Applied Fluid Mechanics

工程流体力学

李　聪　毛欣炜　董飞龙
饶永芳　毛根海　罗　峰　编著

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Preface

The motivation to write a book is because the bilingual course about fluid mechanics need to have a simplified English book matching with 40 class hours. This is the fluid book covering in a typical one-semester undergraduate fluid mechanics course. This book was written based on the *Applied Fluid Mechanics* (Chinese version) by Mao Genhai; Shao Weiyun; and Zhang Yan. This is not an easy task: Fluid mechanics is a subject that contains many difficult-to-understand concepts. For example, what is streamline, pathline and streakline? Or what is lone pipe and short pipe? Or what is subcritical flow, critical flow and supercritical flow? A number of changes comparing *Applied Fluid Mechanics* (Chinese version) have been made to simply clarify or expand certain ideas or concepts. In addition, we have attempted to present fluid mechanics so that the students can understand and analyze many of the important concepts and phenomena encountered by the engineer.

One of our aims remains to represent fluid mechanics as it really is an exciting and useful discipline. In the text, we include analyses of numerous examples of fluid phenomena to which students and faculty can easily relate. In the first two chapters, the students are made aware of some fundamental aspects of fluid mechanics and fluid statics, including characteristics of fluids, forces on fluid, basic equations for pressure field, hydrostatic force on a plane surface and a curved surface etc. The Bernoulli equation is introduced in Chapter 3 to draw attention, early on, to some of the interesting effects of fluid motion on the distribution of pressure in a flow field. Chapter 4, 5, and 6 expand on the basic analysis methods generally used to solve or to begin solving fluid mechanics problems. Emphasis is placed on how to use infinitesimal and finite control volumes. The advantages of using dimensional analysis and similitude for organizing test data and for planning experiments and the basic techniques involved are featured in Chapter 5.

Chapter 7, 8, and 9 include practical concerns such as orifice flow, nozzle flow, pipe flow and open channel flow. Chapter 10, 11, and 12 include weir flow and seepage flow. A major new feature of this book is addition of chapter 12 compressible gas flow. This new chapter, explain the compressible gas flow phenomena to make students and faculty in civil engineering easily understand.

New features in the book include: information about computational fluid dynamics, with supporting figures and photograph; and the characteristics and properties of the

main types of equations used in fluid mechanics.

We express our thanks to many students and colleagues who have helped in the achievement of this text, special thanks to Duan Haojie, Chen Xinbo, Zhang Tuqiao, He Guilin, Zhang Yiping, Yang Yulong, Zhang Yan. In addition, we are very grateful for the care, assistance, and guidance that Wang Bo at Zhejiang University Press and education project at college of civil engineering and architecture in Zhejiang University in preparing this book. We hope that this new, concise and English introduction to fluid mechanics will be appealing to students, especially for Chinese students and will make the material more readily accessible to them. Our goal has been to develop a unique, user-friendly, introductory text that clearly focuses on the essential aspects of the subject. Further comments and suggestions from users, are always welcome.

Li Cong

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Chapter 1 Introduction

§ 1.1 Summary

1.1.1 Task of fluid mechanics

Fluid mechanics is an independent branch of mechanics that studies the mechanics of fluids (liquids, gases, and plasma) and the forces on them.

Fluid mechanics includes two branches. The first one deals with the fluids at rest, which embraces the study of the conditions under which fluids are at rest and in stable equilibrium. This branch is called fluid statics or hydrostatics. The second one deals with fluid flow—the natural science of fluids (liquids and gases) in motion. This branch is called fluid dynamics.

Fluid mechanics can be also divided into (1) theoretical fluid mechanics and (2) applied fluid mechanics (also called engineering fluid mechanics) according to the research contents. The first one focuses on theoretical research and mathematical reasoning. The second one focuses on how to solve practical engineering problems. This book belongs to the second one.

1.1.2 Development of fluid mechanics

1. Major phases for fluid mechanics development

Fluid mechanics originates from a book *On Floating Bodies* written by Archimedes, a Greek scholar who lived in Sicily. He summarized mechanical properties of stationary liquid for the first time.

In 1687, Newton discussed about fluid resistance and wave movement in the famous book *Philosophiae Naturalis Principia Mathematica*, indicating fluid mechanics stepped into main development periods.

