A Bilingual Textbook
for Engineering Fluid Mechanics

工程流体力学
双语教程

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内容简介

本教程是重庆理工大学重庆汽车学院工程力学系为建设国家级力学教学团队，经重庆市教委立项批准而编写的。教程涵盖了工程流体力学所涉及的主要内容，即流体力学的基本概念、流体静力学、流体运动基本方程、漩涡理论与势流理论、相似原理与量纲分析、黏性流体的管内流动与能量损失、孔口及管嘴出流与堰流、边界层理论等，每一章都有适当的例题与习题，以供读者学习及练习，每一道习题都附有参考答案。编写形式为中英文对照，通过阅读本教程，读者可以熟悉与工程流体力学相关的知识及中英文术语，对提高读者的专业英语水平提供必要帮助。

本教程适合作为力学及相近专业本科生与研究生的工程流体力学双语教材，也可作为机械工程类专业教师及一般科技人员提高专业英语水平的阅读材料。

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前 言

本教程适用于56学时或64学时的大学本科生或研究生工程流体力学双语课程,其内容包含了工程流体力学的主要章节,是在参阅了众多的中英文工程流体力学教材基础之上而编写的。参考的主要英文教材包括 John A. Roberson 与 Clayton T. Crowe 编写的 *Engineering Fluid Mechanics*(第2版)、Bruce R. Munson 与 Donald F. Young 编写的 *Fundamentals of Fluid Mechanics*(第6版),Frank M. White 编写的 *Fluid Mechanics*(第5版)等;参考的主要中文教材包括刘鹤年编写的《流体力学》(第2版),张亮、李云波编写的《流体力学》,孙文策编写的《工程流体力学》(第2版),李大美、杨小亮编写的《水力学》(第4版)等。

参加本教程编写的成员有杨含离、杨鄂川、刘妤、王国超、丁军、邓国红、郭长文、徐睿等。其中,第1章~第4章由杨含离、郭长文、徐睿完成,第5章与第6章由杨鄂川、王国超完成,第7章与第8章由刘妤、丁军完成,所有翻译工作均由主编杨含离完成。

本教程的编写得到了重庆市教委与重庆理工大学的大力支持,谨此致谢。本教程的英文部分由美国友人 Jean Paul Castagna 先生审阅,中文部分由重庆理工大学邓国红教授审阅,在此编写组对他们表示衷心感谢。

因时间、人力、经费及编写组成员知识水平所限,教程中难免会存在各种各样的不足之处及错误,编写组衷心希望读者们能提出批评与指正。

编 者

2014年12月30日

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Preface
绪 论

1. Features and Tasks for Engineering Fluid Mechanics
工程流体力学的性质与任务

Fluid mechanics is a discipline which studies the equilibrium and macro mechanical motions of fluids, it is one of the most important branches of mechanics. Fluid mechanics may be classified as theoretical fluid mechanics (generally called fluid mechanics) and applicable fluid mechanics (generally called engineering fluid mechanics) according to the difference of aspects it stresses on. The former mainly adopts strict mathematical reasoning, strives for the accuracy and integrity of solutions, whereas the latter puts emphasis on solving problems occurring in engineering practice, not on pursuing the mathematical integrity. Engineering fluid mechanics is a chief technical elementary course for majors such as machinery, power, apparatus, construction, water conservancy, etc., it may lay necessary foundations for the following study of these majors' main courses.

流体力学是研究流体平衡与宏观机械运动规律的一门学科,是力学最重要的分支之一。流体力学按其研究内容侧重方面的不同,分为理论流体力学(通称流体力学)和应用流体力学(通称工程流体力学)。前者主要采用严密的数学推理方法,力求准确性和严密性。后者则侧重于解决工程实际中出现的问题,而不去追求数学上的严密性。工程流体力学是机械、动力、仪器、土木、水利类等专业的一门主要技术基础课,它为这些专业主要后续专业课程的学习打下必要的理论基础。

Basic tasks of engineering fluid mechanics lie in establishing fundamental equations describing the movement of a fluid, determining velocity and pressure distribution rules for flows in different pipes and immersed bodies, probing calculation methods for energy exchange and various energy losses, and solving interactive problems between fluids and solid bodies.

