中国农业大学
水利与土木工程学院
流体机械与流体工程系

DEPARTMENT OF FLUID MACHINERY AND FLUID ENGINEERING
COLLEGE OF WATER RESOURCES AND CIVIL ENGINEERING
CHINA AGRICULTURAL UNIVERSITY

能源与动力工程专业英语（2024秋）

Academic English of Energy and Power Engineering（Fall, 2024）

第一章 流体力学导论
Chapter 1 Fluid Mechanics Intro

October 29, 2024

1.0 Viscosity of Fluids 流体黏性

Viscosity is that property of a fluid by virtue of which it offers resistance to shear.

黏性是流体能够抵抗剪切力所依靠的特征。

Newton’s law of viscosity states that for a given rate of angular deformation of fluid the shear stress is directly proportional to the viscosity.

牛顿黏滞定律表明，对于给定的角变形，流体所受到的切应力与其黏度成正比。

1.0 Viscosity of Fluids 流体黏性

黏性还是粘性？

粘 nián

姓。

另见 5625 页 zhān。

粘割韩奴 金人。熙宗皇统四年（1144 年）奉命出使西辽，为西辽主所杀，金世宗赠昭毅大将军。

粘罕 即“完颜宗翰”（4549 页）。

黏性 亦称“内摩擦”，旧称“黏滞性”。液体、气体和等离子体内部阻碍其相对流动的一种特性。如果在流动的流体中平行于流动方向将流体分成流速不同的各层，则在任何相邻两层的接触面上就有与面平行而与相对流动方向相反的阻力或曳力存在。这种阻力或曳力称“黏力”，或称“内摩擦力”。实验表明，对于有些流体，相邻流层单位接触面上的黏力 τ（称“切应力”）与速度梯度（相邻流层的速度差 dv 与流层间距 dx 之比 $\frac{dv}{dx}$，称“切变率”）成正比，即 $\tau=\eta\frac{dv}{dx}$，比例系数 η 称“动力黏度”，简称“黏度”，或称“黏滞系数”、“内摩擦系数”。这一关系称“牛顿黏滞定律”。黏度反映流体黏性的大小。黏度的单位为帕·秒（在厘米·克·秒制中为泊）。流体的黏度随温度而变，当温度升高时，液体的黏度减小，而气体的黏度增加。

1.0 Viscosity of Fluids 流体黏性

The viscosity of a gas increases with temperature, but the viscosity of a liquid deceases with temperature.

气体的黏度随着温度的升高而增加，但液体的黏度却随着温度的升高而减小。

The resistance of a fluid to shear depends upon its cohesion and upon its rate of transfer of molecular momentum.

流体抵抗剪切力依靠的是它的内聚力和分子动量的转移速率。

1.0 Viscosity of Fluids 流体黏性

Cohesion appears to be the predominant cause of viscosity in a liquid; and since cohesion decreases with temperature, the viscosity does likewise.

在液体中，由于内聚力随温度升高而下降，所以内聚力对其黏性占有支配作用。

A gas, on the other hand, has very small cohesive forces. Most of its resistance to shear stress is the result of transfer of molecular momentum.

对于气体，它的内聚力很小，其绝大部分抵抗切应力的能力是由分子动量的转移所体现。

1.0 Viscosity of Fluids 流体黏性

The viscosity μ is frequently referred to as the absolute viscosity or the dynamic viscosity to avoid confusing it with the kinematic viscosity ν which is the ratio of viscosity to mass density

经常提到的黏度 μ 通常是指绝对黏度或者动力黏度，以避免与运动黏度 ν （绝对黏度与质量密度的比值）混淆。

$$\nu = \frac{\mu}{\rho}$$

1.1 Scope of Fluid Mechanics

Fluid mechanics is the branch of science concerned with moving and stationary fluids.

Given that the vast majority of the observable mass in the universe exists in a fluid state, that life as we know it is not possible without fluids, and that the atmosphere and oceans covering this planet are fluids, fluid mechanics has unquestioned scientific and practical importance.

