普通高等教育"十二五"规划教材

Fluid Mechanics
流体力学

英语教学版

金晓宏　李远慧　主编

中国电力出版社
CHINA ELECTRIC POWER PRESS

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内 容 提 要

本书为普通高等教育“十二五”规划教材。

本书是针对普通高等院校机械类本科专业“工程流体力学”课程英汉双语教学编写的，主要内容包括流体性质、流体静力学、流体流动概念和基本方程组、流动阻力及流体力学的应用等。书中附录给出了常见度量衡和压强等英制单位制与国际单位制的换算、常见流体性质以及课程教学安排。为方便学生复习，本书还按书中出现的先后顺序，给出了主要关键词和大部分习题答案。

本书可作为普通高等院校机械工程及其自动化、机械制造及其自动化、机械电子工程、材料成型及模具和车辆工程等专业教材，也可作为机械类和近机械类专业留学生的参考用书。

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前　言

双语教学的任务一是知识，二是语言，两者相辅相成。于是，知识点讲解、技术内容中的思路及思想方法在内容上的贯穿，成为本书编写的内容主体。书中以常用专业技术文本语言习惯和书写规范进行文字编写，文体上由浅入深、循序渐进，避免生僻或高难语言现象；总体上立足基础知识，强化知识的工程应用，加强学生的语言能力学习。

本书为工科双语类教材，教学内容采用英语编写。考虑到国内学生所具备的英语能力仅停留在日常公共英语的语言基本能力阶段，在英语语言环境下的工程技术术语和规范上尚存在诸多欠缺，书中特加入数学、力学和流体力学等常用专门术语的注解和个别疑难句子的翻译。本书的特色体现在：

（1）以机液系统中常用流体力学基础概念、基本知识、基本方法为内容，通过适量例题和习题，以强化训练学生综合解决问题的能力。

（2）强化学科知识、专业术语的规范和表达。

（3）在有利于知识点学习的基础上，遵从循序渐进的学习原则，增加有助于问题主题理解的思考题，以拓宽知识面并提高对问题的理解深度。

（4）加入疑难词、句和专业用法的中文注解。

（5）以英文为主、中文为辅的知识学习和能力培养，体现学科知识和语言双重收获。

本书以机械工程中常用的单管流动、缝隙流动为主要内容，引入机液等系统常见流动现象的相关内容，以强化工程应用。书中内容分 5 章进行介绍：第 1 章为流体性质，以连续性和主要物理性质（特别是黏度）为主，简单介绍完全气体主要方程；第 2 章为流体静力学，包括静压强、压强的度量，静压基本方程和受力计算；第 3 章为流动相关基本概念，控制体积法、雷诺输运方程及其应用，连续性、能量和动量方程及其应用；第 4 章为流动阻力，侧重直管流动黏性阻力的计算，介绍雷诺数、平行板间层流、圆管层流、边界层和管流起始段流动的概念，以及圆管紊流流动、局部阻力和综合应用；第 5 章为孔口流量、汽穴和水击计算。书中附录给出了常见度量衡和压强等英制单位制与国际单位制的换算等，书后还给出了大部分习题答案。

本书由武汉科技大学金晓宏、李远慧主编。其中，第 1 章由黄浩编写，第 2 章由朱学彪编写，第 3 章和附录由金晓宏编写，第 4 章由李远慧编写，第 5 章由许仁波编写。全书由金晓宏统稿。