工程流体力学的基本任务在于建立描述流体运动的基本方程,确定流体经各种通道及绕流不同物体时速度、压强的分布规律,探求能量转换和各种能量损失计算方法,并解决流体与固体之间的相互作用的问题。

2. Development History of Fluid Mechanics
流体力学发展简史

Fluid mechanics is one of the most primitive branches of physics, its development is closely related with the development of mathematics and ordinary mechanics, it is the achievement of human beings fighting against the natural world, and the wealth created by all the people. There was a legendary story in ancient China about King Yu taming flood and making rivers flow; in Qin Dynasty, Libin and his son leaded workers built Dujiang Weir, which is still in operation nowadays. The first one contributed to the formation of fluid mechanics was an ancient Greek, Archimedes, who established the equilibrium theorem for liquids, which included the law of buoyancy for bodies and stability for floating bodies, laid the foundation of fluid statics. There was no significant progress on fluid mechanics in about one thousand years since then.

流体力学是物理学中最古老的分支之一，它的发展与数学和普通力学的发展密切相关，它是人类长期与自然界进行斗争的结果，是人类集体创造的财富。古时中国有大禹治水疏通江河的传说；秦朝李冰父子带领劳动人民修建的都江堰，至今还在发挥着作用。对流体力学学科的形成作出第一个贡献的是古希腊的阿基米德，他建立了包括物体浮力定律和浮体稳定性在内的液体平衡理论，奠定了流体静力学的基础。此后，千余年间，流体力学没有重大发展。

The real development of fluid mechanics was started from Newton (1642—1727) era. In 1687, he had already discussed contents such as drags of a fluid and wave movement in his masterwork "Mathematical principles of natural philosophy", which made fluid mechanics an independent offshoot of mechanics. The name, fluid dynamics, was first introduced by Daniel Bernoulli (1700—1783) in his famous book "Fluid Dynamics" in 1738, the prominent equation-Bernoulli equation, was proposed in this book, it setup an universal relationship among pressure, elevation and velocity of fluid particles, and is still a principal law in fluid mechanics up to now. French engineer, Pitot, invented Pitot Tube for measuring flowing velocity on the basis of Bernoulli equation; in 1752, d'Alembert did many experiments about drags on ships moving in river, and proved that the square relationship between drag and moving velocity. In 1755, on the basis of continuum hypothesis, Euler established Euler equation by generalizing the concept of pressure in fluid statics to moving fluids, which describes correctly the movement of non-viscous fluid by using differential equations. The establishment of Euler equation and Bernoulli equation was a symbol for fluid mechanics as a branch discipline. In the first half of nineteenth century, Navier (1785—1836) and Stocks (1819—1903) successively published kinetic theorem on viscous fluid similar to modern form, which is the famous N-S equation. In 1876, Reynolds did many experiments and found there were two different regimes in fluid flow-laminar flow and turbulent flow. In 1904, Prandtl simplified N-S equation, and proposed boundary layer theory, this theory indicates clearly the applicable scope for ideal fluid, and can calculate the frictional resistance while an object is in motion as well.

流体力学的真正发展是从牛顿(1642—1727)时代开始的。1687 年，牛顿在他的名著《原理》中就已讨论了流体的阻力、波浪运动等内容，它使流体力学开始变成力学中一个独立分支。流体动力学的名字是伯努利(Daniel Bernoulli, 1700—1783)于 1738 年在他的名著《流体动力学》一书中首先引用的。在该书中提出了著名的伯努利方程，即在流体的压力、高度和运动速度之间建立了普遍关系，直到现在仍是流体力学中一个主要定律。法国工程师皮托在伯努利方程的基础上，发明了测量流速的皮托管；1752 年，达朗贝尔对运河中船只的阻力进行了许多实验工作，证实了阻力同运动速度之间的平方关系。1755 年，欧拉采用了连续介质假设，把静力学中压力的概念推广到运动流体中，建立了欧拉方程，正确地用微分方程组描述了无黏