1.1 Scope of Fluid Mechanics

Its allure crosses disciplinary boundaries, in part because it is described by a nonlinear field theory and also because it is readily observed.

Mathematicians, physicists, biologists, geologists, oceanographers, atmospheric scientists, engineers of many types, and even artists have been drawn to study, harness, and exploit fluid mechanics to develop and test formal and computational techniques, to better understand the natural world, and to attempt to improve the human condition.

1.1 Scope of Fluid Mechanics

Advances in fluid mechanics, like any other branch of physical science, may arise from mathematical analyses, computer simulations, or experiments.

Analytical approaches are often successful for finding solutions to idealized and simplified problems and such solutions can be of immense value for developing insight and understanding, and for comparisons with numerical and experimental results.

1.1 Scope of Fluid Mechanics

It is probably fair to say that some of the greatest theoretical contributions have come from people who depended rather strongly on their physical intuition.

Ludwig Prandtl, one of the founders of modern fluid mechanics, first conceived the idea of a boundary layer based solely on physical intuition. His knowledge of mathematics was rather limited, as his famous student Theodore von Karman (1954) testifies. Interestingly, the boundary layer concept has since been expanded into a general method in applied mathematics.

1.2 Units of Measurement

For mechanical systems, the units of all physical variables can be expressed in terms of the units of four basic variables, namely, *length*, *mass*, *time*, and *temperature*

TABLE 1.1 SI Units

Quantity	Name of unit	Symbol	Equivalent
Length	Meter	m	
Mass	Kilogram	kg	
Time	Second	s	
Temperature	Kelvin	K	
Frequency	Hertz	Hz	s^{-1}
Force	Newton	N	$kg\ ms^{-2}$
Pressure	Pascal	Pa	$N\ m^{-2}$
Energy	Joule	J	N m
Power	Watt	W	$J\ s^{-1}$

1.2 Units of Measurement

For mechanical systems, the units of all physical variables can be expressed in terms of the units of four basic variables, namely, *length*, *mass*, *time*, and *temperature*

TABLE 1.2 Common Prefixes

Prefix	Symbol	Multiple
Mega	M	10^6
Kilo	k	10^3
Deci	d	10^{-1}
Centi	c	10^{-2}
Milli	m	10^{-3}
Micro	μ	10^{-6}

Penny:
So, how you been?
Sheldon Cooper:
Well, my existence is a ***continuum***, so I've been what I am at each point in the implied time period.
我的存在是一个连续体，所以在指定期间的每个时间点都是一样的。

1.3 Continuum Hypothesis

A fluid is composed of a large number of molecules in constant motion undergoing collisions with each other, and is therefore discontinuous or discrete at the most microscopic scales.

In principle, it is possible to study the mechanics of a fluid by studying the motion of the molecules themselves, as is done in kinetic theory or statistical mechanics.

1.3 Continuum Hypothesis

However, we are generally interested in the average manifestation of the molecular motion.

For example, forces are exerted on the boundaries of a fluid’s container due to the constant bombardment ([bɑːmˈbɑːrdmənt],一连串(想法、要求、质问或批评)) of the fluid molecules; the statistical average of these collision forces per unit area is called pressure, a macroscopic property.

1.3 Continuum Hypothesis

So long as we are not interested in the molecular mechanics of the origin of pressure, we can ignore the molecular motion and think of pressure as simply the average force per unit area exerted by the fluid.

When the molecular density of the fluid and the size of the region of interest are large enough, such average properties are sufficient for the explanation of macroscopic phenomena and the discrete molecular structure of matter may be ignored and replaced with a continuous distribution, called a ***continuum***.

1.4 Dimensional Analysis 量纲分析

Interestingly, a physical quantity’s units may be exploited to learn about its relationship to other physical quantities.

This possibility exists because the natural realm does not need mankind’s units of measurement to function.