本书由李万平主审。他为本书提出了许多宝贵的意见和建议，在此表示衷心的感谢。

在本书的编写过程中，得到了武汉科技大学教务处和机械自动化学院等多方的大力支持，在此谨表由衷的谢意。

限于编者水平，书中不妥之处在所难免，恳请广大读者批评指正。

编　者

2011 年 6 月

致 读 者

为方便读者阅读，特给出下列编写说明。

1\. 符号

书中变量为斜体，表示三维矢量时加粗。例如：$\boldsymbol{u}$ 为点速度，或为流线、微小流管断面平均速度，V 为过流断面平均速度。

2\. 注解

（1）技术术语（文中单词或词组用斜体表示）注解在出现处直接注出，如 *pressure*（压强）。

（2）疑难单词注解，如 thick（稠的）。

（3）人名注解，如 Reynolds（雷诺，人名）。

（4）疑难词、句和专业用法的中文注解，用符号“†”表示，注解内容列于相应章的 Annotation 中。

3\. 练习题

（1）Exercises 为课后思考自测题。

（2）Problems 为习题。

（3）思考自测题和习题大部分给出了答案。

（4）凡标记有“*”的习题，表示有一定难度。

4\. 关键词

本书附录按单词在文中出现的先后顺序，给出了主要关键词。建议读者以此为基础，梳理学过的内容。应指出的是，仅会写出这些词是远远不够的，建议读者自问自答如下：

（1）该词的含义为何？并用自己的话语表达出来。

（2）如果该词的含义是公式，那么该公式的各项参数含义为何？该公式计算中有何限制？

（3）如果该词的含义是理论，则用自己的思路将该理论表达出来，同时应特别注意该理论的假设、前提条件和适应范围。

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1 Fluid Properties

In this chapter, the definition of a fluid[†1] is mentioned. The units of force, mass, length and time are reviewed. The main physical properties of the fluid and the force acting on the fluid are expatiated (详述). The continuity, viscosity and bulk modulus of fluid are the key terms in this chapter.

1.1 Definition of a Fluid

Fluid may be divided into liquid or gas. As compared with solid, the intermolecular attraction of fluid is very small and its molecular motion is very intense, so the arrangement of its molecules is very loose. This gives the common character of fluid: fluid can not maintain certain shape and has the fluidity (流动性).

Withstanding the pressure, tension and shear force, it is the characteristic of solid. So a small deformation of solid occurs under the action of external forces. Fluid can only resist the pressure, and can not resist any small tension and shear force. For this reason, fluid can not maintain its certain shape. No matter how small the shear force is applied to a fluid, the fluid will deform continuously. In addition, there is no static friction in fluid.

The distance between molecules of liquid is almost equal to the effective diameter of molecule. So liquid is often called incompressible fluid. Generally, the distance between the molecules of gas is very large, for example, at normal temperature and pressure, the distance between the molecules of air is 3×10^{-7} centimeter, the order of magnitude of its molecules' effective diameter is 10^{-8} centimeter. Consequently, gas is often called compressible fluid.

When the compressibility is not referred, the laws in fluid mechanics are suitable to liquid as well as gas. When the compressibility is involved, the problem of gas and liquid must be dealt with individually. In this book, liquid is mainly discussed.

From the physics viewpoint, fluid and all substances are consisted of molecules, obviously there are gaps between the molecules. In fluid mechanics what really interested is not the microscopic motion of individual molecules, but the macroscopic motion of fluid under action of external forces (such as gravity, pressure difference, etc) because the *macrofluid* (宏观流体) is consisted of a large number of molecules[†2]. The physical quantities of macrofluid (such as pressure, velocity and density) are the statistical average and the behavior of most fluid molecules.

The continuous media was first proposed as macrofluid model by Euler (欧拉，人名) in 1753. That is, the real fluid is considered as no-gap continuous media, called the basic assumption of continuity of fluid or the continuum (连续体，连续性) of fluid, in which the continuous fluid is consisted of fluid particles which are composed of a sufficiently enough number of molecules[†3]. The fluid particle is considered as an element volume of fluid. The definition of continuum of fluid shows that the volume of particle is sufficient small and can be neglected as compared with the dimensions of flow field; but it is large enough compared with both of the dimensions of molecule and the distance between molecules. The number of molecules is 2.7×10^{16} in one cubic millimeter of air at *standard conditions*[†4] (标准状态), so the neglect of the gap between molecules is valid and feasible.

Of course, the continuity assumption of fluid is relatively applied. For example, in a vacuum pump, the air at 133.336×10^{-3} Pa (10^{-3} mmHg) and 293K, the distance between molecules is about 4.5 millimeter; the value can be compared with the dimension of vacuum pump. In this case, the flow is the molecular flow of rarefied gas (稀薄气体), and the gas can not be considered as continuous media.

