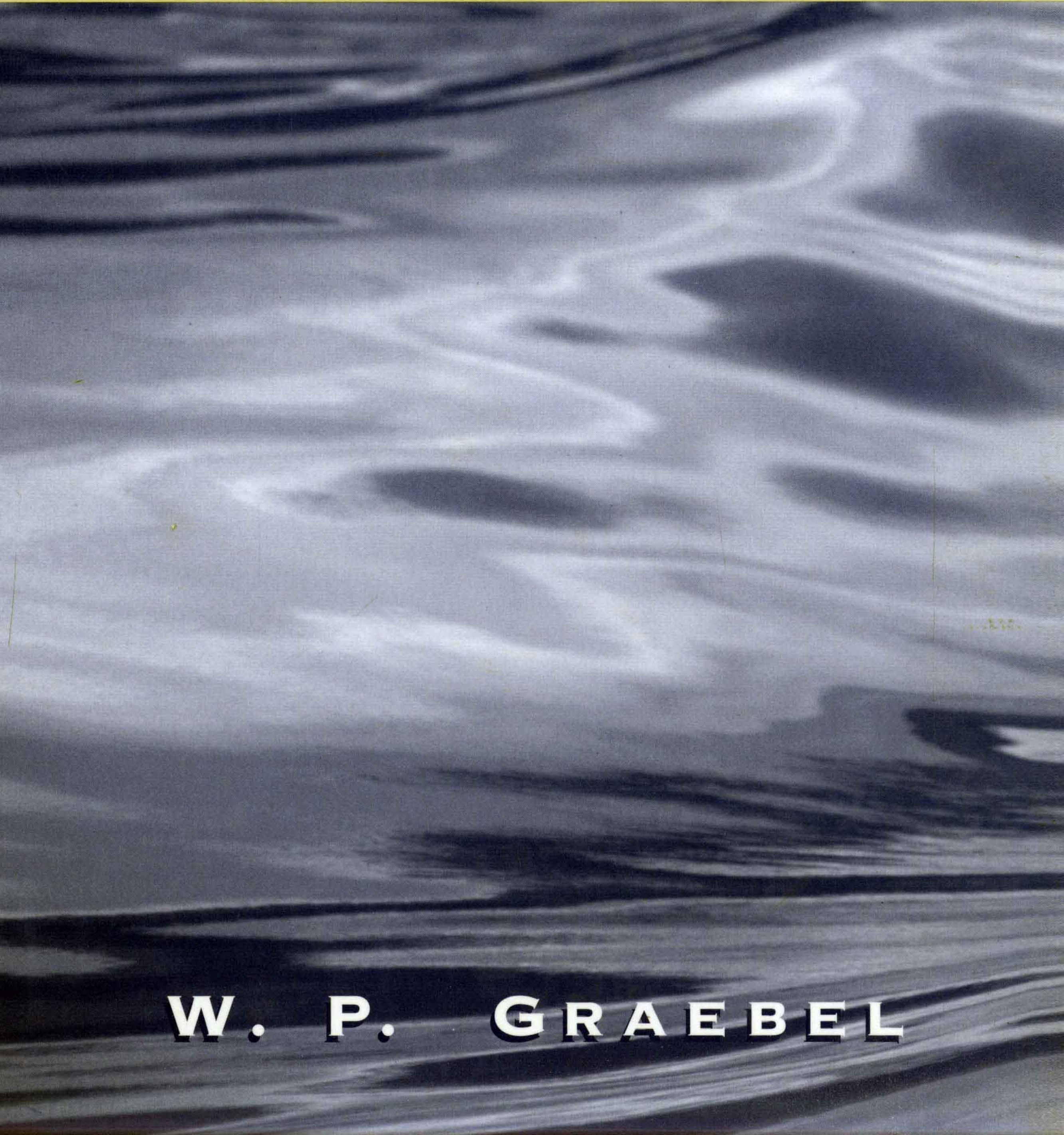
ENGINEERING FLUID MECHANICS



W. P. GRAEBEL

Engineering Fluid Mechanics

by
W. P. Graebel
Professor Emeritus
Dept. of Mechanical Engineering
and Applied Mechanics
The University of Michigan

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Engineering Fluid Mechanics

Preface

This text covers the necessary material for an introductory course in fluid mechanics. There is sufficient material presented that it could serve as a text for a second course as well.

The text is designed to emphasize the physical aspects of fluid mechanics and to develop analytical skills and attitudes in the engineering student. Example problems follow most presentations of theory to ensure that the student grasps the implications of the theory and is able to apply it. In topics that involve more than elementary calculations, step-by-step processes outline the procedure used so as to generalize the students' problem-solving skills. To demonstrate the design process beyond the problem-solving techniques, an appendix presents some of the more general considerations involved in the design process.

Elementary fluid mechanics is one of the basic core courses of undergraduate engineering, along with statics, dynamics, mechanics of materials, thermodynamics, and heat transfer. I have endeavored to show linkages to these subjects as well as to elementary physics, to both build on previously learned knowledge and to provide a bridge to courses to be taken in the future.

