CHAPTER 1

INTRODUCTION

Pipeline systems range from the very simple ones to very large and quite complex ones. They may be as uncomplicated as a single pipe conveying water from one reservoir to another or they may be as elaborate as an interconnected set of water distribution networks for a major metropolitan area. Individual pipelines may contain any of several kinds of pumps at one end or at an interior point; they may deliver water to or from storage tanks. A system may consist of a number of sub-networks separated by differing energy lines or pressure levels that serve neighborhoods at different elevations, and some of these may have pressurized tanks so that pumps need not operate continuously. So these conveyance systems will adequately fulfill their intended functions, they may require the inclusion of pressure reducing or pressure sustaining valves. To protect the physical integrity of a pipeline system, there may be a need to install surge control devices, such as surge relief valves, surge tanks, or air-vacuum valves, at various points in the system.

How do these systems work? What principles are involved, and how are the systems successfully analyzed and understood? How can the behavior of a preliminary design be evaluated, and how can the design be modified to correct deficiencies? These are some, of many, questions that immediately confront any engineer who is involved in creating the physical infrastructure to satisfy a basic need of mankind: the delivery of water when and where it is wanted at a price that is affordable. It is the primary objective of these engineers to develop and apply their knowledge to make the system work. Success at this task first requires an adequate knowledge of some fundamental principles of fluid mechanics. Some experience with the solution of hydraulic flow problems is certainly desirable, and it will come with time and effort. These days an understanding of some particular numerical methods and the ability to implement them on a computer, sometimes for the solution of very large problems, is also a vitally needed skill. Computations associated with engineering practice have changed dramatically in the past quarter century from the estimation of a few key values by using a slide rule to the generation of pages of computer output that are the result of detailed simulations of system performance in response to various alternative designs, so that the consequences of various ideas can be ascertained quantitatively. The volume of computer output can overwhelm one's ability to glean the most pertinent information from the numbers. The purpose of this book is to empower the reader with the knowledge, experience, and tools to accomplish this objective.

This book will present to the reader a comprehensive and yet relatively practical study of pipeline hydraulics, with a substantial component being the use of computers for detailed computations that are not practical to perform by hand. The intent of the authors was to create a book, and an accompanying CD, that will serve well any of the following roles: (1) as a text for senior-level courses for BS students electing to specialize in fluid mechanics, hydraulics, water supply and distribution, and/or water resources; (2) as a text for graduate engineering courses in the same subject areas; (3) to provide instructional material for professional practicing engineers who wish to update their knowledge of specialties associated with the distribution, conveyance, and control of fluids in pipelines; (4) to provide resource material for engineers in governmental agencies at all levels who have responsibilities to design and/or approve plans for pipeline systems; and (5) to provide reference material for consultants who are asked to solve problems, review plans, or suggest project alternatives in the subject areas of this book.

The study of the hydraulics of pipeline systems builds on a small number of fundamental principles that are found in a first course on fluid mechanics; such a course is normally taken in the third full year of college study by all students in civil and environmental engineering, mechanical engineering, agricultural and irrigation engineering, and in some related engineering fields. Ideally this course is a judicious mix of the development of basic theory and its application, but it is not uncommon for such a course to emphasize theory over practice or *vice versa*. The authors will assume that readers have already acquired some knowledge of fundamental fluid mechanics principles; it is hoped that they also have in their individual libraries an elementary text on fluid mechanics that can be a resource for (1) refreshing their understanding of the basic concepts and (2) finding an occasional supplementary equation when it is needed to enhance the understanding and application of the developments in this book. Such a reference will also be useful as a source of data on fluid properties.

To establish a base on which to build in subsequent chapters, the authors begin in Chapter 2 with a review of elements of basic fluid mechanics that are pertinent to pipe system hydraulics. Because pumps are such a common part of (especially the larger) pipeline systems, Chapter 2 includes a short primer on pump behavior and the summary of such behavior by pump characteristic curves. Chapter 2 concludes with several basic flow examples that are much like those that are usually found in a first course. The remainder of the book then addresses three general categories of pipeline system analysis. The first category, examined in Chapter 3, considers pipe manifolds, relatively the least complex type of pipe system. Although any pipe manifold is basically a relatively large pipe which delivers fluid to many outflow points or ports, it is an example of a spatially varied flow; such flows are often not studied in undergraduate books on fluid mechanics, so some care is needed to avoid conceptual errors. A single manifold pipe is examined at several levels of completeness, and the chapter ends with a design example and some comments about developing a manifold design with the aid of a computer program.