Natural laws are independent of any unit system imposed on them by human beings.

1.4 Dimensional Analysis 量纲分析

Consider Newton's second law, generically stated as

$$\textit{force} = (\textit{mass}) \times (\textit{acceleration}),$$

it is true whether a scientist or engineer uses cgs (centimeter, gram, second), MKS (meter, kilogram, second), or even English (inch or foot, pound, second) units in its application.

1.4 Dimensional Analysis 量纲分析

Because nature is independent of our systems of units, we can draw two important conclusions:

1) all correct physical relationships can be stated in dimensionless form (leading to the ***dimensional analysis***, also named as scaling-law-development technique)

2) in any comparison, the units of the items being compared must be the same for the comparison to be valid (known as the principle of ***dimensional homogeneity***)

1.4 Dimensional Analysis 量纲分析

dimensional homogeneity

It requires all terms in an equation to have the same dimension(s) and thereby provides an effective means for error catching within derivations and in derived answers.

If terms in an equation do not have the same dimension(s) then the equation is not correct and a mistake has been made.

1.4 Dimensional Analysis 量纲分析

Step 1. Select Variables and Parameters

Creating the list of variables and parameters to include in a dimensional analysis effort is the most important step. The parameter list should usually contain only one unknown variable, the solution variable.

The rest of the variables and parameters should come from the problem’s geometry, boundary conditions, initial conditions, and material parameters. Physical constants and other fundamental limits may also be included.

1.4 Dimensional Analysis 量纲分析

Step 1. Select Variables and Parameters

For the round-pipe pressure drop example, select Δp as the solution variable, and then choose as additional parameters:

Δx distance between the pressure measurement locations,
d the inside diameter of the pipe,
ε the average height of the pipe's wall roughness,
U the average flow velocity,
ρ the fluid density,
μ the fluid viscosity.

$$f(\Delta p, \Delta x, d, \varepsilon, U, \rho, \mu) = 0$$

1.4 Dimensional Analysis 量纲分析

Step 2. Create the Dimensional Matrix

The dimensions of all these variables can be expressed in terms of four basic dimensions --- mass M, length L, time T, and temperature θ

We shall denote the dimension of a variable q by $[q]$. For example, the dimension of the velocity u is $[u] = \mathrm{L/T}$, that of pressure is $[p] = [\mathrm{force}]/[\mathrm{area}] = \mathrm{MLT^2/L^2} = \mathrm{M/LT^2}$.

	Δp	Δx	d	ε	U	ρ	μ
M	1	0	0	0	0	1	1
L	−1	1	1	1	1	−3	−1
T	−2	0	0	0	−1	0	−1

1.4 Dimensional Analysis 量纲分析

Step 3. Determine the Rank of the Dimensional Matrix

The ***rank*** r of any matrix is defined to be the size of the largest square submatrix that has a nonzero determinant.

$$
\begin{array}{c|ccccccc}
 & \Delta p & \Delta x & d & \varepsilon & U & \rho & \mu \\
\hline
\mathrm{M} & 1 & 0 & 0 & 0 & 0 & 1 & 1 \\
\mathrm{L} & -1 & 1 & 1 & 1 & 1 & -3 & -1 \\
\mathrm{T} & -2 & 0 & 0 & 0 & -1 & 0 & -1
\end{array}
$$

$$
\begin{vmatrix} 1 & 0 & 0 \\ -1 & 1 & 1 \\ -2 & 0 & 0 \end{vmatrix} = 0
$$

$$
\begin{vmatrix} 0 & 1 & 1 \\ 1 & -3 & -1 \\ -1 & 0 & -1 \end{vmatrix} = -1
$$

1.4 Dimensional Analysis 量纲分析

Step 3. Determine the Rank of the Dimensional Matrix

For dimensional matrices, the rank is less than the number of rows only when one of the rows can be obtained by a linear combination of the other rows. For example

$$\begin{vmatrix} 0 & 1 & 0 & 1 \\ -1 & 2 & 1 & -2 \\ -1 & 4 & 1 & 0 \end{vmatrix}$$

has r = 2, as the last row can be obtained by adding the second row to twice the first row.

