Engineering Fluid Mechanics

FLUID MECHANICS AND ITS APPLICATIONS
Volume 85

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Engineering Fluid Mechanics

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Preface

This book is intended for advanced engineering students in university or college and could serve as a reference for practical engineers. In recent years the development of fluid machineries has required a wider range of study in order to achieve a new level of developmental and conceptual progress. The field of fluid engineering is quite diverse in the sense that so many variations of flow exist in fluid machinery or an installation, whose characteristics are wholly dependent upon the flow field which is determined by the function of the machine setting itself. One who is studying fluid engineering, for the purpose of gaining a working knowledge of fluid machineries and their relevant installations, must understand not only the type of fluids used in practice, but also the fundamental flow problems associated with actual fluid machineries. Hence, the intended purpose of this book is to provide the fundamental and physical aspects of fluid mechanics and to develop engineering practice for fluid machineries.

The subject of fluid engineering is most often approached at the senior undergraduate or postgraduate level of study. At this stage, the student or practical engineer is assumed to already have a basic mathematical background of vector and tensor analysis with a fair understanding of elementary fluid mechanics, such as Bernoulli equation, potential flow, and Poiseuille flow. The information in this book is organized by subject matter in such a way that students can understand basic theory and progressively deepen their level of knowledge, following the order of presentation. In each section chapter exercises are provided, and problems are also given so as to enable students to understand the theoretical implications and to apply them to engineering problems. Suggestions of further readings and relevant references are listed at the end of each chapter for students eager to delve more deeply into various topics. The SI units system has been provided at the end of the introduction. Exercises and problems are worked out by SI Units throughout this text.

Chapter 1 concerns the fundamentals of continuum mechanics. The chapter involves a description of the nature of continuum, and the basis of kinematic fluid flow. Mathematical treatments necessary for describing quantities of fluid motion, which lay the groundwork for proceeding chapters, are also dealt with at this stage.

Chapter 2 encompasses the general conservation laws of fluid flow, involving mass, linear momentum, angular momentum and energy conservation. These will allow us to provide constitutive equations (relations) for the (unconstituted) conservation equations; thus, a closed system of equations, namely the governing equations of a specified fluid flow, can be obtained. Newtonian fluid, non-Newtonian fluid, viscoelastic fluid, and magnetic fluid are developed in later chapters.

Chapters 3 and 4 provide the basic theory for fluid engineering in an inviscid flow, from which hydrostatics, potential flows and incompressible flows are derived for practical use in Chapter 3. Thermodynamics equations are also introduced for analysis in this chapter. Specific engineering terms and concepts are defined in the proceeding chapters when appropriate. The importance in derivation of the Bernoulli equation is considered from the view of applying the equation to various engineering problems.

In consideration of engineering applications, Chapter 4 deals with fundamental methods to characterize turbomachines, and provides definitions of efficiencies. The concept of efficiencies is largely based on energy transfer and conversion. This chapter in particular explicates the basic treatments of hydraulic machineries, which are widely used in engineering practice. Although there are a large variety of hydraulic machineries available, each serving its needs and purposes, the treatment for these fluid machineries in this chapter is oriented more towards the turbomachineries in general rather than the specific type.

Chapter 5 is concerned with basic theory for compressible flow. In particular, unidirectional steady state flow process is considered. Fanno and Rayleigh processes in compressible flows are treated in more detail in view of wider applications to engineering practice. Shock waves are also touched on in this chapter.

Chapter 6 focuses on Newtonian flow. Viscosity, the most important concept in fluid mechanics is brought into the discussion, which leads us to the derivation of Navier-Stokes equations. Viscous flows are the objective in this chapter. Basic flows in many engineering applications are introduced, in which boundary layer theories are more thoroughly examined.

Chapter 7 explores some of the more advanced topics in fluid engineering so that the student wishing to further develop their interest in research fields or gain perspective for their future careers may glean some insight from these discussions. This chapter concerns non-Newtonian fluid flow in particular, which cannot be characterized in the same way as Newtonian fluids. The topic chiefly discussed here is polymeric fluid in light of more advanced applications, involving not only non-Newtonian viscosity, but also elasticity in regard to the rheological properties of fluids. Some constitutive equations of viscoelastic fluids are introduced in this chapter, for the purpose of applying them to numerical work.

In the final chapter, Chapter 8, ferrohydrodynamics is introduced along side recent developments in magnetic fluids. The fundamental treatment of magnetic fluids is based on the modeling of suspensions of magnetic grains, whose scale is in the order of 10nm. The novel idea of suspension through the process of magnetization is introduced in deriving a closure system of ferrohydrodynamics equations. Some engineering applications of magnetic fluids are outlined.

There are four appendixes in which further details have been included. The appendixes are arranged in such a way that readers can, when necessary, refer to basic mathematical treatments and extend their understanding on a specific subject in the main text. Tables of physical properties are also provided as reference for readers requiring data for solving problems in the text or for more practical designing works. References are provided at the end of each chapter, some of which are to be regarded as suggestions for further reading and others as cited sources.

Finally the author wishes to acknowledge his indebtedness to Ms. Jacobs, associated editor of SPRINGER, for her encouragement in the publication of this book. The author also wish to express his appreciation to Professor Mingjun Li, Dr. Xin-Rong Zhang, Mr. Takuya Kuwahara, Mr. Yuta Ito, Mr. Minoru Masuda and postgraduate students from the fluid engineering laboratory in Doshisha University for their useful suggestions and assistance after reading parts of the manuscript. And thanks also to Professor Sigemitsu Shuchi and Ms. Cleito Feugas for offering amendments and proofing the manuscript.

