"十三五"江苏省高等学校重点教材

流体力学基础（双语版）

Fundamentals of Fluid Mechanics

周剑锋　邵春雷　主编

顾伯勤　主审

化学工业出版社

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·北京·

本书系"十三五"江苏省高等学校重点教材，本书内容涉及流体力学基本概念、基本理论和研究方法等几个方面，全书共9章，包括流体力学简介、流体静力学、流体运动学、流体流动的有限控制体分析、流体流动的微分分析、相似理论和量纲分析、管内流动、平面势流和绕物流动。与其他流体力学教材不同，本书是以介绍流体力学基础知识为主，内容简单。采用双栏格式，中英文对照，可提高学生英文阅读能力。为了加强学生对内容的理解，每章均配有习题。

本书可作为高等院校非力学专业本科生流体力学课程教材，也可供相关人员参考使用。

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前言

Preface

本书是为高等院校非力学专业本科流体力学课程中英双语教学编写的。考虑到目前流体力学课程的教学课时数有限，所以本教材以介绍流体力学基础知识为主，内容浅显，易于理解。本书旨在介绍流体力学的基本概念、基本理论和解决流体力学问题的基本方法，为本科生后续课程的学习及未来从事的工作提供必要的流体力学基本知识，同时提高学生阅读相关英文科技文献的能力。

本书共 9 章，包括流体力学简介、流体静力学、流体运动学、流体流动的有限控制体分析、流体流动的微分分析、相似理论和量纲分析、管内流动、平面势流以及绕物流动。全书文字部分采用双栏格式排版，中英文对照。为便于学生学习和理解教材内容，每章都附有一定数量的例题和习题。

本书第 1 章至第 5 章由南京工业大学邵春雷编写，第 6 章至第 9 章由南京工业大学周剑锋编写，全书由南京工业大学顾伯勤主审。本书得到了江苏高校品牌专业建设工程项目（PPZY2015A022）的资助。

限于编者水平，书中不足之处在所难免，恳请读者批评指正。

编　者

2017 年 10 月 10 日　于南京

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Chapter 1 Introduction of Fluid Mechanics
第1章 流体力学简介

Fluid mechanics is the discipline within the field of applied mechanics concerned with the behavior of fluids at rest or in motion. Fluid mechanics has a wide range of applications, including for mechanical engineering, civil engineering, chemical engineering, biology, and so on.

流体力学是应用力学领域中的一门学科，研究流体在静止或运动状态下的行为。流体力学在机械工程、土木工程、化学工程和生物学等领域具有广泛的应用。

Many interesting questions can be answered by using relatively simple fluid mechanics ideas. A foundation of the fluid mechanics will be introduced in this chapter.

许多有趣的问题可以通过利用相对简单的流体力学思想来解答。本章简单介绍流体力学基础知识。

1.1 Brief History of Fluid Mechanics

1.1 流体力学简史

Before the study of fluid mechanics, the history of this important engineering science should be reviewed briefly.

学习流体力学前，先简要回顾一下这门重要工程科学的发展史。

Before second century A. D., Archimedes (287—212 B. C.), who is a Greek mathematician and inventor, first expressed the principles of hydrostatics and flotation. However, for the next 1000 years, no significant development has been made for fluid mechanics.

公元2世纪以前，古希腊数学家和发明家阿基米德首先阐述了流体静力学和漂浮的基本原理。然而，随后的一千多年中，流体力学几乎未得到任何发展。

About from the fifteenth century to eighteenth century, a rather continuous series of contributions form the basis of fluid mechanics. Leonardo da Vinci (1452—1519) described many different types of flow phenomena. The work of Galileo Galilei (1564—1642) marked the beginning of experimental mechanics. Since then, a large number of famous scientists, such as Newton, Bernoulli, Euler and d' Alembert, etc., made great contributions in theory and mathematics. Experimental aspects of fluid mechanics were also advanced during this period, but the two different methods, theoretical and experimental, developed along separate paths.

从15世纪到18世纪，科学家们的一系列贡献形成了流体力学的基础。达·芬奇描绘了许多不同类型的流动现象，伽利略的工作标志着实验力学的开端。此后，出现了一大批著名的科学家，如：牛顿、伯努利、欧拉和达朗贝尔等，在理论和数学方面作出了重大贡献。这一时期，实验流体力学也得到了发展。但是，理论和实验这两种方法各自沿着不同的路径发展。

During the nineteenth century, the differential equations were used to describe fluid motions, and further contributions were made to both theoretical hydrodynamics and experimental hydraulics. Experimental hydraulics gradually became a free-standing science, and many of those experimental results are still used today.

