教材与参考书

Fluid Mechanics: Fundamentals and Applications, 4^{th} edition

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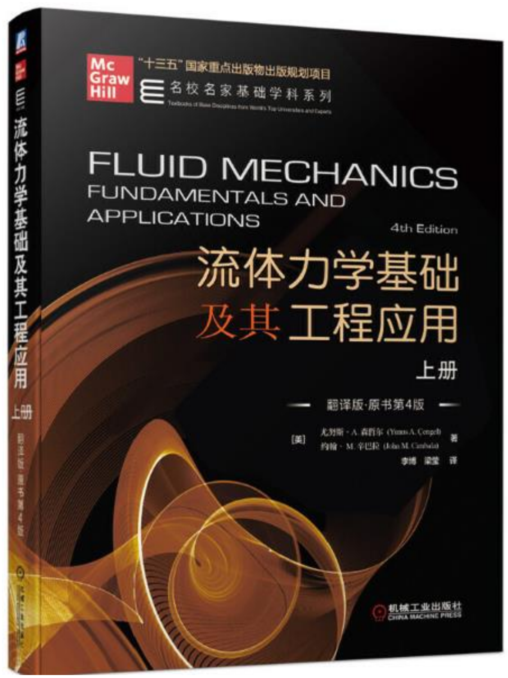
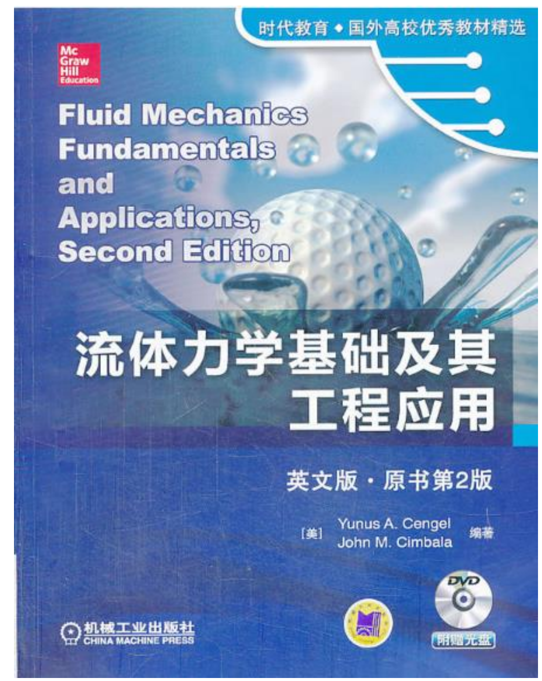




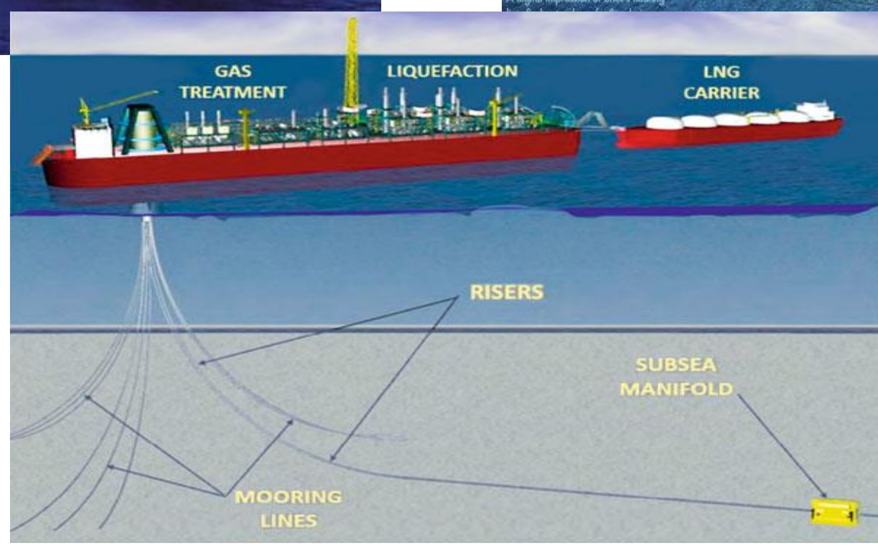
Motivation for Studying Fluid Mechanics

- 流体力学无所不在
  - Aerodynamics （航空动力学）
  - Naval Architecture & Ocean Engineering （船舶与海洋工程）
  - Bioengineering （生物工程）
  - Energy generation （发电）
  - Meteorology （气象学）
  - Geology （地质）
  - Hydraulics and Hydrology （水力学）
  - Water Resources （水资源）
  - Hydrodynamics （水动力学）
  - …numerous other examples…
- Fluid Mechanics is beautiful

