Hongqing Song

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Based on an original Chinese edition:
《工程流体力学及环境应用》，冶金工业出版社，2016.

图书在版编目(CIP)数据

工程流体力学=Engineering Fluid Mechanics：英文/
宋洪庆主编．—北京：冶金工业出版社，2018. 9
ISBN 978-7-5024-7911-4

Ⅰ．①工…　Ⅱ．①宋…　Ⅲ．①工程力学—流体力学—
英文　Ⅳ．①TB126

中国版本图书馆 CIP 数据核字(2018)第 229981 号

出 版 人　谭学余
地　　址　北京市东城区嵩祝院北巷 39 号　邮编　100009　电话　(010)64027926
网　　址　www. cnmip. com. cn　电子信箱　yjcbs@ cnmip. com. cn
责任编辑　夏小雪　美术编辑　彭子赫　版式设计　孙跃红
责任校对　王永欣　责任印制　牛晓波
ISBN 978-7-5024-7911-4
冶金工业出版社出版发行；各地新华书店经销；北京建宏印刷有限公司印刷
2018 年 9 月第 1 版，2018 年 9 月第 1 次印刷
155mm×235mm；17 印张；298 千字；256 页
57. 00 元
冶金工业出版社　投稿电话　(010)64027932　投稿信箱　tougao@cnmip.com.cn
冶金工业出版社营销中心　电话　(010)64044283　传真　(010)64027893
冶金书店　地址　北京市东四西大街 46 号(100010)　电话　(010)65289081(兼传真)
冶金工业出版社天猫旗舰店　yjgycbs. tmall. com

前言

流体力学是研究流体平衡及其运动规律的一门学科。本书在连续介质模型的基础上，阐述了流体力学的基本原理。全书主要包括以下几部分内容：流体力学基本概念和流体静力学（第1、2章），流体动力学、流态、水头损失和管流计算（第3、4、5章），渗流力学基础及相关应用（第6章），流体机械（第7章），相似原理和量纲分析（第8章），基于渗流力学理论对CO_2封存效果的评价分析（第9章）。

书中提供了许多实用的表格，它们包含在工程领域中经常使用的各种参数。例如，第1章的表中给出了在标准大气压下不同流体的重度值，以及不同条件下水的黏度、弹性模量和膨胀系数。第2章中列出了常见结构的几何性质，如面积、质心坐标、惯性矩等，它们可以用来确定合外力的作用位置。为了使用方便，在第4章中列出了不同类型圆管的局部阻力系数，第5、6、8章分别列出了不同物体表面的粗糙度、不同类型土壤的渗透系数和相似模型的比值尺。

书中采用两种方法推导了达西定律。方法一是基于达西实验，这也是大多数教科书中所采用的方法；方法二是基于自由流和渗流之间的联系，从N-S方程出发，推导达西定律，该方法有助于读者进一步研究纳米尺度的流动。此外，书中还针对

当下的一个研究热点——二氧化碳的捕捉与封存，来展示如何应用渗流力学基本原理来研究解决跨学科问题。

最后，书中每章的结尾都列出了一些新颖而重要的问题，以便于教师在教学过程中布置作业、提高学生解决工程实际问题的能力。

本书主要针对高年级本科生、研究生、讲师以及从事流体力学及其应用的研究人员。书中用通俗易懂的语言介绍了流体力学的基本理论知识，使读者更能理解和掌握。与此同时，书中清晰地描述了自由流和渗流之间的区别与联系，并且还涵盖了纳米尺度流动的最新知识。此外，书中还引入了关于二氧化碳捕捉与封存方面的知识，以引起读者对环境问题的关注。本书对读者最大的益处是它全面的介绍了流体力学的各个方面知识，并涵盖了所有相关的领域。

本书已列入北京科技大学校级规划教材，教材的编写与出版得到了北京科技大学教材建设经费的资助。

宋洪庆

中国，北京

2018 年 3 月

Preface

Fluid mechanics is a discipline which focuses on the fluid equilibrium and its movement. Based on the continuum model, we present the research of fluid mechanics to reader in this book. Contents of the book have been organized into broad topic areas: Introductory concepts and fluid statics (Chaps. 1, 2); Fluid dynamics, flow regimes, head loss, and pipe flow calculation (Chaps. 3, 4, 5); Fundamentals of fluid mechanics through porous media and corresponding applications (Chap. 6); Analysis of fluid machinery (Chap. 7); Similitude and dimensional analysis (Chap. 8); and Evaluation and analysis of CO_2 storage effect according to principles of seepage mechanics (Chap. 9).