流体的运动。欧拉方程和伯努利方程的建立，是流体动力学作为一个分支学科建立的标志。在19世纪上半叶，纳维(1785—1836)和斯托克斯(1819—1903)先后独立发表了接近现代形式的黏性流体运动理论，即著名的N-S方程。雷诺(1842—1919)在1876年做了大量的实验，并发现了流体流动中两种不同的流态——层流和湍流。普朗特于1904年将N-S方程作了简化，建立了边界层理论，这一理论既明确了理想流体的适用范围，又能计算物体运动时遇到的摩擦阻力。

In the beginning of the twentieth century, the emergence of airplane accelerated tremendously the development of aerodynamics. People wanted to know surrounding pressure distribution and resistance of an aircraft, it facilitated the development of fluid mechanics on aspects of experiment and theoretical analysis. Scientists represented by Joukowsky, Chaplygin and Planck, etc., founded airfoil theory on the basis of potential theory for incompressible non-viscous fluid. The establishment and development of airfoil theory and boundary layer theory was a remarkable progress of fluid mechanics, they combined non-viscous fluid theory and boundary layer theory of viscous fluid perfectly. After 1940s, space travel was realized because of the application of jet propulsion and rocket technology, this resulted in the research of high-speed gas moving forward rapidly, and the forming of offshoot disciplines such as gas dynamics and physico-chemical hydrodynamics. In recent years, with the development of computer, the method of numerical calculation in each branch of fluid mechanics has developed quickly, many problems that could not be solved in the past may have numerical solutions, thus forms an important discipline-computational fluid mechanics.

20世纪初，飞机的出现极大地促进了空气动力学的发展。人们期望能够揭示飞行器周围的压力分布及飞行器阻力等问题，这就促进了流体力学在实验和理论分析方面的发展。以儒科夫斯基、恰普雷金、普朗克等为代表的科学家，开创了以无黏不可压缩流体势流理论为基础的机翼理论。机翼理论和边界层理论的建立和发展是流体力学的一次重大进展，它使无黏流体理论同黏性流体的边界层理论很好地结合起来。20世纪40年代以后，由于喷气推进和火箭技术的应用，实现了航天飞行，使气体高速流动的研究进展迅速，形成了气体动力学、物理—化学流体动力学等分支学科。近年来，随着计算机的发展，在流体力学的各个分支中数值计算方法都得到了迅速发展，许多过去不能解决的复杂问题，都可以数值求解，从而形成了计算流体力学这一重要的学科。

Therefore, with the development of manufacturing, science and technology, study fields and objects of fluid mechanics will no doubt be intensified and expanded. At present, except for mainly investigating macro mechanical movement of fluid and interactive forces between fluid and surrounding bodies, fluid mechanics also involves in the regulations of heat and mass transmission, its research object also extends from Newton fluid to non-Newton fluid and multiphase fluid. Fluid mechanics is not only an ancient discipline, but a discipline full of vitality as well, and for sure it will develop and thrive continuously.

因此，随着生产和科技的发展，流体力学研究的领域和物质对象亦日益深化和扩大。目前，流体力学除了主要研究流体的宏观机械运动和它与周围物体间力的作用外，还涉及传热、传质的规律，研究的物质对象亦由主要是牛顿流体扩展到非牛顿流体和多相流体。流体力学既是一门古老的学科，又是一门富有生机的学科，并将不断地得到蓬勃发展。

Chapter One Basic Concepts of Fluid Mechanics and Fluid Properties

第1章 流体力学的基本概念与流体的特性

1.1 The Definition of a Fluid and Continuum Hypothesis 流体的定义与连续介质假设

1.1.1 Definition of a Fluid 流体的定义

In nature, a substance exists generally in the form of one of the following three states: solid, liquid and gas. It is known that a solid can resist shear stress, and the deformation of a solid under shear stress is definite when the magnitude of the shear stress does not exceed the elastic limit of the material. In contrast to a solid, a fluid is a substance of which the particles may easily move and change their relative position. More specifically, a fluid is defined as a substance that will continuously deform, that is, flows under the action of a shear stress, no matter how small that shear stress may be, as shown in Fig. 1 - 1. The rate of deformation of a fluid is related to the applied shear stress and the viscosity of the fluid, a unique property of the fluid, and we will discuss this property in corresponding section.