Exercises 1.1

1.1.1 What is the concept of fluid? What is the fluid composed of?

1.1.2 Can the fluid resist tensile stress?

1.1.3 A fluid is a substance that can not be subjected to:(a) tensile forces; (b) shear forces; (c) tensile forces and shear forces; (d) tensile forces and shear forces but can only resist the pressure.

1.2 Units and Conversion

1.2.1 System of units

In fluid mechanics, consistent units of force, mass, time, etc are helpful to simplify the solutions. The consistency of mechanics units system is that unit force accelerates unit mass at unit acceleration.

The International System of Units (SI, 国际单位制) has the newton (N) as unit of force, the kilogram (kg) as unit of mass, the meter (m) as unit of length, and the second (s) as unit of time[†5]. This system has been adopted by our country and many other countries. With the kilogram, meter, and second as defined units, the "newton" is derived from Newton's second law of motion.

$$1\text{N}=1\text{kg}\frac{1\text{m}}{\text{s}^2} \tag{1.1}$$

In the United States the U.S. customary system of units[†6], an Inch Units, is still in use. The consistent set of units is pound (lb) force, the slug (斯勒格, 质量单位) mass, the foot (ft) length, and the second (s) time. The slug is the derived unit; it can be determined from Newton's second law of motion, i.e., one pound force accelerates one slug at one foot per second squared.

$$1\text{ lb}=1\text{slug}\frac{1\text{ft}}{\text{s}^2} \tag{1.2}$$

Centimeter-gram-second system of units, universal CGS unit (通用物理单位制，又称厘米—克—秒制), is also adopted in fluid mechanics. The consistent set of units is dyne (达因) force, the gram (g) mass, the centimeter (cm) length, and the second (s) time. One dyne force accelerates the unit mass at one centimeter per second squared, or

$$1\,\text{dyne} = 1\,\text{g}\frac{1\text{cm}}{\text{s}^2} \tag{1.3}$$

1.2.2 Unit Conversion

In practical application, many physical parameters and technical data may be in the International System of Units or the Inch Units. In these two systems of units, in order to use and calculate them correctly, the units of physical quantity and conversion (换算) for SI units and U.S. customary units are shown in Table 1.1.

Table 1.1 SI units, U.S. customary system units, and conversion

Quantity（物理量）		SI units（国际单位制）			U.S. customary system（美国习惯英制）	Conversion（换算关系）
Name（名称）	symbol（符号）	Chinese symbol（中文符号）	International symbol（国际符号）	Basic unit（基本单位）		
Length	l	米	m	m	ft（英尺）	1ft=0.3048m
Mass	m	千克	kg	kg	slug（斯勒格）	1slug=14.59kg
Time	t	秒	s	s	s（秒）	1s=1s
Force	F	牛	N	$\text{m}\cdot\text{kg}\cdot\text{s}^{-2}$	lb（磅）	1lb=4.448222N
Density	ρ	千克/米^3	kg/m^3	$\text{m}^{-3}\cdot\text{kg}$	slug/ft^3（斯勒格/英尺^3）	$1\text{slug/ft}^3=515.4\text{kg/m}^3$
Specific volume	υ	米^3/千克	$\text{m}^3\text{/kg}$	$\text{m}^3\cdot\text{kg}^{-1}$	$\text{ft}^3\text{/slug}$（英尺^3/斯勒格）	$1\text{ft}^3\text{/slug}=0.001940\text{m}^3\text{/kg}$
Specific weight	γ	牛/米^3	N/m^3	$\text{m}^{-2}\cdot\text{kg}\cdot\text{s}^{-2}$	lb/ft^3（磅/英尺^3）	$1\text{lb/ft}^3=157.1\text{N/m}^3$
Pressure	p	牛/米^2，帕	N/m^2, Pa	$\text{m}^{-1}\cdot\text{kg}\cdot\text{s}^{-2}$	lb/ft^2（磅/英尺^2）	$1\text{lb/ft}^2=47.88\text{Pa}$
Work	W	牛·米，焦	N·m, J	$\text{m}^2\cdot\text{kg}\cdot\text{s}^{-2}$	ft·lb（英尺·磅）	1ft·lb=1.356J
Power	P	焦/秒，瓦	J/s, W	$\text{m}^2\cdot\text{kg}\cdot\text{s}^{-3}$	ft·lb/s（英尺·磅/秒）	1ft·lb/s=1.356 N·m/s