Aerodynamics（航空动力学）

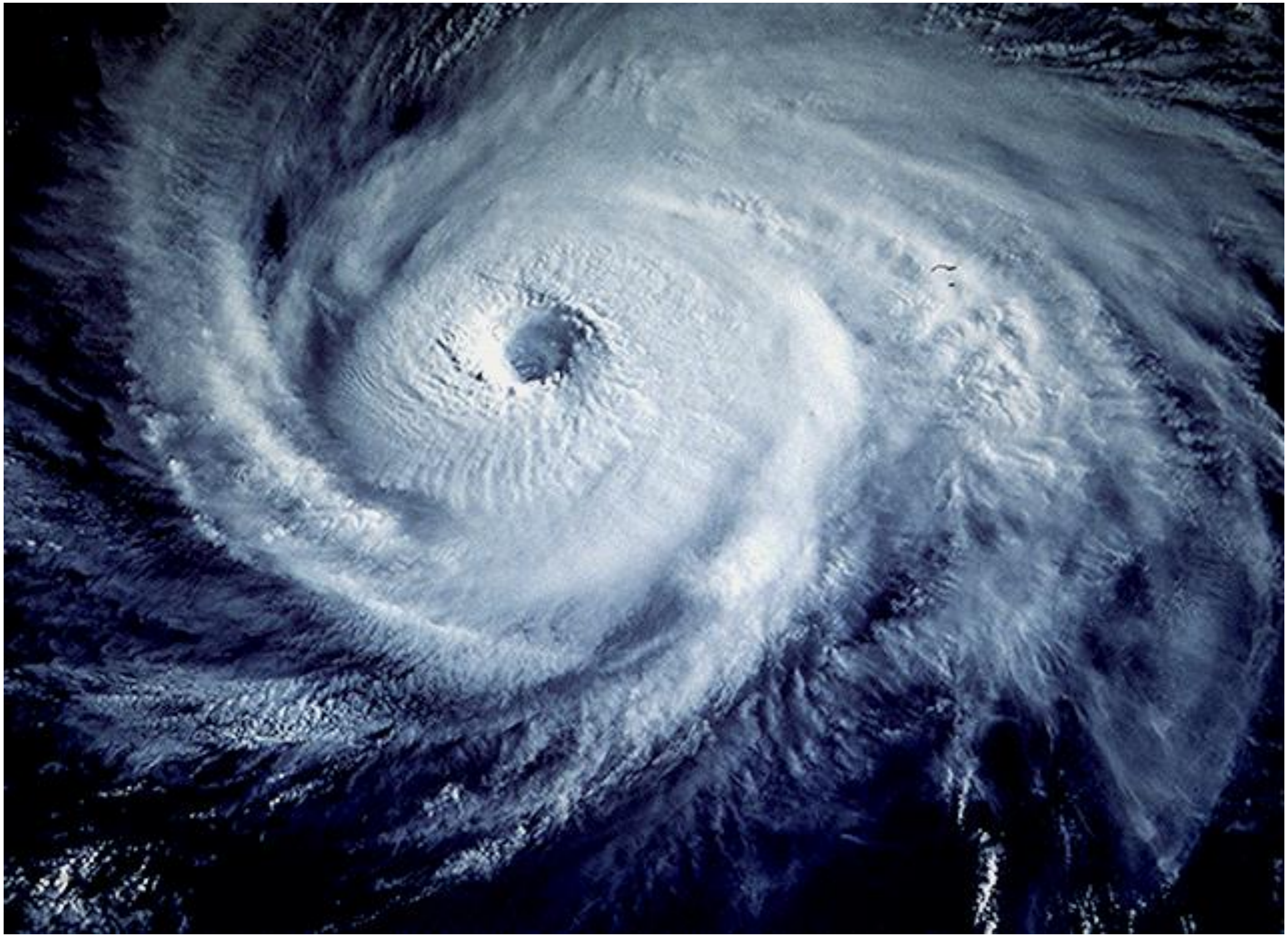
Aerodynamics（航空动力学）

Naval Architecture & Ocean Engineering（船舶与海洋工程）



Power generation（发电）

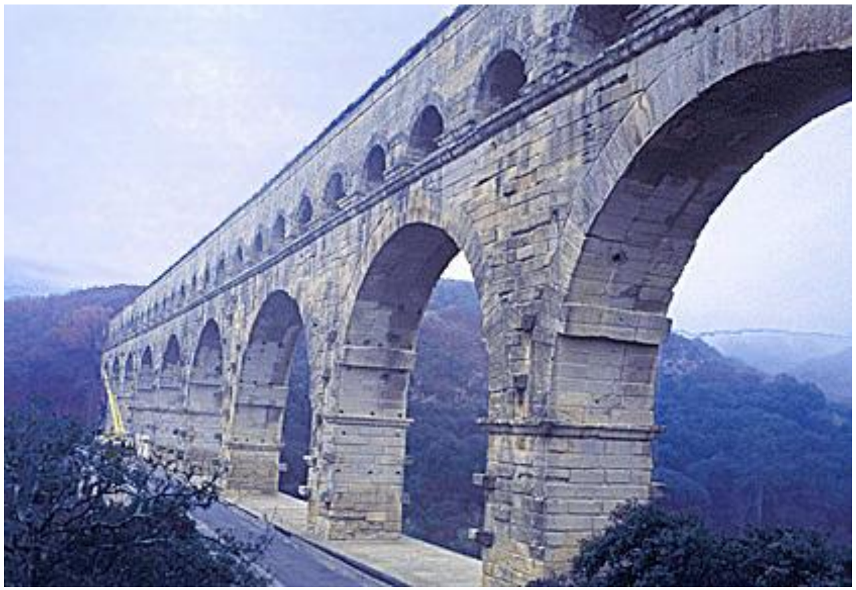
Meteorology （气象学）



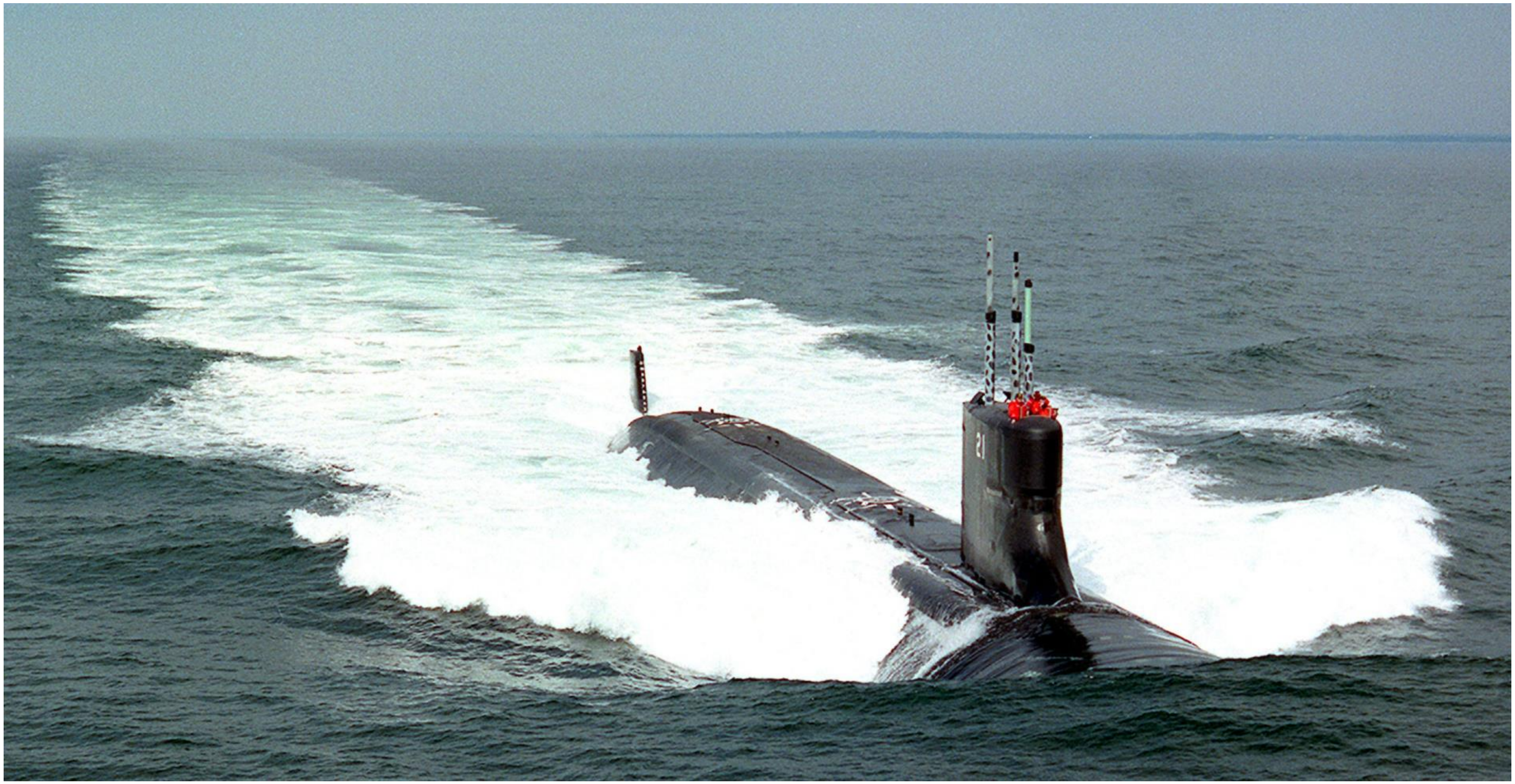