I have included frequent references to applications throughout the text, as well as an appendix on the history of fluid mechanics. Fluid mechanics is a required subject for many engineering programs, and a student starting such a course is frequently not sure why the subject is of importance. I have found that including such material in my own teaching has enhanced student interest in the subject and resulted in a more appreciative audience.

The subject matter is organized in the following manner:

- Chapters 1 and 2 serve as an introduction to the subject. Terms and concepts are defined and the student is given practice with pressure calculations. A general procedure for attacking engineering problems is suggested.
- Chapter 3 is really the heart of the book. The concept of control volume is presented, along with the fundamental equations of continuity, momentum, and energy. These presentations are for one-dimensional analysis. Chapter 4 extends this theory to three dimensions with the development of the Euler and Navier-Stokes equations. I have included some simple solutions of these equations, which is not traditional for textbooks at this level. I have done so because I feel that without applications, development of the theory leaves the typical undergraduate student with rather

a "so-what" feeling. This chapter can either be presented following Chapter 3 or delayed to a later portion of the course, depending on the instructor's goals. Some instructors may wish to omit it completely.

- Chapter 5 considers the subject of dimensional analysis and provides a road map to the chapters that follow.
- Chapters 6 and 7 develop elementary viscous flow theory and general Reynolds number effects. Chapter 6 deals exclusively with laminar flows, and Chapter 7 with turbulent flows. In pipe flow calculations I have supplemented the traditional Moody diagram with two others, so that the student can solve problems directly and avoid having to deal with trial-and-error solutions of pipe flow problems.
- Chapter 8 deals with open channel flows and Froude number effects. For courses that focus on such flows, it could follow chapter 3 directly.
- Chapter 9 deals with compressible flows and Mach number effects. The material starts with a general discussion of compressibility, then goes to a brief discussion of compressibility effects in liquids before finishing with a discussion of compressibility in gases.
- Chapter 10 gives a summary of measurement techniques suitable for fluid flows, and Chapter 11 discusses aspects of hydraulic machines.
- The concluding chapter points out some of the more advanced topics in fluid mechanics, and indicates to the student the type of courses that might be useful in developing further interest in fluid mechanics.

While at The University of Michigan I have been fortunate to teach a wide variety of engineering subjects to students in engineering mechanics, mechanical engineering, civil engineering, chemical engineering, aerospace engineering, naval architecture and marine engineering, and meteorology and oceanography. This, along with seminars, serving on doctoral committees, and research and consulting activities, has broadened my interests and has given insight into the wide range of applications of fluid mechanics in many areas of engineering. I have tried to include a flavor of many of these applications in my presentation of the material in this book.

No book can suit all students. When I learn a new subject, I find three or four—or more—books dealing with it and study all of them. I find that different authors coming from different points of view help me to find the thread on which to base my own understanding of the subject, to place it in the context of things I am already familiar with. I encourage students to do likewise, and to utilize the library at their institution to the fullest extent.

Many people have influenced my presentation of the material in the book. Certainly the students I have taught have been a great help in teaching me what is effective in teaching. Reviewers of early drafts of the book have also been helpful in their criticisms. I would especially like to thank my wife, June, for her help during the preparation of this book in typing and grammar suggestions, and in her general support and understanding of the effort. I would also like to honor the memory of two cherished people: Chia-Shun Yih, my teacher, colleague, and friend, who first sparked my interest in fluid mechanics, and who taught me much, much more; and Vernon A. Phelps, who broadened my outlook on engineering and suggested new paths to follow. The world is poorer for their absence.

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chapter 1

Introduction to Fluid Mechanics

Chapter Overview and Goals

This chapter introduces some of the concepts that we will be using throughout our study of fluid mechanics. We start by defining the term "fluid" and introduce a number of common fluid properties such as mass density, bulk modulus, viscosity, and surface tension. The concepts of stress, absolute and gage pressure, cavitation, Newtonian fluids, and non-Newtonian fluids, together with the no-slip boundary condition, are also introduced and discussed. Several examples of applications are given.

By the end of the chapter, you should be familiar with these concepts, and also with those units of the British gravitational and SI systems of units that are applicable to fluid mechanics. With the help of Appendix A, you should be able to express all quantities in both sets of units.

You should also begin to have a grasp of the magnitudes of the numbers that are reasonable for the various quantities in each set of units, so that you will be able to make judgments as to whether numbers you obtain in calculations are reasonable. The definitions and concepts introduced in this chapter will occur throughout the book; therefore it is important to become accustomed to them.

1. Introduction

Since prehistory, mankind has been interested in being able to predict and/or control how fluids flow. Weather prediction has always been important for agriculture, fishing, and water transportation. Civilizations have started—and ceased—because of the availability of water supplies. The transport of water for agriculture, drinking, and bathing led to such engineering marvels as the aqueducts of the early Romans. Some of these are still in use after more than 2000 years. Control of air flow to decrease erosion of the ground; drag on cars, trucks, and airplanes; and the dispersion of pollutants are all important in our modern lives. Instrumentation for monitoring pressures and flow rates in blood vessels and pressures in the eye has become an important diagnostic tool for medicine.