In most fluid mechanics problems without thermal effects, r = 3.

1.4 Dimensional Analysis 量纲分析

Step 4. Determine the Number of Dimensionless Groups

The number of dimensionless groups is n - r where n is the number of variables and parameters, and r is the rank of the dimensional matrix.

In the pipe-flow pressure difference example, the number of dimensionless groups is 4 = 7 - 3.

1.4 Dimensional Analysis 量纲分析

Step 5. Construct the Dimensionless Groups

This can be done by **exponent algebra** or by **inspection**. The latter is preferred because it commonly produces dimensionless groups that are easier to interpret, but the former is sometimes required.

1.4 Dimensional Analysis 量纲分析

Step 5. Construct the Dimensionless Groups

Exponent Algebra

Select *r* parameters from the dimensional matrix as repeating parameters that will be found in all the subsequently constructed dimensionless groups.

These repeating parameters must span the appropriate *r*-dimensional dimension space of M, L, and/or T, that is, the determinant of the dimensional matrix formed from these *r* parameters must be nonzero.

1.4 Dimensional Analysis 量纲分析

Step 5. Construct the Dimensionless Groups

Exponent Algebra

For many fluid-flow problems, a characteristic velocity, a characteristic length, and a fluid property involving mass are ideal repeating parameters.

To form dimensionless groups for the pipe-flow problem, choose U, d, and ρ as the repeating parameters.

1.4 Dimensional Analysis 量纲分析

Step 5. Construct the Dimensionless Groups

Each dimensionless group is formed by combining the three repeating parameters, raised to unknown powers, with one of the nonrepeating variables or parameters from the list constructed for the first step.

Here we ensure that the first dimensionless group involves the solution variable raised to the first power

$$\Pi_1 = \Delta p U^a d^b \rho^c$$

1.4 Dimensional Analysis 量纲分析

Step 5. Construct the Dimensionless Groups

$$\Pi_1 = \Delta p U^a d^b \rho^c$$

$$\mathrm{M}^0\mathrm{L}^0\mathrm{T}^0 = \left[\Pi_1\right] = [\Delta p U^a d^b \rho^c] = (\mathrm{ML}^{-1}\mathrm{T}^{-2})(\mathrm{LT}^{-1})^a(\mathrm{L})^b(\mathrm{ML}^{-3})^c = \mathrm{M}^{c+1}\mathrm{L}^{a+b-3c-1}\mathrm{T}^{-a-2}$$

Equating exponents between the two extreme ends of this extended equality produces three algebraic equations that are readily solved to find a=2, b=0, c=1, so

$$\Pi_1 = \Delta p/\rho U^2$$

1.4 Dimensional Analysis 量纲分析

Step 5. Construct the Dimensionless Groups

$$\Pi_1 = \Delta p/\rho U^2$$

A similar procedure with Δp replaced by the other unused variables (Δx, ε, μ) produces Π

$$\Pi_2 = \Delta x/d, \ \Pi_3 = \varepsilon/d, \ \text{and} \ \Pi_4 = \mu/\rho U d$$

1.4 Dimensional Analysis 量纲分析

Step 6. State the Dimensionless Relationship

This step merely involves placing the (n - r) Π-groups. For the pipe-flow example, this dimensionless relationship is

pipe's roughness ratio

$$\frac{\Delta p}{\rho U^2} = \varphi\left(\frac{\Delta x}{d}, \frac{\varepsilon}{d}, \frac{\mu}{\rho U d}\right)$$

pipe's aspect ratio

where φ is an undetermined function.