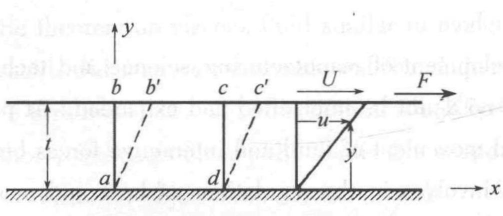

Fig. 1 - 1 Deformation under Action of F

图1-1 力F作用下的变形

在自然界中,物质一般是以以下三种形态之一存在:固态、液态与气态。众所周知,固体可以抵抗剪应力,并且当剪应力值不超过材料的弹性极限时,固体的变形是确定的。与固体相反,流体是一种质点极易运动与改变相对位置的物质,或者更确切地说,流体被定义为在任何微小的剪应力作用下,都能够连续变形一流动的物质,如图1-1所示。流体变形的速率与所施加的应力及流体的黏性有关,黏性是流体特有的性质,我们将在相应的章节讨论。

Thus we get the definition of a fluid as follows: A fluid is a substance which can bear pressure, but cannot bear shearing stress and resist tangential deformation, i. e., once under the action of shear stress, no matter how small that shear stress may be, a fluid will continuously deform; and if that shear stress keeps acting on a fluid, the deformation of it will be infinitely large.

因此,流体可定义如下:流体是一种可以承受压力但不能承受剪应力、抵抗剪切变形的物质,即一旦在剪应力的作用下,无论该剪应力多么小,流体都将连续变形。在剪应力的持续作用下,流体的变形将会无限大。

1.1.2 Hypothesis of Continuum Model
连续介质模型假设

From the view of microscopic level, a fluid is composed of a large quantity of molecules in irregular motion with gap between molecules, it means a fluid is not continuous, but discrete on molecular level. Since fluid mechanics does not investigate the microscopic movement of molecules, it only concerns with macroscopic mechanical movement of fluids, this mechanical movement is the statistical mean behavior of a large quantity of molecules. Moreover, the characteristic dimensions studied in fluid mechanics are far larger than the distance between molecules, an imaginary fluid model—fluid element will be adopted in the study of fluid mechanics.

从微观的角度看,流体是由大量作不规则运动的分子所构成的,分子间有间距,即从分子的尺度讲,流体是不连续的、离散的。由于流体力学并不研究分子的微观运动,而只关心流体的宏观机械运动,这种宏观机械运动是大量分子的平均统计行为,另外,流体力学所研究的特征尺寸远比分子间的距离大,因此一种假想的流体模型——流体微团将被用于流体力学的研究中。

Fluid element is an aggregation of fluid molecules whose volume is small enough with enough molecules to make sure that the macroscopic mean density has definite value.

流体微团是一个体积足够小、所包含的分子足够多,以至于其宏观平均密度有确定值的这样一个流体分子的集合。

Most engineering problems are concerned with physical dimensions much larger than this limiting volume, so that the density is actually a point function and fluid properties can be thought of as in continuous variation in space. Such a fluid is called a continuum, which simply means that its variation in properties is so smooth that differential calculus is valid for all the analysis in the study of fluid mechanics. Thus we give the Continuum Hypothesis as follows.

大多数工程问题所涉及到的尺寸远远大于这一极限体积,因此密度实际上是点的函数,并且流体的性质可以认为是随空间位置连续变化的。这样的流体被称为连续介质,该称谓表明流体性质的变化是平滑的,在流体力学的所有研究分析中可以使用微积分进行处理,从而给出连续介质假设如下。

Euler put forward the following hypothesis of continuous medium mechanical model in 1753: A fluid is composed of fluid elements, which occupy flowing space continuously with inter molecular distance and molecular motion ignored.