Phase Ⅰ: Energy estimation of liquid motion proposed by Daniel Bernoulli and analytic method of liquid movement proposed by Leonhard Euler laid a solid foundation for the studies of the law of liquid motion. As a result, a classical "Hydrodynamics" which belongs to mathematics was formed.

Phase Ⅱ: Based on the classical "Hydrodynamics", Claude-Louis Navier and

George Gabriel Stokes proposed a famous basic motion equation of viscous fluid, which laid a theoretical foundation for the long-term development of fluid mechanics. However, engineering problems cannot be solved due to the complexity of mathematical solution and the limitations of fluid model. Therefore, "experimental fluid mechanics" which used experimental methods to summarize empirical formula was formed. The development of initial "experimental fluid mechanics" is limited due to a lack of theoretical foundation.

Phase Ⅲ: The contents of classical hydrodynamics and experimental fluid mechanics had been continually renewed since the late 19th century. In the meantime, the combination of theoretical analytic methods and experimental analytic methods leads to the generation of modern fluid mechanics which emphasizes both theory and practice. Since 1960s, fluid mechanics has been applied increasingly widely due to the development and popularity of computer science.

2. Major events in the field of fluid mechanics

In 1738, Daniel Bernoulli, a Swiss mathematician and physicist proposed Bernoulli equation in his famous book *Hydrodynamica*.

In 1757, Leonhard Euler proposed an important set of equations for inviscid flow, now known as the Euler equations.

In 1781, Joseph-Louis Lagrange proposed a concept "stream function" for the first time.

In 1822, Claude-Louis Navier, a French engineer and physicist, and in 1845, George Gabriel Stokes, an English mathematician and physicist proposed Navier-Stokes equations.

In 1876, Osborne Reynolds, an English physicist, found two states of fluid flow: laminar flow and turbulent flow.

In 1886, Hermann von Helmholtz, a German physician and physicist, proposed Helmholtz's theorems for vortex dynamics in inviscid fluids.

In the late 19th century, the theory of similarity was proposed.

In 1904, Ludwig Prandtl, a German engineer, described the boundary layer in his groundbreaking paper "Fluid Flow in Very Little Separation".

Since 1960s, computational fluid mechanics was developed rapidly, and the connotation of fluid mechanics has also been continuously enriched and improved.

China has a long history of water conservancy. People gradually deepen the understanding of the law of fluid motion through long-term practice. For example:

"Dayu flood control" already knew water control should follow the nature of water before 4000 years.

Three water conservancy projects (Dujiang Weir, Zhengguo Canal and Ling Canal) were built from 256 B. C. to 210 B. C.

The Grand Canal was built from A. D. 587 to 610, indicating people knew the water flow and weir flow of open canal very well.

Depending on the cognition and utilization of ocean current and air currents, Zheng He's seven voyages to western countries was a miracle in the history of human voyage.

During Yong Zheng years of the Qing Dynasty, He Mengyao proposed the flow of water was equal to the area of the cross section multiplied by the average velocity of water in his book *Suandi*.

1.1.3 The methodology of fluid mechanics

1. Theoretical methodology

Theoretical methodology is: reasonable theoretical model is proposed through scientific abstraction of physical properties and flow characteristic of liquid, and closed equations of controlling liquid motion are built according to universal law of mechanical motion. As a result, specific flow issues can be transformed to mathematical problems which can be worked out under corresponding boundary conditions and initial conditions. The key of theoretical methodology lies in proposing ideal model and working out theoretical results through mathematical methods in order to reveal the law of fluid motion. However, it is hard to solve many practical flow issues accurately due to mathematical difficulties.

Among the theoretical methods, major laws cited in fluid mechanics.

(1) Conservation of mass: $\frac{\mathrm{d}m}{\mathrm{d}t}=0$

(2) Momentum law: $\sum F=\frac{\mathrm{d}(mu)}{\mathrm{d}t}$

(3) Newton's second law of motion: $F=ma$

(4) Mechanical energy transformation and conservation law: kinetic energy + pressure energy + potential energy + energy loss = constant

Because pure theoretical methodology suffers mathematical difficulties, a set of analytic methods which combines theory and experiment are gradually perfected during the era when computer has not yet developed. This set of analytic methods is simple and practical. Today, with the computer more and more sophisticated, it is still applicable.