19 世纪，微分方程被用于描述流体运动，理论水动力学和实验水力学得到了进一步发展。实验水力学逐渐成为一门独立的科学，许多实验结果至今仍在使用。

Both the theoretical hydrodynamics and experimental hydraulics were highly developed at the beginning of the twentieth century, and some attempts were made to unify them. In 1904 Ludwig Prandtl (1857—1953) proposed the concept of boundary layer, which laid the foundation for the unification of the theoretical and experimental aspects of fluid mechanics. Prandtl is generally accepted as the founder of modern fluid mechanics.

20 世纪初，理论水动力学和实验水力学均得到高度发展，人们试图将它们统一起来。1904 年，普朗特提出了边界层的概念，为流体力学理论与实验研究的统一奠定了基础。他被公认为现代流体力学的奠基人。

Also, during the first decade of the twentieth century, powered flight was first successfully demonstrated with the subsequent vastly increased interest in aerodynamics. The design of aircraft required a degree of understanding of fluid flow and an ability to make accurate predictions of the effect of air flow on bodies, so the development of aerodynamics provided a great stimulus for the rapid development in fluid mechanics.

此外，20 世纪前十年，动力飞行的首次演示成功引起了人们对空气动力学的浓厚兴趣。由于飞机的设计要求对流体流动有一定程度的了解，且要求能准确预测空气对飞行物的作用，所以空气动力学的发展大大推动了流体力学的发展。

Main contributions of the pioneers in fluid mechanics are summarized in Table 1.1.

表 1.1 总结了前人在流体力学方面的主要贡献。

Table 1.1 Contributions of the pioneers in fluid mechanics

表 1.1 前人在流体力学方面的贡献

Name 人名	Contributions 贡献
Archimedes 阿基米德(287—212 B.C.)	Established elementary principles of buoyancy and flotation 建立了浮力和漂浮的基本原理
Leonardo da Vinci 达·芬奇(1452—1519)	Expressed elementary principle of continuity; observed and sketched many basic flow phenomena; designed hydraulic machinery 表达了连续性的基本原理，观察并描述了许多基本的流动现象，设计了水力机械
Galileo Galilei 伽利略(1564—1642)	Indirectly stimulated experimental hydraulics; revised Aristotelian concept of vacuum 间接促进了实验水力学，修正了亚里士多德真空的概念
Evangelista Torricelli 托里拆利(1608—1647)	Invented barometer 发明了气压计

Name 人名	Contributions 贡献
Blaise Pascal 帕斯卡(1623—1662)	Put forward the law that the fluid can transfer pressure, the so-called Pascal's law 提出流体能传递压力的定律,即所谓帕斯卡定律
Isaac Newton 牛顿(1642—1727)	Explored various aspects of fluid resistance, inertia, viscosity and wave 探索了流体阻力、惯性、黏性和波浪的各个方面
Henri de Pitot 皮托(1695—1771)	Invented the pitot tube used for the measurement of flow velocity 发明了测量流速的皮托管
Daniel Bernoulli 伯努利(1700—1782)	Established the basic equation of fluid dynamics, which is called the Bernoulli equation 建立了流体动力学的基本方程,称为伯努利方程
Leonhard Euler 欧拉(1707—1783)	First explained role of pressure in fluid flow; formulated basic equations of motion; introduced concept of cavitation and principle of centrifugal machinery 首先解释了压力在流体流动中的作用,阐述了基本的运动方程,介绍了离心机械的空化概念和原理
Jean le Rond d'Alembert 达朗贝尔(1717—1783)	Originated notion of velocity and acceleration components, and differential expression of continuity 提出了速度和加速度分量的概念和连续性的微分表示
Giovanni Battista Venturi 文丘里(1746—1822)	Performed tests on various forms of mouthpieces, in particular, conical contractions and expansions 对多种喷口形式进行了试验,尤其是圆锥收缩和扩张形式的喷口
Louis Marie Henri Navier 纳维(1785—1836)	Established the basic equations of fluid motion considering "molecular" forces 建立了考虑分子力的流体运动的基本方程
George Gabriel Stokes 斯托克斯(1819—1903)	Established the basic equation of viscous fluid motion, which is called Navier-Stokes equation 建立了黏性流体运动的基本方程,称为纳维-斯托克斯方程
Ernst Mach 马赫(1838—1916)	One of the pioneers in the field of supersonic aerodynamics 超音速空气动力学领域的先驱
Osborne Reynolds 雷诺(1842—1912)	Discovered the similarity law of flow; introduced a dimensionless number, that is the Reynolds number, as the criterion for judging the flow states 发现流动的相似律,引入无量纲数,即雷诺数,作为判别流态的标准
John William Strutt, Lord Rayleigh 瑞利(1842—1919)	Investigated hydrodynamics of bubble collapse, wave motion, jet instability and dynamic similarity 研究了气泡破裂、波动、射流不稳定性和动力相似性等流体力学问题
Vincenc Strouhal 斯特劳哈尔(1850—1922)	Investigated the phenomenon of "singing wires" 研究了丝线发声现象
Edgar Buckingham 白金汉姆(1867—1940)	Stimulated interest in the United States in the use of dimensional analysis 激发了美国在量纲分析使用方面的兴趣
Moritz Weber 韦伯(1871—1951)	Formulated a capillarity similarity parameter 阐述了毛细相似参数
Ludwig Prandtl 普朗特(1875—1953)	Introduced concept of the boundary layer and is generally considered to be the father of present-day fluid mechanics 引入了边界层的概念,被认为是现代流体力学之父
Lewis Ferry Moody 莫迪(1880—1953)	Provided many innovations in the field of hydraulic machinery. Proposed a method of correlating pipe resistance data 在水力机械领域有许多创新,提出了关于管道阻力数据的相关方法