欧拉在1753年提出了以下的连续介质力学模型假设:流体由流体微团所构成,流体微团连续充满了流动占据的空间,而忽略其内部分子的间距与分子的运动。

Under this assumption, all physical properties of a fluid are the continuous functions of space coordinates and time.

在这一假设下,流体的所有物理性质都是空间坐标与时间的连续函数。

1.1.3 Advantages of Continuum Hypothesis 连续介质假设的优点

(1) Exclude complexity of molecules' motion.

排除了分子运动的复杂性。

(2) Physical properties, such as density, speed, pressure, shear stress and temperature, are the continuous functions of space and time, so we can use mathematical tools of continuous function and field theory to solve flowing problems.

流体的物理性质,如密度、速度、压强、剪应力及温度,成为空间坐标与时间的连续函数,从而我们可以使用关于连续函数与场论等数学工具处理流动问题。

1.1.4 Distinction between a Gas and a Liquid 气体和液体之间的区别

A fluid may either be a gas or a liquid. The molecule distance of a gas is much larger than that of a liquid. Therefore, a gas is very compressible, and when all external pressure is removed, it tends to expand indefinitely, a gas is therefore in expansion equilibrium only when it is completely enclose. A liquid is relatively incompressible, and if all pressure, except that of its own vapor pressure, is removed, the cohesion between molecules holds them together, so that the liquid does not expand indefinitely. Therefore a liquid may have a free surface, a surface from which all pressure is removed, except that of its own vapor.

流体可以是气体或液体。气体分子之间的距离远大于液体分子间的距离。因此,气体可压缩,当所有的外部压力去除,它往往无限扩散,气体只有当完全封闭时扩散才能平衡。相对不可压缩的液体,除了液体自身的蒸气压力,如果全部压力被去掉,认为分子间的凝聚力使它们在一起,以至于液体不能无限扩展。因此,除去表面的所有压力(自身的蒸气压力除外),液体具有自由表面。

The main distinctions between a gas and a liquid lie in their compressibility and fluidity. Since the molecular weight of a gas is small, distance between molecules are large, mutual restriction between molecules is small; while the molecular weight of a liquid is large, distance between molecules is small, mutual restriction between molecules is large. Therefore, by comparing with a liquid, a gas has higher compressibility and fluidity. Moreover, a liquid has definite volume and free surface, but a gas has no definite volume and free surface.

气体与液体的主要区别在于它们的可压缩性和流动性。由于气体的分子量较小,分子之间的间距较大,故分子间的相互约束较小;液体的分子量较大,分子之间的间距较小,故分子间的相互约束较大。所以与液体相比,气体具有较大的可压缩性与流动性。另外,液体具有一定的容积,存在一个自由液面,而气体没有固定容积,不存在自由液面。

1.2 Physical Properties of a Fluid
流体的物理性质

1.2.1 Density
密度

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

密度是单位体积所包含的物质的质量。它表征了流体在空间的密集程度,通常用希腊字母 ρ 表示,其国际单位是 kg/m^3。

For homogenous fluid, each point has the same density:

对于均质流体,各点的密度相等:

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

For nonhomogeneous 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.

对于非均质流体,围绕某空间点取一微小体积 ΔV,其中流体的质量为 Δm,比值 $\Delta V/\Delta m$ 就是该微小体积内的平均密度。令 $\Delta V \to 0$,该比率的极限值就是该点的密度。

$$\rho = \lim_{\Delta V \to 0} \frac{\Delta m}{\Delta V} = \frac{dm}{dV} \tag{1.2}$$

Table 1 - 1 gives the density of water, air and mercury at standard atmospheric pressure and different temperature.

表 1 - 1 给出了水、空气与水银在标准大气压下不同温度时的密度。

Table 1 - 1 Density of Water, Air and Mercury at Different Temperature (kg/m^3)

表 1 - 1 水、空气、水银在不同温度下的密度(kg/m^3)

Temp. /℃ 温度	Density (kg/m^3) 密度			Temp. /℃ 温度	Density (kg/m^3) 密度		
	Water 水	Air 空气	Mercury 水银		Water 水	Air 空气	Mercury 水银
0	999.87	1.29	13 600	60	983.24	1.06	13 450
10	999.73	1.24	13 570	80	971.83	0.99	13 400
20	998.23	1.20	13 550	100	958.38	0.94	13 350
40	992.24	1.12	13 500				

1.2.2 Relative Density
相对密度

Relative density of a fluid is the ratio of its density to that of pure water at 4℃, which is usually denoted by d. It has no unit and is dimensionless.