The second category is steady-state pipe network analysis. The largest single segment of the book is devoted to this topic. Relative to the coverage of this topic in other books, the exploration of the topic here is both broad and thorough (or, as some say, 'in-depth'). (Even so, much that is known about optimal design technniques could not be included here, owing to limitations on the size and cost of this book!) The study of networks progresses from the simple to the complex. The simple networks are used to emphasize the principles, and the larger networks allow one to experience a taste of the real world and to learn to cope with additional complexity. Enough details of the numerical and programming techniques are presented so the reader can see how the entire analysis works. Chapter 4 concentrates on analysis techniques and completely describes the three primary alternative approaches to the formulation of a mathematical model for a pipeline system; then a method for solving each of them is presented. The primary elements of each solution method, in this and subsequent chapters, are implemented in Fortran and C programs that are contained in the CD that accompanies this book. The logic that is required to integrate the relatively complicated pressure reducing and back pressure valves into a system is carefully described. Chapter 5 goes on to describe effective approaches to the design of pipe networks; the first objective of most pipeline system designs is to determine the smallest acceptable, and commercially available, pipe diameters to fulfill specified delivery requirements, and in this chapter one finds out how to formulate a problem with some of the pipe diameters as unknown variables. This approach is in distinct contrast to the usual design approach of initially estimating (guessing?) all of the pipe sizes, conducting an analysis of the resulting network, and then iteratively adjusting the sizes until a satisfactory design is found. Methods will be described that allow one to decide rationally which component(s) of a large network should be altered to eliminate most effectively a deficiency in the network's performance; this decision process is based on the quantification of the sensitivities of dependent variables to independent variables. For example, the pumping station (with power as the independent variable) that produces the largest sensitivity to pressure at the node with the lowest pressure (the dependent variable) should be enlarged to eliminate a problem involving excessively low pressures. Finally, in Chapter 6 the reader is introduced to extended time simulations and additional economic considerations in network design.

The last of the major topics in this book is the analysis of several types of transient flow in pipelines and in networks. These chapters begin with a relatively brief section in Chapter 7 on slowly-varying flows that can be called quasi-steady. Chapter 7 then goes on to introduce two types of true transients, those in which only inertial effects are important and those for which the additional consideration of the elasticity of both pipe and fluid is essential to capture the true behavior of these flows. In Chapters 8 through 13 various transient flows in systems that range from single pipelines to entire pipeline networks are examined, as well as procedures and devices for controlling these transients.

Even if it is not already clear to the reader at the outset, it will become clear during the reading and study of this book that the solution of pipeline hydraulics problems, especially as the systems become larger, can require substantial computational effort. The routine computation of solutions to larger problems in either networks or transients can involve the heavy use of a modern desktop computer or a workstation. This type of computation, which normally requires the solution of either a moderate to large set of initially nonlinear algebraic equations or one to many differential equations, depends heavily on the use of reliable and reasonably efficient methods from numerical analysis, a branch of applied mathematics that also has some input from computer science.

In the steady-state analysis and design of networks, large systems of nonlinear algebraic equations must be solved; this book will emphasize the relatively reliable Newton method for the solution of these equation sets. The inclusion of inertia in unsteady flows will require us to solve a system, which can become very large for networks, of differential and algebraic equations, also called DAE's. Although research papers on the solution of DAE's began to appear in the 1980s, relatively little of this subject appears to have been previously applied to pipeline hydraulics problems, so far as the authors can tell, even though there are many applications in engineering practice in which such combined systems of equations govern. The presentation of a technique for the solution of these systems of equations is one of the contributions of this book. As the future requires more sophisticated simulations of engineering problems, similar solution techniques will become commonplace.