Name 人名	Contributions 贡献
Theodor Von Kármán 冯卡门 (1881—1963)	One of the recognized leaders of twentieth century fluid mechanics. Provided major contributions to our understanding of surface resistance, turbulence and wake phenomena 被认为是20世纪流体力学的领袖之一,为人们理解表面阻力、湍流和尾迹现象作出了重要的贡献
Paul Richard Heinrich Blasius 布拉修斯 (1883—1970)	Provided an analytical solution to the boundary layer equations. Also, demonstrated that pipe resistance was related to the Reynolds number 提供了边界层方程的解析解,并证明了管道阻力与雷诺数有关

1.2 Dimensions and Units

1.2.1 Dimensions

In the study of fluid mechanics, we will deal with a variety of fluid characteristics, so it is necessary to develop a system for describing these characteristics both qualitatively and quantitatively. The qualitative aspect refers to identify the nature or type of the characteristics (such as length, time, stress and velocity), whereas the quantitative aspect provides a numerical measure of the characteristics. The quantitative description requires both a number and a standard by which various quantities can be compared. A standard for time might be a second or hour, for mass a kilogram or gram, and for length a meter or millimeter. Such standards are called units.

The qualitative description is given in terms of certain primary quantities, such as length, L, time, T, mass, M, and temperature, Θ. These primary quantities can then be used to provide a qualitative description of any other secondary quantities: for example, area$\doteq L^2$, velocity$\doteq LT^{-1}$, density$\doteq ML^{-3}$, where the symbol indicates the dimensions of the secondary quantity in terms of the primary quantities. Thus, velocity, v, can be described qualitatively as

1.2 量纲和单位

1.2.1 量纲

在流体力学的学习过程中，会遇到流体的各种特性，所以有必要建立一个体系以定性和定量地描述这些特性。定性方面是指特性的本质或类型（如：长度、时间、应力和速度），而定量方面提供了特性的数量。定量描述需要具体的数值和度量衡标准，通过它可以比较不同的量。如时间的度量衡标准可以是秒或小时，质量可以是千克或克，长度可以是米或毫米。这样的度量衡标准称作为单位。

根据主量（如：长度 L、时间 T、质量 M 和温度 Θ）可以进行定性描述，任何其他二次量的定性描述可由主量导出，例如：面积$\doteq L^2$，速度$\doteq LT^{-1}$，密度$\doteq ML^{-3}$，这些符号表示根据主量得到的二次量的量纲。因此，速度 v 可定性地描述为

$$v \doteq LT^{-1}$$

that is, the dimensions of velocity equal length divided by time. The primary quantities are also referred to as basic dimensions.

也就是说，速度的量纲等于长度除以时间。主量也被称为基本量纲。

For most fluid mechanics problems, only the three basic dimensions, L, T and M are usually required. Table 1.2 provides a list of dimensions for common physical quantities.