2. Experimental methodology

Applied fluid mechanics is a basic subject which combines theory and practice. Many practical formula and factors are derived from experiments. Many engineering problems which can be worked out through modern theoretical analysis and numerical calculation should also be examined and corrected with the help of experiments.

Major ways of experimental study: a. Prototype measurement (directly observe practical engineering or natural flow distribution); b. Systematic experiment (study

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artificial flow phenomenon systematically in the laboratory); c. Model study (simulation of the conditions for practical engineering and study through previewing or repeating flow phenomenon).

Basic theories for experimental study: similarity theory and dimensional analysis.

3. Numerical methodology

Numerical methodology is to build various numerical models by means of various discretization methods, and then to obtain a collection of many data in time and space through numerical calculation and numerical experiment, and eventually obtain numerical solution which describes flow field quantitatively. In the past two or three decades, this methodology has been greatly developed to form a new subject—computational fluid mechanics.

4. Simplification of flow analysis

Due to the complexity of fluid motion state, it is very difficult and it is not necessary to take account of all the factors involved in fluid motion. Thus, it is essential to categorize and simplify various movement states. For example, flow can be categorized into one dimensional and multi-dimensional flow, constant flow and unsteady flow, uniform flow and non-uniform flow, rapidly varied flow and gradually varied flow, laminar and turbulent flow.

1.1.4 Fluid mechanics in civil engineering

1. The nature and purpose of the course

(1) Nature

This course is a compulsory professional basic course for the majors of civil engineering and water conservancy. The objects of study are water, air and compressible fluid. Research contents include fluid equilibrium, fluid mechanical motion law and engineering application.

(2)Purposes

This course provides students with basic concepts, theories, computational methods and experimental skills. This course helps the cultivation of students' ability to analyze problems and the creative ability required in their future study and work.

(3)Status

This course provides many courses such as hydrology, hydraulics, soil mechanics, engineering geology, civil engineering, hydraulic structure and construction equipment with fluid mechanics principles, and helps students understand the relationship between civil engineering, water conservancy and atmosphere, water environment deeply.

(4)Others

This course is a compulsory course for professionals in the field of construction engineering.

2. Application of fluid mechanics in civil engineering

Fluid is a physical form which comes across to human life and production. Many scientific and technical departments concern fluid mechanics. The solution of flow problems in the fields of irrigation works, civil engineering, traffic transportation, machinery manufacturing, oil production, chemical industry, and bioengineering depends on fluid mechanics. Actually, it is impossible to find a course or field which is not involved with fluid mechanics.

(1)Application in construction engineering such as water lowering of groundwork, roadbed drainage, groundwater seepage, stress analysis of underwater and underground structures, cofferdam construction, buoyancy and resistance to external disturbance of offshore platform.

(2) Application in municipal engineering such as aperture design of bridge and culvert, water supply and drainage, calculation of pipe network, design of pump station and water tower, ventilation of tunnel. The theories of fluid mechanics are theoretical basis for design and operation control of water supply and drainage system.

(3)Application in flood control works such as discharge capacity of river course, the force and seepage of dike and dam, discharge capacity of gate dam controlling flood.

(4) Application in building environment and equipment engineering such as heat supply, ventilation and design of pump station.

(5) Application in water conservancy. Water conservancy is more dependent on fluid mechanics than other courses. For the professionals in the field of water conservancy, engineering hydraulics is also a compulsory course.

3. Basic requirements of this course

(1)Completely understand basic theories.

①Understand basic concepts in the field of fluid mechanics.

②Learn the analytic methods of gross flow, methods of combining dimension analysis and experiment and the ways to work out simple planar potential flow.

③Understand the rules of energy transformation and head loss of fluid motion.

(2)Have analytical and computational skills for general flow problems, including:

①Calculation of hydraulic load.

②Calculation of discharge capacity of tunnel, canal, and weir as well as seepage of wells.

③Analysis and calculation of head loss.

(3) Master the conventional methods for the measurements of water level, pressure, flow rate and flux well, and know how to observe flow phenomenon, analyze experimental data and write experimental report.

(4) Grasp basic concepts, basic equations and basic application, i. e. basic knowledge of fluid mechanics.