1.2.3 Abbreviations of SI units

Abbreviations of SI units are written in lowercase letters (小写字母) for terms like hours (h), meters (m), and seconds (s). When a unit is named after a person, the abbreviation (but not spelled form) is capitalized; examples are watt (W), pascal (Pa), and newton (N). Multiples and submultiples (约数) in powers of 10^3 are indicated by prefixes, which also are abbreviated. Common prefixes are shown in Table 1.2. Note that prefixes may not be doubled up[†7]: the correct form for 10^{-9} is the prefix n-, as in nanometers; combinations of millimicro-, formerly acceptable, are no longer to be used.

Table 1.2 Selected prefixes for powers of 10 in SI units

Multiple（因数）	SI prefix（SI 制前缀）	Abbreviation（缩写词）	Multiple（因数）	SI prefix（SI 制前缀）	Abbreviation（缩写词）
10^9	giga（千兆）	G	10^{-3}	milli（毫）	m
10^6	mega（兆）	M	10^{-6}	micro（微）	μ
10^3	kilo（千）	k	10^{-9}	nano（纳，毫微）	n
10^{-2}	centi（厘）	c	10^{-12}	pico（皮可，微微）	p

Exercises 1.2

1.2.1 Convert 1000psi into SI units.

1.2.2 The weight, in newton, of 4kg mass on a planet where g=10m/s^2 is: (a) 0.40; (b) 4.44; (c) 39.2; (d) 40; (e) none of these answers.

1.2.3 A pressure of 10^6 Pa may be written: (a) μPa; (b) kPa; (c) MPa; (d) GPa; (e) none of these answers.

1.3 Fluid Properties

1.3.1 Force on the fluid

Force causes the motion of fluid. The forces acting on fluid consist of mass forces and surface forces.

1.3.1.1 Mass Force

Mass force acting on the center of mass in a substance is directly proportional to the mass. A free body (isolated body, 分离体) of volume V is taken from the fluid in motion or relative balance as shown in Figure 1.1. The density of fluid is ρ and the mass of free body is $m=\rho V$.

The fluid is under the action of acceleration of gravity g (g=9.806m/s^2), the gravitational force is

$$G = mg \tag{1.4}$$

In the solution for dynamics problems by the statics, a *D' Alembert's force* (达朗伯力) must be added. For example, a container filled with liquid is in a linear motion with a constant acceleration$a$, as shown in Figure 1.2, the inertia force I is

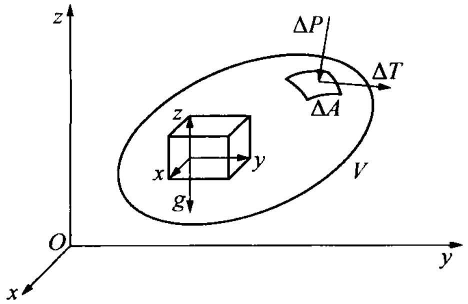

Figure 1.1 Free body in the fluid

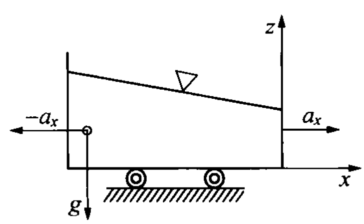

Figure 1.2 A container filled with liquid in a linear motion

$$I = -ma_x \quad (1.5)$$

Another example is that a container filled with liquid rotates on its center shaft z with a constant angular velocity ω, as shown in Figure 1.3. The *centrifugal acceleration* (离心加速度) for point A of mass m is $\omega^2 r$ and its centrifugal force is

$$R = m\omega^2 r \quad (1.6)$$

in which r is the radius of point A.