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Contents

Introduction

Since the beginning of human civilization, communities have consistently been established at locations that feature a viable source of flowing water. Throughout history, people have continuously attempted to manipulate the natural flow of water, in order to affect an improvement in such areas as agricultural stability, living environment, and transportation. Indeed, even sensitivity to air currents and cloud flow has been important to the development of civilization's ability to adapt, and adapt to, the natural environment. Along with a reliable source of water, weather prediction and awareness of seasonal changes have been critical to basic social structures like farming, animal husbandry, and housing.

As understanding of the natural world has grown, and modern technologies have emerged, we have become increasingly reliant on the fundamental principles of fluid flow. Humanity has come to depend upon the development and design of modern transport, like cars and aircraft, which are rooted in an essential understanding and knowledge of fluid flows. Not only are fluid flows critical for solving aerodynamics problems, but also for a plethora of engineering problems concerning energy conservation and transmission. Time and again, methodological engineering, and even bio-medical studies, have proven the universally accepted tenant that understanding fluid flow is critical to the development of applied knowledge. Furthermore, it is clear that they are all, in the end, derived from the field of fluid engineering, which is key to opening the mental door to various forms of inspiration.

Topics covered in fluid engineering are quite diverse. However, the theoretical background of fluid engineering is based upon fluid mechanics (or hydrodynamics), which assumes that all basic equations relating to the conservation law, i.e. mass, linear momentum, angular momentum and energy, are derived from the concept of continuum mechanics. From the common definition of a fluid, avoiding complicated discussions on fluid characteristics, it is seen that both the gaseous and liquid phases of matter can customarily be qualified as fluids. In dealing with the mechanics of fluid flow, a continuum concept has to be introduced before commencing discussion on the kinematics of fluid. We can treat fluids as continuum if they are homogeneous, uniform and of macroscopic volume, in which only bulk properties are interested by taking mean molecules, atoms and aggregations of the like, which consist of the fluid.

When deriving governing fluid mechanics equations, particularly for fluids of low molecular weight, for instance water or air, the Navier-Stokes equation can be obtained directly through Newton's law of viscosity. These have been called Newtonian fluids in consideration of their conservation of linear momentum. Based on the Navier-Stokes equation together with continuity and energy equations, all the practical equations and formula in fluid engineering dealing with conventional hydraulic and air machineries can be satisfactorily obtained. Moreover, decades of experiments and engineering practices have demonstrated the dependability of this theory.

However, there exist fluids, which do not necessarily obey Newton's law of viscosity, and those fluids, so-called non-Newtonian fluids, include polymeric fluids – polymer solutions, polymer melts and multi-phase systems, and electro-magnetic fluids – magnetic fluids, plasmas, and so forth. All basic equations of the conservation law derived from continuum mechanics can still be upheld, but in each case for non-Newtonian fluid the relationship between the internal stress and the applied strain, namely the constitutive equation (or relation) must be specified, instead of Newton's law of viscosity. Due to growing interest in industrial applications, flows of non-Newtonian polymeric fluids and magnetic fluids are introduced in this book as advanced topics in fluid engineering, which may serve to catalyze interest in very challenging subjects for readers who wish to further extend their knowledge.

In science and engineering, when converting from absolute to engineering unit and vice versa, some confusion occasionally arises. In 1960, the metric system of units (Système International d'Unités or more commonly known as the S.I. system) was introduced to overcome this problem. The S.I. system, is dimensionally consistent as it uses the absolute M.K.S system (M for Meter [m]; K for Kilogram [kg]; and S for Second [s]). Other fundamental units include the Ampere [A] for electric current; mol [mol] for molecular weight; and Candela [Cd] for brightness of light. It also includes the two supplementary units radian [rad] for angle and steradian [st rad] for solid angle, as well as degrees Kelvin [K] for temperature. With the S.I. system the units for heat, work and energy are the same (i.e. Joule [J], which is defined as the work done when a force of 1N is displaced through 1m along its direction). This is one of the advantages of the S.I. system.

Furthermore, it is noted that in the S.I. system of units, some of the units are named after scientists, such as Newton [N] for force; Kelvin [K] for temperature; Stokes [St] for dynamic viscosity; Poise [P] for kinematic viscosity; Watt [W] for power; Pascal [Pa] for pressure; Hertz [Hz] for frequency; Joule [J] for energy: Coulomb [C] for electric charge; Ampere [A] for electric current; and Tesla [T] for magnetic flux density. These units, and combinations thereof, are the fundamental units of the S.I. system. The typically combined units frequently used in fluid engineering are listed in Table 1.1. Throughout this book, the numerical examples and problems are given in the S.I. system of units.

Table 1 Named-combined unit

Unit	Abbreviation	Combined relation
Ampere	A	$1\ \mathrm{A} = 1\ \mathrm{C/s}$
Gauss	G	$1\ \mathrm{G} = 10^4\ \mathrm{T}$
Hertz	Hz	$1\ \mathrm{Hz} = 1 \mathrm{Cycle/s}$
Joule	J	$1\ \mathrm{J} = 1\ \mathrm{N \cdot m}$
Newton	N	$1\ \mathrm{N} = 1\ \mathrm{Kg \cdot m/s^2}$
Oersted	Oe	$(1000/4\pi)\mathrm{A/m}$
Pascal	Pa	$1\ \mathrm{Pa} = 1\ \mathrm{N/m^2}$
Poise	P	$1\ \mathrm{dyn s/cm^2} = 0.1\ \mathrm{Pa \cdot s}$
Stokes	St	$1\ \mathrm{St} = 1\ \mathrm{cm^2/s} = 10^4\ \mathrm{m^2/s}$
Tesla	T	$1\ \mathrm{T} = \mathrm{N/A \cdot m}$
Watt	W	$1\ \mathrm{W} = 1\ \mathrm{J/s}$

Non-S.I. system of units C ;electric charge, Coulomb