对于大多数流体力学问题而言，物理量通常只需要 L、T 和 M 三个基本量纲。表 1.2 给出了常用物理量的量纲。

Table 1.2 Dimensions associated with common physical quantities

表 1.2 常用物理量的量纲

Physical quantities 物理量	Dimension 量纲	SI Units 国际单位
Acceleration 加速度	LT^{-2}	m/s^2
Angle 角度	$M^0L^0T^0$	1
Angular acceleration 角加速度	T^{-2}	s^{-2}
Angular velocity 角速度	T^{-1}	s^{-1}
Area 面积	L^2	m^2
Density 密度	ML^{-3}	kg/m^3
Energy 能量	ML^2T^{-2}	J
Force 力	MLT^{-2}	N
Length 长度	L	m
Mass 质量	M	kg
Modulus of elasticity 弹性模量	$ML^{-1}T^{-2}$	Pa
Moment of a force 力矩	ML^2T^{-2}	N・m
Momentum 动量	MLT^{-1}	kg・m/s
Power 功率	ML^2T^{-3}	W
Pressure 压强	$ML^{-1}T^{-2}$	Pa
Specific weight 重度	$ML^{-2}T^{-2}$	N/m^3
Strain 应变	$M^0L^0T^0$	1
Stress 应力	$ML^{-1}T^{-2}$	MPa
Surface tension 表面张力	MT^{-2}	N/m
Temperature 温度	Θ	K
Time 时间	T	s
Torque 扭矩	ML^2T^{-2}	N・m
Velocity 速度	LT^{-1}	m/s
Viscosity(dynamic) 动力黏度	$ML^{-1}T^{-1}$	$N \cdot s/m^2$
Viscosity(kinematic) 运动黏度	L^2T^{-1}	m^2/s
Volume 容积	L^3	m^3
Work 功	ML^2T^{-2}	J

All theoretically derived equations are dimensionally homogeneous; that is, the dimensions of the left side of the equation must be consistent with those on the right side, and all additive separate terms must have the same dimensions. For example, the equation for the velocity of uniformly accelerated body is

所有理论推导得到的方程都是量纲和谐的，也就是说，方程左边的量纲必须与方程右边的量纲一致，所有加和项具有相同的量纲。例如：匀加速物体的速度方程为

$$v = v_0 + at \tag{1.1}$$

where v_0 is the initial velocity, a is the acceleration, and t is the time interval. In terms of dimensions the equation is

式中，v_0 为初速度；a 为加速度；t 为时间间隔。上式采用量纲表示为

$$LT^{-1} \doteq LT^{-1} + LT^{-1}$$

and thus Eq. (1.1) is dimensionally homogeneous.

因此，式(1.1) 是量纲和谐的。

Some equations contain constants having dimensions. For example, for a freely falling body, the traveled distance, d, can be written as

有些方程中的常数是有量纲的。例如：对于自由落体，下降的距离可以表示为

$$d = 4.9t^2 \tag{1.2}$$

and the constant must have the dimensions of LT^{-2} if the equation is dimensionally homogeneous. Actually, Eq. (1.2) is a special form of the well-known equation for freely falling bodies.

如果方程是量纲和谐的，那么上式中常数的量纲必须为 LT^{-2}。实际上，式(1.2) 是自由落体运动方程的特殊形式。

$$d = \frac{gt^2}{2} \tag{1.3}$$

where g is the acceleration of gravity. Equation (1.3) is dimensionally homogeneous and valid in any system of units. For $g = 9.8\text{m/s}^2$, the equation reduces to Eq. (1.2) and thus Eq. (1.2) is valid only for the system of units using meter and second. The concept of dimensions forms the basis for the dimensional analysis, which is discussed in detail in Chapter 6.

式中，g 为重力加速度。式(1.3) 对任何单位系统都是量纲和谐的。如果 $g = 9.8\text{m/s}^2$，式(1.3) 就变为式(1.2)，因此，式(1.2) 只对使用米和秒作为单位的系统成立。量纲的概念是量纲分析的基础，将在第 6 章详细讨论。

【EXAMPLE 1.1】 A pipe locates in the side of a tank as shown in Fig. 1.1. The volume flowrate, Q, of liquid through the pipe can be expressed as

【例题 1.1】 一圆管位于容器侧面，如图 1.1 所示。液体通过圆管的体积流量可表达为

$$Q = 0.61A\sqrt{2gh}$$

where A is the area of the pipe, g is the acceleration of gravity, and h is the height of the liquid above the pipe center. Investigate the dimensional homogeneity of this formula.

式中，A 为圆管的面积；g 为重力加速度；h 为圆管中心上方液体的高度。试分析该公式的量纲和谐性。

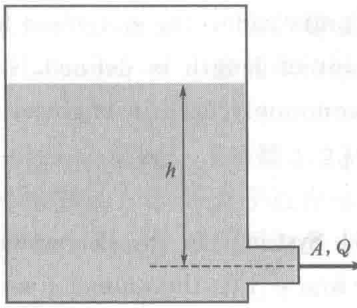

Fig. 1.1 Figure for the example 1.1

图 1.1 例题 1.1 图

SOLUTION The dimensions of the various terms in the equation are $Q \doteq L^3T^{-1}$, $A \doteq L^2$, $g \doteq LT^{-2}$, $h \doteq L$. These terms, when substituted into the equation, yield the dimensional form