§ 1.2 Fluid and modeling

1.2.1 Three states of matter

Matter generally exists in three states: gas, liquid and solid. Liquid and gas are collectively referred to as fluid. The main difference between fluid and solid is that they have different resistance to external forces in terms of mechanical analysis. Solid is characterized by constant shape and volume because the mean distance between the molecules is very small and cohesion between the molecules is great. Solids can bear the pressure, but also can bear the tension and resist tensile deformation. Fluids can bear the pressure. But cannot bear the tension and resist tensile deformation due to large distance and small cohesive force between the molecules. Under any tiny shearing force, fluids are prone to deformation or flow.

Although both liquid and gas are fluid, the two have a certain distinction. Liquid has smaller distance and greater cohesive force between the molecules than gas. As a result, liquids can maintain a relatively constant volume and develop a free surface. Another essential difference between them lies in the greater compressibility of gases.

1.2.2 Fluid particle and continuum model

From the point of view of molecular physics, fluid and other matters comprise of a large number of molecules in random motion, and space exists between molecules. Due to the space between molecules, technically speaking, fluid is not continuous and physical quantities describing fluid (mass density ρ, velocity v, pressure p) are not continuous in space, either. Randomness of fluid molecular motion also leads to discontinuity in time of any physical quantity in space.

Under standard conditions, 1 cm^3 fluid roughly contains 3.3×10^{22} molecules and mean distance between molecules is 3×10^{-8} cm. The task of fluid mechanics is not to study microscopic motion of molecules, but to study macroscopic properties and macro mechanical motion law of the whole fluid. All characteristic scale and characteristic time employed in flow space and time are larger than molecular distance and collision time. Thus, two concepts of fluid particle and continuum model were introduced in order to study fluid motion laws.

1. Fluid particle

The volume which the cluster of molecules occupies must be small compared to the volume occupied by the whole part of the fluid under consideration. On the other hand, the number of molecules in the cluster must be large. This fluid cluster is called a fluid

particle.

2. Continuum model

Fluid continuum model is that fluid was assumed to be a continuum comprised of fluid particles filled with the whole space occupied and physical properties and physical quantities of fluid are continuous. Thus, physical quantities can be considered as continuous functions of place and time. Continuous function theory in mathematical analysis can be used to analyze fluid motion. This hypothesis is applicable for most fluids. However, when the air density is very low, the fluid should be considered as a discrete body and continuum model is not applicable.

§ 1.3 Major physical properties of fluid

Important physical properties of fluid include inertia, compressibility, expansibility, viscosity and surface tension.

1.3.1 Inertia

Inertia is the resistance of any physical object to any change in its state of motion (this includes changes to its speed, direction or state of rest). It is the tendency of objects to keep moving in a straight line at constant velocity. Mass is the quantitative measure of inertia of a body. The greater the mass of a body, the greater is its inertia. Mass density of a substance is its mass per unit volume. The symbol most often used for density is ρ with a unit of kg/m^3. For homogeneous fluid, mass density is defined as mass divided by volume as described in equation(1-1a):

$$\rho=\frac{m}{V} \tag{1-1a}$$

where m is mass and V is volume.

If the fluid is not homogeneous, then its density varies between different regions of the fluid. In that case the density around any given location is determined by calculating the density of a small volume (ΔV) around that location. In the limit of an infinitesimal volume, the density of an inhomogeneous fluid at a point becomes:

$$\rho=\lim_{\Delta V\to 0}\frac{\Delta m}{\Delta V}=\frac{\mathrm{d}m}{\mathrm{d}V} \tag{1-1b}$$

where $\mathrm{d}V$ is an elementary volume at position r.

The density of a material varies with temperature and pressure. This variation is typically small for liquids. The density of liquid can be considered as a constant. For example, water density is 1000 kg/m^3 and mercury density is 13600 kg/m^3.

The density of gas varies with temperature and pressure greatly. Air density is

1.29 kg/m^3 at 0 ℃ and under a standard atmospheric pressure.

1.3.2 Compressibility

1. Compressibility of liquid

In fluid mechanics, compressibility is a measure of the relative volume change of a liquid as a response to a pressure (or mean stress) change. The compressibility of liquid can be quantified by coefficient of compressibility, which can be denoted by k with a unit of Pa^{-1}. The compressibility of liquid can be determined by equation(1-2):

$$k=-\frac{dV}{Vdp} \tag{1-2}$$

where V is volume and p is pressure.