To resolve the engineering problems that arose in these early attempts to predict and/or control how fluids flow, many people developed individual theories to deal with specific isolated problems even before written history. Starting in the fifteenth century with Newton, and in the sixteenth century with Euler and the Bernoulli family, a general mathematical formulation of fluid mechanics was begun, culminating in the mid-nineteenth century with the work of Navier and Stokes. The latter completed the structure needed for the general mathematical formulation of fluid mechanics. The great scientific advances that were made in that period put the mechanics of fluids on a thorough scientific basis, against which both earlier and later theories and approximations could be tested, and our knowledge and understanding of the flow of fluids increased.

This scientific understanding of how fluids behaved was needed for the technical demands of the industrial revolution and the advanced technology that followed. The development of modern ships and aircraft was possible only because of the general scientific formulations of the nineteenth century, and the application of theory to technology in the twentieth century. Based on these fundamental theories, Orville and Wilbur Wright, Frederick Lanchester, Nicolai Joukowski (also spelled Zhukovskii), and Ludwig Prandtl made modern aviation and the space program possible. The use and behavior of fluid flow in transportation, prediction of circulation in the atmosphere and oceans, power transmission and generation, lubrication, transport of mass and heat, and so many other areas, makes fluid mechanics one of the cornerstones of our modern technological society. It would be difficult to imagine our life today without the myriad ways in which we have applied our knowledge of fluid flow.

As fluid mechanics developed and our knowledge of the behavior of how fluids flow grew, the field became divided into specializations, and various technical areas were given special names. Hydraulics, for example, refers to the flow of liquids in channels, canals, and pipelines. Pneumatics deals with the flow of air, usually in small-diameter tubes. Gas dynamics deals with the high-speed flow of gas when compressibility effects are important. If the fluid density is low enough that means free paths between molecules are large, we speak of rarefied gas dynamics. For ionized gases, we talk of plasma flows, and when in the presence of magnetic fields, magnetohydrodynamics. Meteorologists deal with the flow of air in our atmosphere, while oceanographers are their underwater counterparts. Many other specialities exist, and new ones are still appearing.

2. Definition of a Fluid

All matter exists in one of three phases: liquid, vapor (or gas), and solid. The word "fluid" is used as a general term for the first two of these phases, since the basic mechanical behavior of liquids and gases is very similar. Which phase the matter is in depends on the values of the various thermodynamic variables such as pressure and temperature. Two typical plots showing phase and phase changes when the matter is in static thermodynamic equilibrium are given in Figures 1.1 and 1.2. Figures 1.3 and 1.4 are two-dimensional projections made from Figures 1.1 and 1.2. They show planes of constant mass density drawn through the ***critical points*** of Figures 1.1 and 1.2. The point labeled "critical point" in these figures corresponds to the point of highest temperature possible for a liquid-vapor mixture to exist in the equilibrium state.

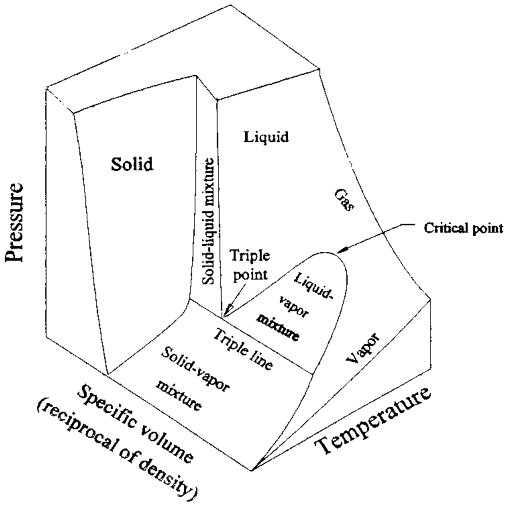

Figure 1.1. Pressure-density-temperature equilibrium surface for a substance that contracts on freezing (e.g., carbon dioxide).

The primary difference between a solid and a fluid is in the strength and type of the molecular bond. A solid is made up of a closely packed molecular structure, where breaking the bonds requires considerable energy. In a fluid the bonds are looser and can be easily broken. A fluid is defined as a substance that will deform and move when a tangential (shear) stress is applied to it, the motion continuing as long as the shear

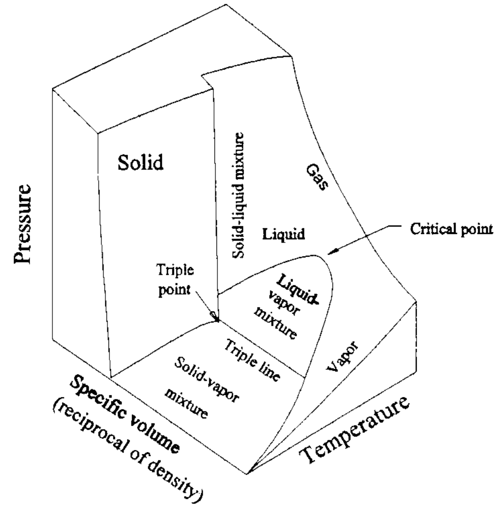

Figure 1.2. Pressure-density-temperature equilibrium surface for a substance that expands on freezing (e.g., water).