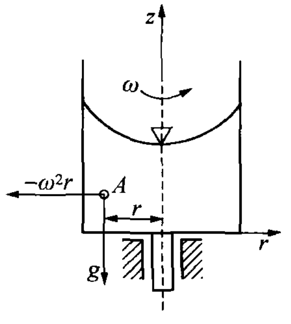

Figure 1.3 A rotating container

The above three kinds of forces are directly proportional to the mass of fluid m and act on the center of mass. So they are mass force (or volume force). If the three mass forces exist at the same time, and the total mass force and resultant acceleration are expressed by $\boldsymbol{W}$ and $\boldsymbol{q}$ respectively, so

$$\boldsymbol{W} = m(\boldsymbol{g} + \boldsymbol{a} + \omega^2 \boldsymbol{r}) = m\boldsymbol{q} = m(X\mathbf{i}+Y\mathbf{j}+Z\mathbf{k}) \quad (1.7)$$

in which X, Y, Z are components of $\boldsymbol{q}$ in the x, y, z coordinates respectively. **i**, **j**, **k** are the unit vectors for the x, y, z coordinates respectively.

From Equation (1.7) the component of resultant force $\boldsymbol{W}$ in the x direction can be expressed as

$$W_x = m(\boldsymbol{g} + \boldsymbol{a} + \omega^2 \boldsymbol{r})_x = m(\boldsymbol{q})_x = mX \quad (1.8)$$

In fluid mechanics, mass force is often expressed by the components of force per unit mass, as follows

$$\left.\begin{aligned} X &= (\boldsymbol{g} + \boldsymbol{a} + \omega^2 \boldsymbol{r})_x = \frac{W_x}{m} \\ Y &= (\boldsymbol{g} + \boldsymbol{a} + \omega^2 \boldsymbol{r})_y = \frac{W_y}{m} \\ Z &= (\boldsymbol{g} + \boldsymbol{a} + \omega^2 \boldsymbol{r})_z = \frac{W_z}{m} \end{aligned}\right\} \quad (1.9)$$

The above equations state that the component of force per unit mass in a direction (such as in the x direction) is just the projection of resultant acceleration (such as the X in the x direction) in the same direction. In other words, the force per unit mass is the resultant acceleration, and the axial component of force per unit mass is acomponent of the resultant acceleration in each corresponding direction.

If the mass force acting on the fluid is only gravity and inertia force, in the coordinates as shown in Figure 1.2, the components of force per unit mass are

$$\frac{W_x}{m} = X = -a,\quad \frac{W_y}{m} = Y = 0,\quad \frac{W_z}{m} = Z = -g$$

1.3.1.2 Surface Force

Surface force is the force acting on the surface of isolated body, and it is directly proportional to the area of surface. Surface force is the force acting not only on the outer surface of fluid (external force), but also on any internal surface (internal force). In fluid, the surface forces on the surfaces which contact with each other are a pair of action and reaction.

The isolated body is gotten from the fluid, and the forces acting on the surface of isolated body is the external force.

Figure 1.1 shows a element force ΔP acting on the element area ΔA. If the surface is a plane, the total pressure will be

$$P=\bar{p}A \tag{1.10}$$

in which $\bar{p}$ is average force per unit area, or *pressure stress* (压应力), usually called *pressure* (压强).

Because of viscosity, on the surface of isolated body, the distributed friction must be with a kind of law. The element friction force ΔT acting on the element area ΔA is shown in Figure 1.1. If the surface is a plane, the total friction is

$$T=\bar{\tau}A \tag{1.11}$$

in which $\bar{\tau}$ is mean friction force per unit area, or mean shear stress.

The above two forces acting on the surface are called the surface forces and they are directly proportional to the surface area of isolated body A.

If there is no relative motion between the surface of isolated body and the surroundings, or the fluid is ideal fluid, the friction force T=0.

1.3.2 Density, specific weight, relative density

1.3.2.1 Density

The mass of an object is a fundamental property of the object. Density is the mass of a unit volume. For homogeneous fluid, density is the ratio of the mass of fluid to its volume.

$$\rho=\frac{m}{V} \tag{1.12}$$

in which ρ is the density of fluid, kg/m^3; m is the mass of fluid, kg; and V is the volume of fluid, m^3.