1.5 Dimensionless Number

$$\mathrm{Re} = \text{Reynolds number} \equiv \frac{\text{inertia force}}{\text{viscous force}} \propto \frac{\rho u(\partial u/\partial x)}{\mu(\partial^2 u/\partial x^2)} \propto \frac{\rho U^2/l}{\mu U/l^2} = \frac{\rho U l}{\mu}.$$

$$\mathrm{St} = \text{Strouhal number} \equiv \frac{\text{unsteady acceleration}}{\text{advective acceleration}} \propto \frac{\partial u/\partial t}{u(\partial u/\partial x)} \propto \frac{\Omega U}{U^2/l} = \frac{\Omega l}{U},$$

$$\mathrm{Fr} = \text{Froude number} \equiv \left[\frac{\text{inertia force}}{\text{gravity force}}\right]^{1/2} \propto \left[\frac{\rho u(\partial u/\partial x)}{\rho g}\right]^{1/2} \propto \left[\frac{\rho U^2/l}{\rho g}\right]^{1/2} = \frac{U}{\sqrt{gl}}$$

The symbol ∂ is a rounded 'd'.

$\frac{\partial f}{\partial x}$ pronounces as 'dee-eff dee-ex' or 'partial f partial x'.

1.5 Dimensionless Number

$$\mathrm{Re} = \text{Reynolds number} \equiv \frac{\text{inertia force}}{\text{viscous force}} \propto \frac{\rho u(\partial u/\partial x)}{\mu(\partial^2 u/\partial x^2)} \propto \frac{\rho U^2/l}{\mu U/l^2} = \frac{\rho U l}{\mu}.$$

$$\mathrm{St} = \text{Strouhal number} \equiv \frac{\text{unsteady acceleration}}{\text{advective acceleration}} \propto \frac{\partial u/\partial t}{u(\partial u/\partial x)} \propto \frac{\Omega U}{U^2/l} = \frac{\Omega l}{U},$$

$$\mathrm{Fr} = \text{Froude number} \equiv \left[\frac{\text{inertia force}}{\text{gravity force}}\right]^{1/2} \propto \left[\frac{\rho u(\partial u/\partial x)}{\rho g}\right]^{1/2} \propto \left[\frac{\rho U^2/l}{\rho g}\right]^{1/2} = \frac{U}{\sqrt{gl}}$$

The symbol ∂ is a rounded 'd'.

$\frac{\partial f}{\partial x}$ pronounces as 'dee-eff dee-ex' or 'partial f partial x'.

1.5 Dimensionless Number

For flow around an immersed body, like a sphere, we can define the (dimensionless) drag and lift coefficients

$$C_D \equiv \frac{F_D}{(1/2)\rho U^2 A} \quad \text{and} \quad C_L \equiv \frac{F_L}{(1/2)\rho U^2 A},$$

1.5 Dimensionless Number

$$M = \text{Mach number} \equiv \left[\frac{\text{inertia force}}{\text{compressibility force}}\right]^{1/2} \propto \left[\frac{\rho U^2/l}{\rho c^2/l}\right]^{1/2} = \frac{U}{c}$$

$$\mathrm{Ec} = \text{Eckert number} \equiv \frac{\text{kinetic energy}}{\text{thermal energy}} = \frac{U^2}{C_\mathrm{p}(T_w - T_o)}$$

$$\mathrm{Pr} = \text{Prandtl number} \equiv \frac{\text{momentum diffusivity}}{\text{thermal diffusivity}} = \frac{\nu}{\kappa} = \frac{\mu_o/\rho_o}{k_o/\rho_o C_\mathrm{p}} = \frac{\mu_o C_\mathrm{p}}{k_o},$$

1.5 Dimensionless Number

$$\mathrm{We} = \text{Weber number} \equiv \frac{\text{inertia force}}{\text{surface tension force}} \propto \frac{\rho U^2 l^2}{\sigma l} = \frac{\rho U^2 l}{\sigma}$$

$$\mathrm{Bo} = \text{Bond number} \equiv \frac{\text{gravity force}}{\text{surface tension force}} \propto \frac{\rho l^3 g}{\sigma l} = \frac{\rho l^2 g}{\sigma}$$

$$\mathrm{Ca} = \text{Capillary number} \equiv \frac{\text{viscous stress}}{\text{surface tension stress}} \propto \frac{\mu U / l}{\sigma / l} = \frac{\mu U}{\sigma}$$

1.6 Conservation Laws

The governing principles in fluid mechanics are the conservation laws for mass, momentum, and energy.