This book provides many practical tables containing various parameters that are frequently used in engineering field. For example, Chap. 1 gives some tables about specific weights of various fluids at standard atmospheric pressure, along with water viscosity, water elastic modulus, and water expansibility coefficient at different conditions. In Chap. 2, the geometric properties of various structures are used for the determination of action location of resultant force, such as area, centroid coordinate, inertial moment, and so on. In Chap. 4, minor loss coefficients of different kinds of tubes are listed to facilitate utilization. Roughness coefficients of different kinds of surfaces, hydraulic conductivities of different kinds of soils, and ratio scales of similitude models are listed in Chaps. 5, 6, and 8, respectively.

This book also introduces two different ways to derive Darcy's law. The first method is based on the well-known Darcy's experiment, which is widely chosen in most textbooks. The other way presented in this book is to derive Darcy's law from N-S equation based on the connection between free flow and porous flow, which is helpful for readers to further study nanoscale flow. Furthermore, an advanced interdisciplinary case study on carbon dioxide capture and storage concerning energy and environment is presented. With this case study, we intend to provide a survey of the most increasing amounts of the world's energy needs from renewable resource.

At last, we select a number of novel and significant problem sets at the end of each chapter to help instructor assign homework and improve readers' ability to solve engineering problems.

This book is written for senior undergraduates, graduate students, lecturers, and researchers engaged in fluid mechanics and its application. It mainly introduces the basic theoretical knowledge with concise and understandable words, which is much easier for readers to understand. Meanwhile, this book describes clearly the difference and connection between free flow and porous flow, and incorporates the newest knowledge about nanoscale flow. What is more, the knowledge of carbon dioxide capture and storage is also introduced to bring readers' attention to environmental problems. The main benefit for reader is a sound introduction into all aspects of fluid mechanics covering all relevant subfields.

Beijing, China
March 2018

Hongqing Song

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Introduction

1

Abstract

Fluid mechanics is a discipline which focuses on the fluid equilibrium and its movement. It has great significance on our daily lives. In this chapter, we will first introduce the developing trends and research methods of fluid mechanics. Then we will give definitions of continuum model for fluids. Finally, we will discuss major properties of fluid, such as specific weight, viscosity, compressibility and so on.

Keywords
Specific weight · Viscosity · Compressibility · Expansibility · Surface tension

1.1 Background

1.1.1 Definition of Fluid Mechanics

Fluid mechanics is a discipline which studies the fluid equilibrium and its movement law. In contrast to a solid, a fluid is a substance the particles of which easily moves and changes their relative position. More specifically, a fluid is defined as a substance that will deform continuously, that is, flows under the action of a sheer stress, no matter how small that shear stress may be. A fluid can either be a gas or a liquid.

The significance of fluid mechanics becomes apparent when we consider the vital role it plays in our everyday lives. For example, when we turn on our water taps, we activate flow in a complex hydraulic network of pipes, valves, and pumps. And our very lives depend on a very important fluid mechanic process—the flow of

H. Song, *Engineering Fluid Mechanics*,
https://doi.org/10.1007/978-981-13-0173-5_1

blood through our veins and arteries. Fluid mechanics is involved in some of the most significant environmental problems, such as air pollution and underground hazardous waste.

1.1.2 Trends in Fluid Mechanics

The science of fluid mechanics began with the need to control water for irrigation purposes in ancient Egypt, Mesopotamia, and India. Although these civilizations understood the nature of channel flow, there is no evidence that any quantitative relationships had been developed to guide them in their work. It was not until 250 B.C. that Archimedes discovered and recorded the principles of hydrostatics and flotation. Although the empirical understanding of hydrodynamics continued to improve with the development of fluid machinery, better sailing vessels, and more intricate canal systems, the fundamental principles of classical hydrodynamics were not set forth until the seventeenth and eighteenth centuries. Newton, Daniel Bernoulli, and Euler made the greatest contributions to these principles establishment.