In thermodynamics and aerodynamics, the measurement of volume of gas is expressed by *specific volume* (比体积). The specific volume is the volume occupied by unit mass of fluid. For homogeneous fluid, specific volume v is the ratio of the volume of fluid to its mass.

$$v=\frac{V}{m}=\frac{1}{\rho} \tag{1.13}$$

The specific volume is the reciprocal (倒数) of density, so the unit of v is m^3/kg.

1.3.2.2 Specific weight

Under the action of gravity, an object has gravitational force or weight. The *specific weight* (重度) of fluid is its weight per unit volume. For homogeneous fluid, specific weight is the ratio of the weight of fluid to its volume.

$$\gamma=\frac{G}{V} \tag{1.14}$$

in which γ is the specific weight of fluid, N/m^3; G is the weight of fluid, N.

It may also be expressed as the product of density ρ and acceleration of gravity g.

$$\gamma=\rho g \tag{1.14a}$$

1.3.2.3 Relative density and specific gravity

The *relative density* (相对密度) RD of a fluid is the ratio of its density to the density of a given reference material.

$$RD = \frac{\rho}{\rho_{ref}}$$

in which ρ is the density of the fluid being measured, and ρ_{ref} is the density of the reference.

Generally the reference material is water at 4℃ i.e. $\rho_{ref} = \rho_{water}$ with the exception of a specific use.

The *specific gravity* (比重) SG of a fluid is the ratio of its weight to the weight of an equal volume of water at standard condition and may be as a ratio of its specific weight to that of water.

$$SG = \frac{G}{G_{water}} = \frac{\gamma}{\gamma_{water}}$$

in which γ_{water} is the specific weight of water.

The term "relative density" is often preferred in modern scientific usage. Relative density or specific gravity is a dimensionless quantity and they are numerically equal.

$$RD = \frac{\rho}{\rho_{ref}} = \frac{\rho g}{\rho_{ref} g} = SG$$

The relative density of a gas RD_{air} is often measured with respect to dry air at 20℃ and 101.325kPa absolute.

$$RD_{air} = \frac{\rho_{gas}}{\rho_{air}}$$

in which ρ_{gas} and ρ_{air} are the densities of gas and air respectively.

1.3.3 The compressibility and expansibility of fluid

The volume of fluid changes under different pressure. This character is the *compressibility* (压缩性) of fluid. The volume of fluid changes with the temperature, this character is the *expansibility* (膨胀性) of fluid. There are apparent differences in these two characters for liquid and gas and they will be discussed separately.

1.3.3.1 Compressibility

As the temperature is constant, the magnitude of compressibility is expressed by the coefficient of volume compressibility β_p, a relative variation rate of volume per unit pressure.

$$\beta_p = -\frac{dV/V}{dp} \tag{1.15}$$

in which V is the original volume, m^3; dV is the variation in volume, m^3; dp is the variation of pressure, Pa; and β_p is also called as the bulk compressibility, Pa^{-1}.

Because the pressure increases as the volume decreases, a minus sign is added in equation above to make the coefficient β_p a positive value.

The compressibility of a liquid is also expressed by its *bulk modulus of elasticity* (体积弹性模量). The bulk modulus of elasticity K is the reciprocal of the coefficient of volume compressibility β_p. And it is the pressure needed for variation rate of a unit volume.

$$K = \frac{1}{\beta_p} = -\frac{dp}{dV/V} \tag{1.16}$$

Since dV/V is dimensionless, the unit of K is Pa. Several bulk modulus of elasticity of commonly used materials are shown in Table 1.3.