Geology（地质学）

Hydraulics（水力学）

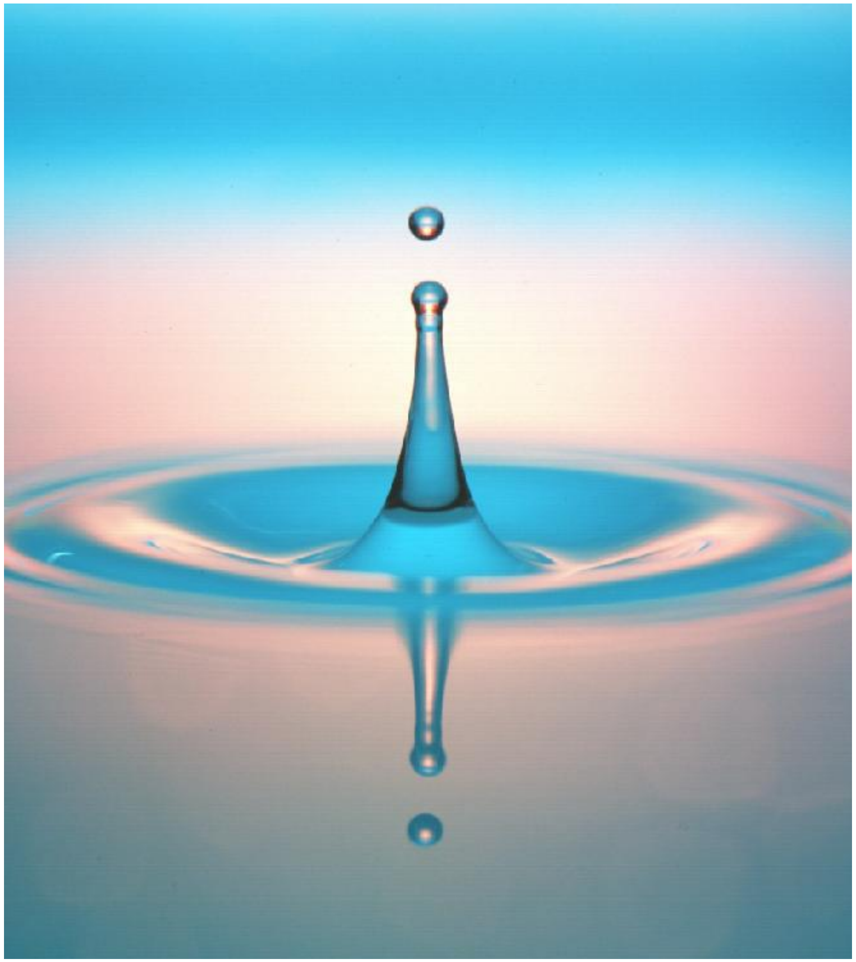
Water Resources （水资源）



Hydrodynamics（水动力学）



Fluid Mechanics is Beautiful



Methods for Solving Fluid Dynamics Problems

- *Analytical Fluid Dynamics (AFD, 分析流体力学)*：

   Mathematical analysis of governing equations（控制方程），including exact and approximate solutions（精确解和近似解）

- *Computational Fluid Dynamics (CFD, 计算流体力学)*：Numerical solution of the governing equations（数值解）

- *Experimental Fluid Dynamics (EFD, 实验流体力学)*：Observation and data acquisition.