解 公式中 Q 的量纲为 L^3T^{-1}，A 的量纲为 L^2，g 的量纲为 LT^{-2}，h 的量纲为 L。代入上式得

$$(L^3T^{-1}) \doteq (0.61)(L^2)(2)^{1/2}(LT^{-2})^{1/2}(L)^{1/2}$$

$$(L^3T^{-1}) \doteq [(0.61)(2)^{1/2}](L^3T^{-1})$$

it can be seen that both sides of the equation have the same dimensions of L^3T^{-1}, the equation is dimensionally homogeneous, and the numbers [0.61 and $(2)^{1/2}$] are dimensionless. If g is replaced with the value of $9.8 m/s^2$, the equation can be rewritten as

可见，上式两边具有相同的量纲 L^3T^{-1}，该式量纲和谐，0.61 和 $(2)^{1/2}$ 为无量纲的数。如果用 $9.8 m/s^2$ 代替 g，公式可重写为

$$Q = 2.7A(h^{1/2}) \qquad (1.4)$$

A check of the dimensions reveals that

量纲分析表明

$$L^3T^{-1} \doteq (2.7)(L^{5/2})$$

and, therefore, the equation expressed as Eq. (1.4) can only be dimensionally correct if the number 2.7 has the dimensions of $L^{1/2}T^{-1}$. Whenever a number appearing in an equation or formula has dimensions, it means that the specific value of the number will depend on the system of units used.

因此，只有当 2.7 的量纲为 $L^{1/2}T^{-1}$ 时，式(1.4)的量纲才正确。当一个方程或公式中的数具有量纲时，这就意味着，这个数的具体值取决于所用的单位系统。

1.2.2 Units

In addition to the qualitative description of the various quantities, it is generally necessary to have a quantitative measure of any given quantity. For example, if the width of a desk is 2 units wide, the statement has no meaning until the unit of length is defined. Now three systems of units commonly used in engineering are introduced as follows.

1.2.2 单位

除了定性地描述以外，对任意给定的量，通常还要定量测量。例如：一张课桌的宽度为 2 个单位宽，这样的描述是没有意义的，除非定义了长度的单位。工程上常用的三种单位系统介绍如下。

British Gravitational (BG) System In the BG system, the unit of length is the foot (ft), the unit of time is the second (s), the unit of force is the pound (lb), and the unit of temperature is the degree Fahrenheit (℉) or the unit of thermodynamic temperature is the degree Rankine (°R). The unit of mass, called the slug, is defined from Newton's second law (force = mass × acceleration) as $1lb=(1slug)(1ft/s^2)$. This relationship indicates that a force of 1lb acting on a mass of 1slug will give the mass an acceleration of $1ft/s^2$.

BG 单位系统 在 BG 单位系统中，长度的单位是英尺（ft），时间的单位是秒（s），力的单位是磅（lb），温度的单位是华氏度（℉）或者热力学温度的单位兰金度（°R），两者的关系为°R=℉+459.67。质量的单位称为斯勒格，根据牛顿第二定律定义为 $1lb=(1slug)(1ft/s^2)$。该式表明，1lb 力作用在 1slug 的质量上，产生 $1ft/s^2$ 的加速度。

English Engineering (EE) System In the EE system, units for force and mass are defined independently; thus special care must be exercised when using this system in conjunction with Newton's second law. The basic unit of mass is the pound mass (lbm), the unit of force is the pound (lb). It is also common practice to use the notation, lbf, to indicate pound force. The unit of length is the foot (ft), the unit of time is the second (s), and the thermodynamic temperature scale is the degree Rankine (°R).

EE 单位系统 在 EE 单位系统中，力和质量分别定义。因此，在结合牛顿第二定律使用这个单位系统时应特别注意。质量的基本单位是质量磅（lbm），力的单位是磅（lb），通常也使用 lbf 这个符号来表示力磅，长度的单位是英尺（ft），时间的单位是秒（s），热力学温度单位是兰金度（°R）。

International System (SI) In 1960 the Eleventh General Conference on Weights and Measures formally adopted the International System of Units (termed SI) as the international standard. This system has been widely adopted worldwide. In SI the unit of length is the meter (m), the unit of time is the second (s), the unit of mass is the kilogram (kg),

SI 单位系统 1960 年，第十一届度量衡会议正式采用国际单位系统（SI）作为国际标准，该系统被各国广泛采用。在 SI 系统中，长度的单位是米（m），时间的单位是秒（s），质量的单位是千克（kg），温度的单位是开尔文（K）。开尔文温