Table 1.3 Bulk modulus of elasticity of commonly used materials at 20℃

Materials（材料）	Water, pure（水，纯）	Mineral oil, pure（矿物油，纯）	Mineral oil, with 1% gas（矿物油，混气 1%）	Carbon steel（碳钢）	Copper（紫铜）	Brass（黄铜）	Aluminum alloy（铝合金）	Rubber（橡胶）
K (GPa)	2.1	1.4~2.0	0.7	210	120	100	72	0.002~0.006

From the Table 1.3, it can be concluded that the volume of water only changes 4.825 hundred thousandths for the variation of one atmosphere pressure. The compressibility of water is very little as well as other liquid, so the liquid is considered as incompressible in engineering. But under the special circumstances, such as in *waterhammer* (水击) and *high pressure hydraulic power transmission system* (高压液压传动系统), the compressibility of liquid must be considered.

Example 1.1 A mineral oil in cylinder has a volume of 1000cm^3 at 0.1MN/m^2 and a volume of 998 cm^3 at 3.1MN/m^2. What is its bulk modulus of elasticity?

Solution

$$K = -\frac{\Delta p}{\Delta V / V} = -\frac{3.1\times10^6 - 0.1\times10^6}{(998-1000)/1000} = 1.5\times10^9 \text{(Pa)}$$

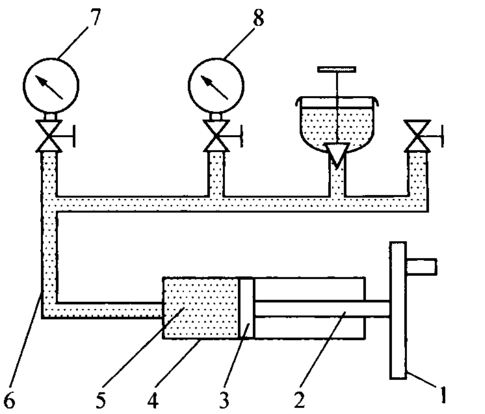

Figure 1.4 A pressure gauge tester

1—handwheel; 2—screw; 3—piston; 4—cylinder; 5—oil; 6—pipeline; 7—standard gauge; 8—gauge to be tested

Example 1.2 A pressure gauge tester is shown in Figure 1.4. The cylinder is filled with oil, β_p=475×10^{-12}Pa^{-1}. As the handwheel rotates, the well sealed piston is screwed in and the oil is compressed then the two pressure gauges reach a desired pressure. The diameter of piston is D=10mm and the *screw pitch* (螺距) is t=2mm. At the atmospheric pressure the volume of oil in the cylinder including pipeline is V=200cm^3. For the reading of 20.0MPa in the pressure gauge, how many revolutions do the handwheel screw?

Solution

From Equation (1.15), the decrease of volume of oil is

$$dV = -\beta_p V dp$$

The variation of volume in the cylinder as the handwheel screws in is

$$dV_1 = V_1 - V = -\frac{\pi}{4}D^2 tn$$

When $dV_1=dV$, the desired pressure dp is reached, so

$$\frac{\pi}{4}D^2tn=\beta_p V\mathrm{d}p$$

The desired revolution n is

$$n=\frac{4\beta_p V\mathrm{d}p}{\pi D^2 t}=\frac{4\times475\times10^{-12}\times200\times10^{-6}\times20\times10^{6}}{\pi\times(10\times10^{-3})^2\times2\times10^{-3}}=12.1(\mathrm{r})$$

1.3.3.2 Thermal expansibility

The volume of liquid increases as the temperature rises. The *coefficient of cubical expansion* (体积热膨胀系数) is the relative variation rate of volume per unit temperature change.

$$\beta_t=\frac{\mathrm{d}V/V}{\mathrm{d}t} \tag{1.17}$$

in which β_t is the coefficient of cubical expansion, (℃)$^{-1}$, and dt is the increment of temperature, ℃.

Experiments shows that at 1 atmospheric pressure and low temperature (10~20℃), the relative variation of volume for water is only 1.5 ten thousandth as the temperature rises 1℃, and the relative variation of it is 7 ten thousandths at high temperature (90~100℃). The expansion coefficient of other liquid is also very little. So the expansibility of liquid is not considered in actual computation except special needs.

Exercises 1.3a

1.3.1 The bulk modulus of elasticity: (a) is dependent of viscosity; (b) increases with temperature; (c) decreases with pressure; (d) has the dimensions of pressure.