Analytical Fluid Dynamics (AFD)

How fast do tsunamis travel in the deep ocean?

Incompressible Navier-Stokes equations (N-S方程)

$$\frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U} \cdot \nabla)\mathbf{U} = \frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{U}$$

Linearized wave equation for inviscid, irrotational flow (线性化波动方程)

$$\nabla^2 \phi = 0, \mathbf{U} = \nabla \phi$$

$$\frac{\partial \phi}{\partial z} = 0 \text{ on } z = -h$$

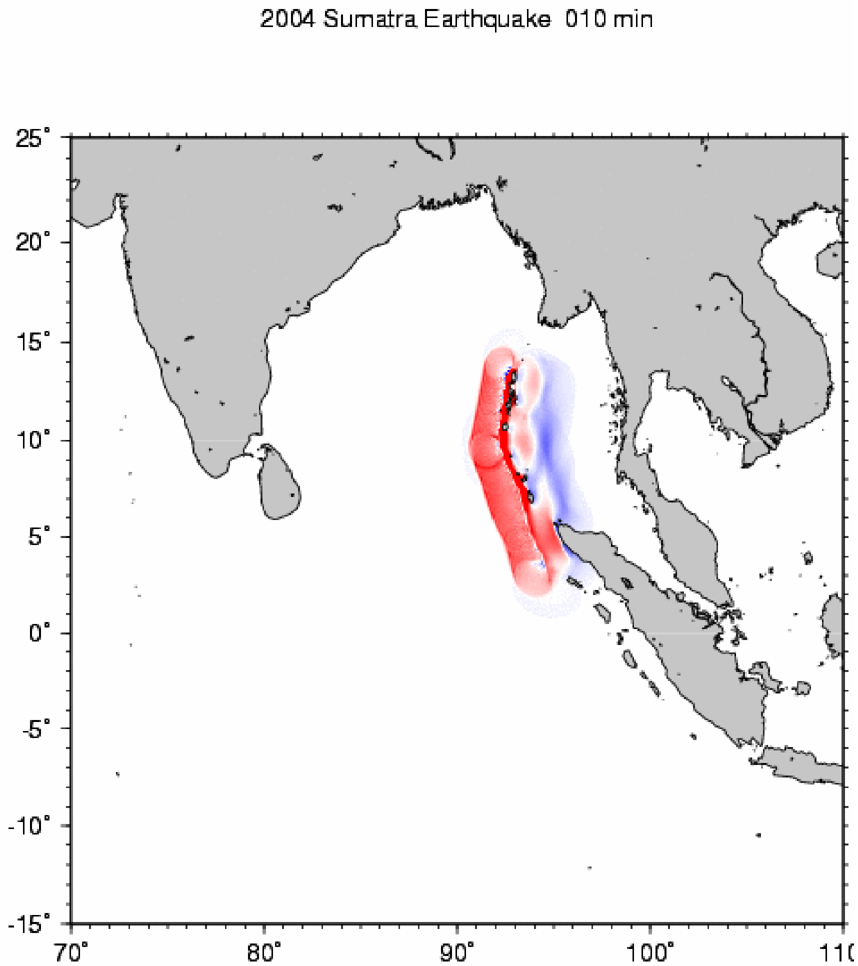
$$\frac{\partial^2 \phi}{\partial t^2} = -g\frac{\partial \phi}{\partial z} \text{ on } z = 0$$