相对密度是流体的密度与4℃的水的密度的比值，通常用 d 表示，它是一个无单位、无量纲的量。

$$d = \frac{\rho_f}{\rho_w} \tag{1.3}$$

Where ρ_f is the density of fluid;

ρ_w is the density of water at 4℃.

式中 ρ_f——流体的密度；

ρ_w——4℃水的密度。

1.2.3 Specific Volume
比容

Specific volume is the volume occupied by unit mass of a fluid, denoted by v, and it is the reciprocal of density. Unit: m^3/kg.

比容是单位质量流体所占有的体积，用 v 表示，是密度的倒数。单位：m^3/kg。

$$\nu = \frac{1}{\rho} \tag{1.4}$$

1.2.4 Density of Mixture Gas and Gas State Equation
混合气体密度与气体状态方程

Density of mixture gas is calculated as volume fraction of each component gas, expressed as follows:

混合气体的密度按各组分气体的体积百分数计算，表达如下：

$$\rho = \rho_1\alpha_1 + \rho_2\alpha_2 + \cdots + \rho_n\alpha_n = \sum_{i=1}^{n}\rho_i\alpha_i \tag{1.5}$$

where ρ_i is the density of each component gas in mixture gas;

α_i is the volume fraction of each component gas.

式中 ρ_i——各组分气体的密度；

α_i——各组分气体的体积百分数。

The equation of state for an ideal gas is given as follows:

理想气体的状态方程由下式给出：

$$\frac{p}{\rho} = RT \tag{1.6}$$

where p is absolute pressure;

ρ is density of gas;

T is absolute temperature;

R is gas constant.

式中 p——绝对压强；

ρ——气体密度；

T——绝对温度；

R——气体常数。

1.2.5 Specific Weight 重度

The specific weight of a fluid is the weight per unit volume, denoted by γ, it has the following relationship with density ρ:

流体的重度是单位体积的重量，用 γ 表示，其与密度 ρ 有如下关系：

$$\gamma = \rho g$$

Here g is the gravitational acceleration. Its unit in SI is N/m^3. For homogenous fluid, each point has the same specific weight, for water, the nominal value of specific weight is $\gamma = 9800\ N/m^3$.

式中 g——重力加速度。重度的国际单位为 N/m^3。在均质流体中，各点的重度相同，水重度的标定值为 $\gamma = 9800N/m^3$。

1.3 Forces on a Fluid 作用在流体上的力

1.3.1 Classification 分类

The equilibrium and motion of an object are the consequence of exerting forces, therefore, before we investigate the fundamental principles of fluid mechanics, it is necessary to analyze the categorization of forces acting on a fluid at first. According to physical properties of forces acting on a fluid, it may be classified as gravity, friction force, inertia force, elastic force and surface tension, etc. According to the acting method of forces on a fluid, it can be simply divided into two kinds of forces: mass force and surface force. The later is usually adopted in the study of fluid mechanics.

任何物体的平衡与运动都是受力作用的结果，因此，在研究流体力学的基本原理之前，首先需要分析作用在流体上的力的种类。根据作用在流体上的力的物理性质，其可分为重力、摩擦力、惯性力、弹性力、表面张力；根据力的作用方式，其可简单分为两类：质量力和表面力。在流体力学的研究中，通常采用后一种分类。

1.3.2 Mass Force 质量力

Massforce is a force exerting on all particles in a fluid by a certain force field, it is a non-contact force. For homogeneous fluids (each point within the fluid has the same density), the magnitude of mass force is in direct proportion to fluid volume. Thus mass force is also known as body force or field force. Its unit in SI is Newton (N). Gravity, inertia force and electromagnetic force belong to mass force.