Modern developments in fluid mechanics, as in all fields, involve the utilization of high-speed computers in the solution of problems. The ever-increasing speed and memory capacity of modern computers are leading to even more exciting applications of computers in fluid mechanics. Armed with more detailed measurements and numerical models, fluid mechanicians have developed higher levels of understanding that have led to sophisticated designs and applications of fluid systems.

1.1.3 Research Methods of Fluid Mechanics

There are three methods for fluid mechanics research: theoretical analysis, experimental test and numerical simulation. For theoretical analysis, there are three steps to investigate fluid flow. At first, several main factors affecting the flow problem are determined after analysis. Then the theoretical mathematic model is established with appropriate assumptions. Eventually the general solution for fluid movement is obtained by mathematical method utilization. For experimental test, the actual flow problem is summarized as a similar experimental model. With the combination of experimental equipment such as wind tunnel and water tunnel, the actual result can be deduced based on phenomena and data according to experiments. For numerical simulation, the calculation results based on theoretical analysis and experimental observation can be obtained with computing approaches, such as finite difference method and finite element method, etc. The numerical simulation is becoming popular with computing technology development since twenty-first century.

These three methods have their own advantages and disadvantages, and the best way is to complement each other to promote the development of fluid mechanics. With the development of modern measurement and computing technology, fluid mechanics will get largely promotion and facilitate for industrial development.

1.2 Continuum Model of Fluid

1.2.1 Fluid Particles

Similar to solid, fluid also has three basic properties: first, it consists of a large number of molecules; second, the molecules keep random thermal motion; third, there are molecular forces between molecules. From the view of microscopic level, a fluid molecule must have a certain shape, which means a fluid is not continuous, although the gap between molecules is very tiny.

However, fluid mechanics mainly focus on macroscopic mechanical movement of fluids rather than microscopic molecules, which is the statistical mean behavior of a large quantity of molecules. Therefore, the concepts of fluid particle and continuum must be adopted for fluid mechanic investigations.

Fluid particle is regarded as an aggregation of fluid molecules with small enough volume and definite macroscopic parameters value such as density, viscosity and velocity, etc.

1.2.2 Continuum Model of Fluid

Assuming that a fluid is composed of fluid particles rather than molecules, then the fluid is a continuum, which means that differential calculus is valid for all the analysis of fluid mechanics. Therefore, all physical properties of fluid particle, such as density, velocity, pressure, and temperature, are the continuous functions of space and time (x, y, z, t) [1–3]. The mathematical tools of continuous function and field theory can be utilized to solve flowing problems.

1.3 Main Properties of Fluid

1.3.1 Density and Specific Weight

Density is the mass of the substance per unit volume. It indicates the intensity of fluid in space, and usually it is denoted by the Greek letter ρ with unit kg/m^3 in SI.

For homogenous fluid, each point has the same density

$$\rho = \frac{m}{V} \tag{1.1}$$

For heterogeneous fluid, take an infinitesimal volume ΔV surrounding a certain point in space, the mass of fluid in it is Δm, then the ratio $\Delta V / \Delta m$ is the average density in volume ΔV. Let $\Delta V \to 0$, the limit of this ratio will be the density at the point inside ΔV.

$$\rho = \lim_{\Delta V \to 0} \frac{\Delta m}{\Delta V} = \frac{\mathrm{d}m}{\mathrm{d}V} \tag{1.2}$$

The specific weight of a fluid is the gravity per unit volume, denoted by γ. For homogenous fluid

$$\gamma = \frac{\mathrm{G}}{V} = \frac{mg}{V} = \rho g \tag{1.3}$$

For heterogeneous fluid:

$$\gamma = \lim_{\Delta V \to 0} \frac{\Delta G}{\Delta V} = \frac{\mathrm{dG}}{\mathrm{d}V} \tag{1.4}$$

The unit of specific weight in SI is N/m^3.

Different fluids have different density and specific weight. The density and specific weight of same fluid also vary with the temperature and pressure. Table 1.1 gives the density and specific weight of various fluids at standard atmospheric pressure. Table 1.2 gives the density and specific weight of water at standard atmospheric pressure with different temperature.

