etc., presented in the text. There are many such examples. There are also practice problems (available at a website) at the end of each chapter. It is believed that most, if not all, of the illustrative examples and practice problems are "original"; some have been drawn from National Science Foundation (NSF) workshops/seminars conducted at Manhattan College, and some have been employed for over such a long period of time that the original authors can no longer be identified and properly recognized. If that be the case, please accept the authors' apologies and be assured that appropriate credit (where applicable) will be given in the next printing.

In constructing this text, topics of interest to all practicing engineers have been included. The organization and contents of the text can be found in the table of contents. The table consists of six main parts—Introduction to Fluid Flow, Basic Laws, Fluid Transport Classification, Fluid Flow Applications, Fluid-Particle Applications, and Special Topics.

It is hoped that this writing will place in the hands of teachers and students of engineering, plus practicing engineers, a text covering the fundamental principles and applications of fluid flow in a thorough and clear manner. Upon completion of the course, the reader should have acquired not only a working knowledge of the principles of fluid flow, but also experience in their application; and, readers should find themselves approaching advanced texts and the engineering literature with more confidence.

Finally, the authors are particularly indebted to Shannon O'Brien for her extra set of eyes when it came time to proofreading the manuscript.

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LOUIS THEODORE

March, 2009

INTRODUCTION

> No one means all he says, and yet very few say all they mean, for words are slippery and thought is viscous.
>
> —Henry Brooks Adams (1837–1918)
> *The Education of Henry Adams*

The history of unit operations is interesting. Chemical engineering courses were originally (late 1800 and early 1900s) based on the study of unit processes and/or industrial technologies. However, it soon became apparent that the changes produced in equipment from different industries where similar in nature, i.e., there was a commonality in the fluid flow, heat transfer, and mass transfer operations in the petroleum industry as with the utility industry. These similar operations became known as unit operations.

This book—"Fluid Flow"—was prepared as both a professional book and as an undergraduate text for the study of the principles and fundamentals of the first of the three aforementioned unit operations. Some of the introductory material is presented in the first two parts of the book. Understandably, more extensive coverage is given in the remainder of the book to applications and design. Furthermore, seven additional topics were included in the last part of the book—special topics. These topics are now all required by ABET (Accreditation Board for Engineering and Technology) to be emphasized in course offerings: each of these seven topics is briefly discussed below.

The first chapter in Part VI addresses environmental concerns; nearly one third of undergraduates chose environmental careers. The second topic is health, safety, and accident prevention; new and existing processes today require ongoing analyze in these areas. To better acquaint the student with human relations, engineering and environmental ethics is the third topic. Numerical methods are the next topic encountered since computers are not only used to design multi-component distillation columns but also routinely used in the work force. The success or failure of any business related activity is tied to economics and finance, and this too receives treatment. The "hot" topic—Biomedical Applications—receives treatment in Chapter 33. Finally, open-ended problems (problems that can have more than one solution), are

treated in the last chapter. This final chapter requires the reader to ask questions, not always accept things at face value, and select a methodology that will yield the most effective and efficient solution. Illustrative examples on each of these topics are included within each chapter.

Although not a complete treatment of the subject, the text has attempted to present theory, principles, and applications of unit operation in a manner that will benefit the reader and/or prospective engineer in their career as a practicing engineer. Those desiring more information on these topics should proceed to specialized texts in these areas.

This book is the result of several years of effort by the Chemical Engineering Department at Manhattan College. The first rough draft was prepared during the 2001–2002 academic year and underwent peripheral classroom testing during the ensuing years; the manuscript underwent significant revisions during this past year, some of it based on the experiences gained from class testing.

In the final analysis, the problem of what to include and what to omit was particularly difficult. However, every attempt was made to offer engineering course material to individuals at a level that should enable them to better cope with some of the problems they will later encounter in practice. As such, the book was not written for the student planning to pursue advanced degrees; rather, it was primarily written for those individuals who are currently working as practicing engineers or plan to work as engineers in the future solving real world problems.

The entire book can be covered in a three-credit course. At Manhattan, Fluid Flow is taught in the second semester of the sophomore year (Heat and Mass Transfer are taught in the junior year). Finally, it should be again noted that the Manhattan approach is to place more emphasis on the macroscopic approach; however, some microscopic material is included.