Shallow-water approximation, l/h >> 1

$$c = \sqrt{\frac{g}{k}\tanh kh} \Longrightarrow c = \sqrt{gh}$$

For g = 32.2 ft/s^2 and h=10000 ft, c=567 ft/s = 172.82 m/s

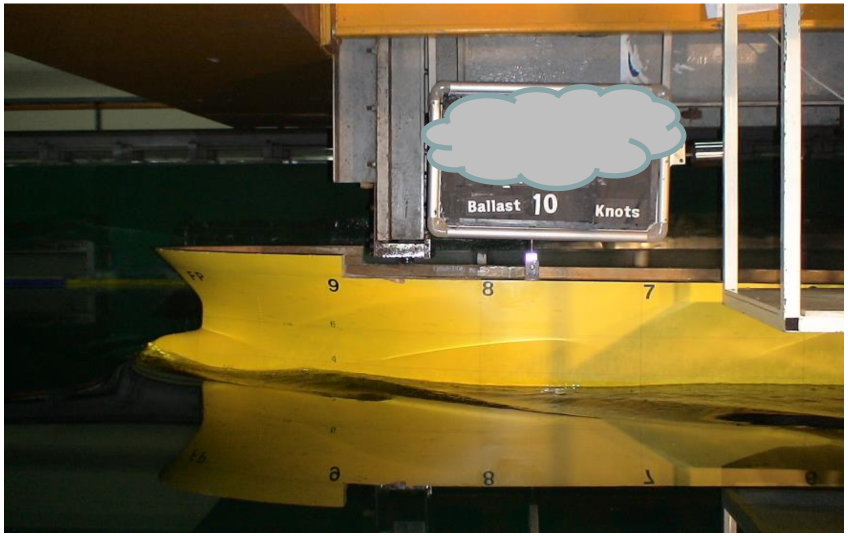
Computational Fluid Dynamics (CFD)



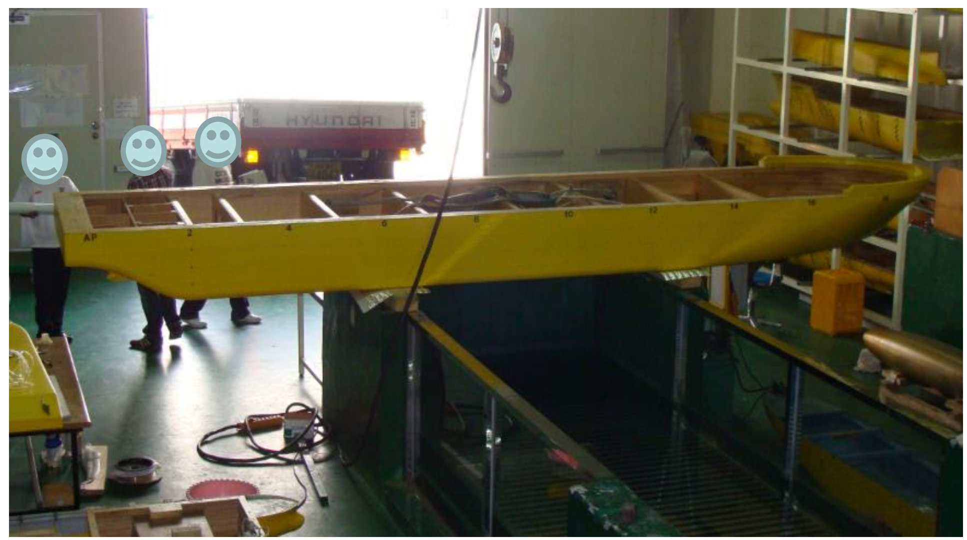
Animation by Vasily V. Titov, Tsunami Inundation Mapping Efforts, NOAA/PMEL

In comparison to **analytical methods**, which are good for providing solutions for *relatively simple geometries*. **CFD** provides a tool for solving problems with *nonlinear physics and complex geometry*.

Experimental Fluid Dynamics (EFD)



- Model-scale experimental facilities
- Dimensional analysis (量纲分析) is very important in designing a model experiment （模型实验） which represents physics of actual problem



本课程包括的内容

- 引言与基本概念
- 流体的性质
- 压强与流体静力学
- 流体运动学
- 伯努利方程与能量方程
- 流动系统的动量分析
- 量纲分析与模型化
- 内流
- ***流体流动的微分分析***
- ***纳维尔-斯托克斯（N-S）方程的近似解***

流体力学上册
所包含的内容

第1章

引言与基本概念

引言

Fluid mechanics (流体力学):

The science that deals with the behavior of fluids at rest (*fluid statics, 流体静力学*) or in motion (*fluid dynamics, 流体动力学*), and the interaction of fluids with solids or other fluids at the boundaries.

流体力学研究静止 (静力学) 或运动流体 (动力学) 的规律, 以及流体与固体或其他流体在边界处相互作用的科学

引言

What is a Fluid?