1.3.2 For 14MPa increase in pressure the density of water has increased, in percent, by about: (a) 2/300; (b) 2/30; (c) 2/3; (d) 1; (e) none of these answers. (The bulk modulus of elasticity of water is K=2.1GPa)

1.3.3 A pressure of 4.1MPa applied to 10m^3 liquid causes a volume reduction of 0.02m^3. The bulk modulus of elasticity in SI unit, newton per square meter, is: (a) −2050; (b) 2050; (c) 20 500 000; (d) 2 050 000 000; (e) none of these answers.

1.3.4 Viscosity (黏性，黏度)

1.3.4.1 Cause of viscosity

In the research of fluid dynamics, the viscosity must be considered firstly in all fluid characteristics. The properties and characteristics of viscosity are discussed in this section. Viscosity is a property of fluid by virtue of which it offers resistance to shear.

The viscosity of a gas increases with temperature, but the viscosity of a liquid decreases with temperature. The resistance of a fluid to shear depends upon its *cohesion* (内聚力) and its rate of *transfer of molecular momentum* (分子动量交换).

Cohesion appears to be the predominant cause of viscosity in a liquid. The cohesion decreases as the temperature rise, so does the viscosity. A gas, on the other hand, has very little cohesive forces. Most of its resistance or shear stress is the result of transfer of molecular momentum. The molecular motion of gas increases with†8 temperature, so does the viscosity of gas.

At ordinary pressure, viscosity of gas is independent of pressure and only depends upon temperature. At very high pressure, gases and most liquids have shown erratic (飘忽不定) variations of viscosity with pressure.

When fluid is at rest, there is no relative motion of adjacent fluid layers, so no matter how much the viscosity of fluid is, no shear forces can be generated. Hence, in the study of static fluid, the shear forces should not be considered. The study of static fluid is greatly simplified because any free body of fluid has only gravity forces and normal surface forces acting on it.

1.3.4.2 Newton's law of viscosity and Newtonian fluid

In Figure 1.5, a substance is filled to the space between two closely spaced parallel plates so large that conditions at their edges may be neglected. The lower plate is fixed, and a force F is applied to the upper plate, which exerts a shear stress F/A on the substance between the plates. A is the area of the upper plate. When the force F causes the upper plate to move with a constant velocity V, no matter how small the magnitude of F, one may conclude that the substance between the two plates is a fluid.

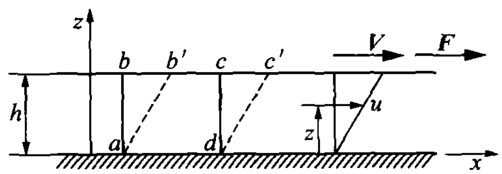

Figure 1.5 Deformation resulting from application of constant shear force

The fluid in immediate contact with a solid boundary has the same velocity as the boundary; i.e., there is no slip at the boundary. This is an experimental fact which has been verified in countless tests with various kinds of fluids and boundary materials. The fluid in the area *abcd* flows to the new position *ab′c′d*, each fluid particle moving parallel to the plate and the velocity u varying uniformly from zero at the stationary plate to V at the upper plate. Experiment shows that F is directly proportional to A and V, and is inversely proportional to thickness h, i.e.

$$F = \mu \frac{AV}{h} \tag{1.18}$$

in which μ is the proportionality factor determined by the characters of fluid.

If the shear stress is $\tau=F/A$, it can be expressed as

$$\tau = \mu \frac{V}{h}$$

The ratio V/h is the angular velocity of line ab, or it is the rate of angular deformation of fluid. The angular velocity may also be written as $\mathrm{d}u/\mathrm{d}z$, as both V/h and $\mathrm{d}u/\mathrm{d}z$ express the velocity change divided by the distance over which the change occurs. However, $\mathrm{d}u/\mathrm{d}z$ is more general, as it holds for situations in which the angular velocity and shear stress change with z. The velocity gradient $\mathrm{d}u/\mathrm{d}z$ may also be visualized as the rate at which one layer moves