An exposition on the hydraulics of pipeline systems can approach this topic in any of several ways, ranging from one extreme where only hydraulic theory and the accompanying descriptive mathematical equation sets are presented, to the other extreme where an array of problem descriptions, computer files and fill-in-the-data sets of instructions for the use of computer programs is presented. In the authors' opinions neither extreme is deserving of commendation. But it is also understood by the authors that individual readers will have goals that do not agree entirely with those of either the authors or other readers of this book. After some deliberation the authors have chosen an intermediate approach to the subject. The first step in each major topic is to present the governing principles and their expression in mathematical equations. The examples of the application of the principles will usually progress from the smaller and simpler to the larger, more realistic and more difficult, both in the text and in the problem sections at the end of most chapters. Most of the numerical and procedural detail of problem solving will be examined when the smaller problems are discussed. Some readers may desire to know more in the way of details in the numerical analysis and/or the computer coding than is presented in the body of the text. To some extent this outcome is an unavoidable consequence of the authors' choice to take the intermediate approach, but those who desire more details on the numerical techniques and the actual computer programming can learn more! Appendix A presents a primer on some numerical analysis techniques. We also encourage readers to extract the source code of computer programs from the CD to list them, to study them, and to use them to solve a variety of problems. The CD contains approximately 250 separate files (not including the executable elements); seven files are document files to explain the use the major executable programs such as USU-NETWK which are on the CD. With few exceptions the source programs are provided in both Fortran and C. The CD contains slightly under one hundred Fortran source programs, ranging in size from less than a page (when listed) up to several pages. Among these are subroutines (also written as C functions) to perform numerical solutions of single, or systems of, ordinary differential equations or tasks such as cubic spline interpolations. In solving many of the problems at the ends of the chapters the reader will find it advantageous to use the vast additional resources on the CD. An INSTALL program on the CD permits the user to extract and decompress the files on the CD by type, or to make individual or group selections.

While this book has been written primarily to describe the hydraulics of pipeline systems, an important secondary objective is to describe with care, and to present examples of the application of, some reliable numerical methods for the solution of the larger, more complex problems that the practicing engineer encounters. Although the examples herein are all pipeline problems, the numerical methods themselves have potentially a far wider range of applications to any topic that can be modeled with similar sets of equations. Engineering colleges everywhere have for many years been debating the relative merits of teaching to their students a procedural programming language such as Fortran, C, or Pascal, vs. the teaching of the use of spreadsheets and interpretative languages as implemented in MathCAD, TK-Solver, or Mathematica. The authors' opinion, formed by observing many students during their university years and after graduation, is that computer programming is a very important, if not a vital, skill today when computers have become an integral part of our professional and personal lives. Individuals who can effectively use a procedural programming language seem to assimilate the use of application software packages more readily than those whose university experience was only with application packages. Consequently the authors conclude that there is much merit is learning how to program effectively not only to complete a task but also because programming requires a concise and correct application of fundamental principles, and the experience enhances an understanding of these principles even more than the solution of small problems that can be done by hand. But if a programming language is to be employed in this book, which language is *the* language? With the years, more and more languages appear, in some respects like the seasons. For example, depending on one's year of birth, the readers and the authors have seen one to several generations of Basic and Fortran, and then Pascal, and more recently C and C++, Java and still other languages appear, each with its own special attributes. How do the authors create a text that addresses the issues without forcing literacy in a particular programming language on the reader? (The answer probably is, with some difficulty, but the authors have tried.) The 'solution' follows in the next paragraph.

The authors have started from the premise that nearly all readers of this book will have some knowledge of computing methods. The authors have also assumed that many readers will be familiar with either Fortran or C as a programming language; however, it is also assumed that not all readers will have this background. Hence, included on the CD are executable program elements which can be used directly, without compilation, for the solution of some but not all of the problems in this book. In addition, the CD contains a few TK-Solver models; they are included because they present equations and the selection of dependent variables in a clear way. It was tempting to include not only more TK-Solver models but also MathCAD models in the text, until it was realized that page limitations would not permit more. It would be a valuable experience for readers to develop their own TK-Solver, MathCAD, Mathematica, spread-sheet, or other software models with interpretative capabilities to solve some of the example problems and problems at the ends of the chapters. The source programs have already been mentioned; of course, each of them may serve as a base from which the reader may create new, specialized programs for their own individual purposes. Any modification of a program will, of course, require its recompilation which, in turn, requires access to the appropriate

Pcompiler. As a reminder to the reader that these programs, which the authors believe are correct, are nevertheless provided as a service to the readers without a guarantee, some of the text programs explicitly contain the following caution:

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*    THIS PROGRAM HAS BEEN INCLUDED FOR THE CONVENIENCE OF THE READER.
*    THE AUTHOR ACCEPTS NO RESPONSIBILITY FOR ITS CORRECTNESS.
*    USERS OF THIS PROGRAM DO SO AT THEIR OWN RISK.
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The authors intend that the reader understand that this caution applies to all of the codes in this book and on the CD, although the caution is not repeated on every file.

The authors are confident that the reader will find the many applications of the basic principles of hydraulics to a wide range of practical problems to be challenging, yet manageable, and useful in either advanced education or professional practice. The authors further hope that the considerable number and range of applicability of the computer programs will provide the user with the tools to analyze a wide range of pipeline systems.