1.6.1 Conservation of Mass

Setting aside nuclear reactions and relativistic([ˌrɛlətɪˈvɪstɪk],相对论的) effects, mass is neither created nor destroyed.

Thus, individual mass elements --- molecules, grains, fluid particles, etc. --- may be tracked within a flow field because they will not disappear and new elements will not spontaneously appear.

continuity equation: $$\frac{1}{\rho(\mathbf{x},t)}\boxed{\frac{D}{Dt}\rho(\mathbf{x},t)} + \nabla\cdot\mathbf{u}(\mathbf{x},t) = 0$$

Incompressible flow

$$\frac{D\rho}{Dt} \equiv \frac{\partial\rho}{\partial t} + \mathbf{u}\cdot\nabla\rho = 0$$

$$\nabla\cdot\mathbf{u} = 0$$

1.6.2 Conservation of Momentum

The momentum-conservation is developed from Newton's second law, the fundamental principle governing fluid momentum.

$$\rho\frac{D\mathbf{u}}{Dt} = -\nabla p + \rho\mathbf{g} + \mu\nabla^2\mathbf{u} \text{ (incompressible)}$$

Navier-Stokes Momentum Equation

If viscous effects are negligible, which is commonly true away from the boundaries of the flow field, the equation above further simplifies to the **Euler equation**

$$\rho\frac{D\mathbf{u}}{Dt} = -\nabla p + \rho\mathbf{g}$$

1.6.3 Conservation of Energy

The energy-conservation is developed from a mathematical statement of conservation of energy for a fluid particle in an inertial frame of reference.

总能（total energy）

$$\frac{\partial(\rho E)}{\partial t}+\nabla\cdot(\rho E\mathbf{u})=\rho\dot{q}-\nabla\cdot(p\mathbf{u})+k\nabla^2 T+\nabla\cdot(\boldsymbol{\tau}\cdot\mathbf{u})+\rho\mathbf{f}$$

内能（internal energy）

$$\frac{\partial(\rho e)}{\partial t}+\nabla\cdot(\rho e\mathbf{u})=\rho\dot{q}-\nabla\cdot(p\mathbf{u})+k\nabla^2 T+(\boldsymbol{\tau}:\nabla\mathbf{u})$$

焓（enthalpy）

$$\frac{\partial(\rho h)}{\partial t}+\nabla\cdot(\rho eh)=\rho\dot{q}+\frac{\mathrm{D}p}{\mathrm{D}t}+k\nabla^2 T+(\boldsymbol{\tau}:\nabla\mathbf{u})$$

总焓（total enthalpy）

$$\frac{\partial(\rho H)}{\partial t}+\nabla\cdot(\rho eH)=\rho\dot{q}+\frac{\partial p}{\partial t}+k\nabla^2 T+(\boldsymbol{\tau}:\nabla\mathbf{u})+\rho\mathbf{f}$$

温度（temperature）

$$\frac{\partial(\rho c_p T)}{\partial t}+\nabla\cdot(\rho c_p T\mathbf{u})=\rho\dot{q}-\nabla\cdot(p\mathbf{u})+k\nabla^2 T+(\boldsymbol{\tau}:\nabla\mathbf{u})$$

END

1.1 Scope of Fluid Mechanics

1.2 Units of Measurement

1.3 Continuum Hypothesis

1.4 Dimensional Analysis

1.5 Dimensionless Number

1.6 Conservation Laws

ANY QUESTIONS?