1.3.2 Viscosity

Viscosity is another important property of a fluid. Viscosity is a measure of the fluid's resistance to flow due to its internal friction. Viscosity is measured in two ways: dynamic (absolute) viscosity μ and kinematic viscosity υ. One must note that a fluid exhibits viscosity only when there is relative motion between fluid elements, or the fluid is in motion. A fluid at rest will not exhibit viscosity. The effect of viscosity indicates that it will restrict relative slip inside a fluid, thereby obstructing a fluid's flow. But this obstruction can only slow down the process of relative slip rather than eliminating this phenomenon, and this is an important feature of viscosity.

1.3.2.1 Newton's Viscosity Law

As shown in Fig. 1.1, two parallel plates are placed horizontally with a distance h. A certain liquid is filled between the two plates, then supposing that the lower plate is fixed and the upper moves with a uniform velocity v_0 to the right under the application of force F. According to the nonslip condition, a viscous fluid will stick to the solid boundary which the fluid attaches, so the fluid layer attaching to the upper plate moves at the velocity v_0 along the direction of x axis, and the fluid layer attaching to the lower plate stays at rest. Fluid between the two plates flows in the direction parallel to the plates, its velocity changes uniformly from zero of the lower

Table 1.1 Physical properties of various fluids at standard atmospheric pressure

Fluid	Temp. (°C)	Density (kg/m^3)	Specific weight (N/m^3)	Dynamic viscosity (Pa s)	Kinematic viscosity (m^2/s)
Distilled water	4	1000	9800	1.52×10^{-3}	1.52×10^{-6}
Seawater	20	1025	10,045	1.08×10^{-3}	1.05×10^{-6}
Carbon tetrachloride	20	1588	15,562	0.97×10^{-3}	0.61×10^{-6}
Gasoline	20	678	6644	0.29×10^{-3}	0.43×10^{-6}
Petroleum	20	856	8389	7.2×10^{-3}	8.4×10^{-6}
Lubricant	20	918	8996	440×10^{-3}	479×10^{-6}
Kerosene	20	808	7918	1.92×10^{-3}	2.4×10^{-6}
Alcohol	20	789	7732	1.19×10^{-3}	1.5×10^{-6}
Glycerol	20	1258	12,328	1490×10^{-3}	1184×10^{-6}
Turpentine	20	862	8448	1.49×10^{-3}	1.73×10^{-6}
Castor oil	20	960	9408	0.961×10^{-3}	1.00×10^{-6}
Benzene	20	895	8771	0.65×10^{-3}	0.73×10^{-6}
Mercury	0	13,600	133,280	1.70×10^{-3}	0.125×10^{-6}
Liquid hydrogen	−257	72	705.6	0.021×10^{-3}	0.29×10^{-6}
Liquid oxygen	−195	1206	11,819	82×10^{-3}	68×10^{-6}
Air	20	1.20	11.76	1.83×10^{-5}	1.53×10^{-5}
Oxygen	20	1.33	13.03	2.0×10^{-5}	1.5×10^{-5}
Hydrogen	20	0.0839	0.8222	0.9×10^{-5}	10.7×10^{-5}
Nitrogen	20	1.16	11.37	1.76×10^{-5}	1.52×10^{-5}
Carbon monoxide	20	1.16	11.37	1.82×10^{-5}	1.57×10^{-5}
Carbon dioxide	20	1.84	18.03	1.48×10^{-5}	0.8×10^{-5}
Helium	20	0.166	1.627	1.97×10^{-5}	11.8×10^{-5}
Methane	20	0.668	6.546	1.34×10^{-5}	2.0×10^{-5}

plate to v_0 of the upper plate. Thus, there is relative motion between every two fluid layers, and inner friction T will be generated on the interface. Assuming that the contacting area of the plate with the fluid is A. Shear stress in a fluid is defined as the inner friction per unit area, and is denoted with the symbol τ, so $\tau = T/A$.

Assuming that flowing velocity distribution complies with the relationship of linearism, as shown in Fig. 1.1. Experiments demonstrate that the magnitude of shear stress τ in a fluid is directly proportional to the velocity of upper plate, but is inversely proportional to the distance between the two plates, so we have

$$\tau = \mu \frac{v_0}{h} \tag{1.5}$$