With the enhancement of pressure, the volume of liquid become smaller and the mass remains unchanged ($dm=0$), leading to the increase of density. The relationship between relative increments can be determined by $dm=d(\rho V)=\rho dV+Vd\rho=0$, and then we can write:

$$\frac{-dV}{V}=\frac{d\rho}{\rho}$$

which was substituted into equation(1-2), then equation(1-2) becomes:

$$k=\frac{d\rho}{\rho d\rho} \tag{1-3}$$

The smaller the value of k, the more difficult is the liquid to be compressed.

The bulk modulus K is used to represent the compressibility of the liquid in engineering. Bulk modulus is the reciprocal of coefficient of compressibility (k).

$$K=\frac{1}{k}=-\frac{Vdp}{dV}=\rho\frac{dp}{d\rho} \tag{1-4}$$

The unit of bulk modulus is Pa (N/m^2), which is same as that of pressure. The greater the value of K, the more difficult is the liquid to be compressed. When K tends to infinity, the liquid is impossible to be compressed.

K and k values vary with the type of liquid. For example, the compressibility of mercury is around 8% of that of water and the compressibility of nitric acid is around 6 times greater than that of water. For the same liquid, the values of k and K vary with temperature and pressure. However, this variation is small.

Bulk modulus variation is not very large at fixed temperature and moderate pressure. Bulk modulus can be approximatively described as:

$$\frac{V_2-V_1}{V_1}=-\frac{p_2-p_1}{K}$$

or

$$\frac{\Delta V}{V_1}=\frac{-\Delta p}{K} \tag{1-5}$$

In the field of engineering design, bulk modulus of water is approximated to be 2.1

$\times 10^9$ Pa, indicating the relative change of the volume ($\frac{\Delta V}{V_1}$) is about $\frac{1}{20000}$ when the variation of the pressure is an atmospheric pressure. Thus, when Δp is not large, the compressibility of water can be ignored and water density can be considered as a constant. However, the compressibility of water is beyond neglect when water-hammer problems of water flow in the pipeline are discussed.

Expansion coefficient α_v can be used to represent expansion of liquid, indicating the relative variation rate of the volume when pressure remains unchanged and variation of liquid temperature is 1 K, which can be described as equation(1-6):

$$\alpha_v = \frac{\mathrm{d}V}{V\mathrm{d}T} = -\frac{\mathrm{d}\rho}{\rho\mathrm{d}T} \tag{1-6}$$

where $\mathrm{d}T$ is temperature variation and the unit of α_v is K^{-1} or $℃^{-1}$.

Expansion coefficient of liquid varies with pressure and temperature. At an atmospheric pressure and 20℃, α_v is 2.1×10^{-4} K^{-1}, which can be ignored. However, expansion of water must be taken into account when the variation of working temperature is large.

2. Compressibility of gas

Gas density is determined by the equation of state.

An ideal gas is a theoretical gas composed of many randomly moving point particles that do not interact except when they collide elastically. Its equation of state can be described as equation(1-7):

$$\frac{p}{\rho} = RT \tag{1-7}$$

where p is absolution pressure of gas, R is ideal gas constant with the value of 287 N·m/(kg·K), and T is absolute temperature.

Ideal gas does not exist. However, at normal conditions such as standard temperature and pressure, most real gases behave qualitatively like an ideal gas. Many gases such as nitrogen, oxygen, hydrogen, noble gases, and some heavier gases like carbon dioxide can be treated like ideal gases within reasonable tolerances.

Example 1-1: The volume of water is 2.5 m^3 at 20 ℃. How much is its volume increase when the temperature rises to 80℃?

Solution: Water density ρ_1 is 998.23 kg/m^3 at 20 ℃ while water density ρ_2 is 971.83 kg/m^3 at 80 ℃. Due to conservation of mass, the volume of water increases with the decrease of density when the temperature rises. Then, we can write

$$\frac{-\mathrm{d}V}{V} = \frac{\mathrm{d}\rho}{\rho}$$

Data were substituted into the equation above, then

$$\Delta V = -\frac{\Delta\rho}{\rho}V = -\frac{\rho_2-\rho_1}{\rho_1}V_1 = -\frac{(971.83-998.23)\mathrm{kg/m^3}}{998.23\mathrm{kg/m^3}}\times 2.5\mathrm{m^3}$$

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