Fluid (流体): *A substance in the liquid or gas phase (液相或气相)*.

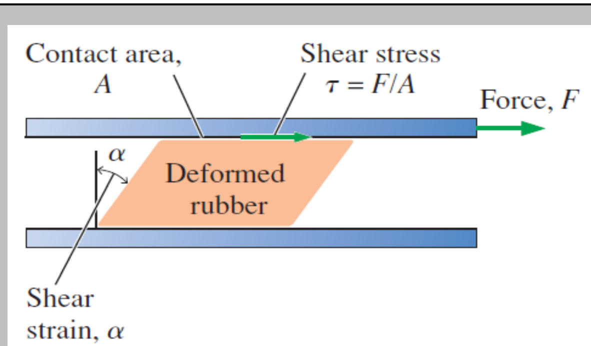
A solid can resist an applied shear stress (切应力) by deforming.

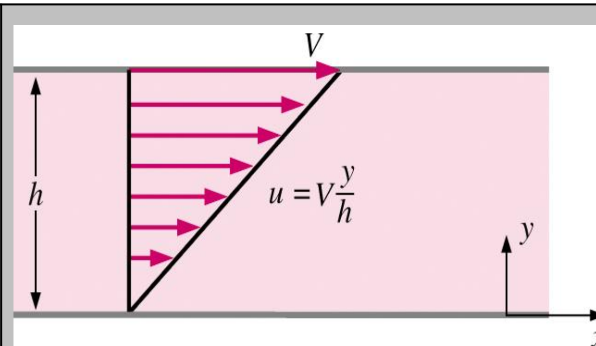
A fluid *deforms continuously (不断变形) under the influence of a shear stress*, no matter how small.

In solids, stress is proportional to *strain* (应变), but in fluids, stress is proportional to *strain rate* (应变率).

Solid

$$\tau = \frac{F}{A} \propto \alpha$$

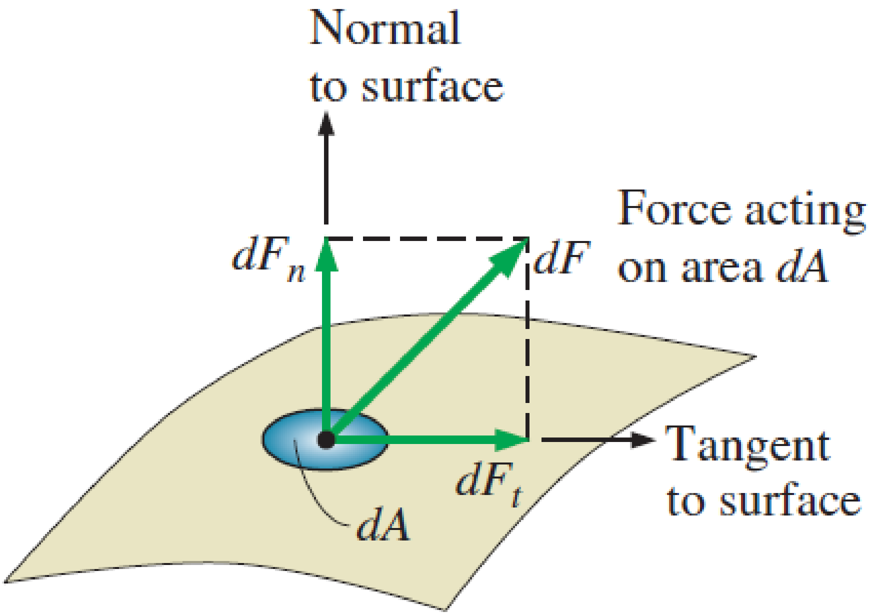




Fluid

$$\tau = \frac{F}{A} \propto \mu \frac{V}{h}$$

引言



$$\text{Normal stress: } \sigma = \frac{dF_n}{dA}$$

$$\text{Shear stress: } \tau = \frac{dF_t}{dA}$$

The normal stress and shear stress at the surface of a fluid element. For fluids at rest, the shear stress is zero and pressure is the only normal stress.

Stress (应力)**:** Force per unit area.

Normal stress (法向应力) **:** The normal component (法向分量) of a force acting on a surface per unit area.

Shear stress (切应力) **:** The tangential component (切向分量) of a force acting on a surface per unit area.

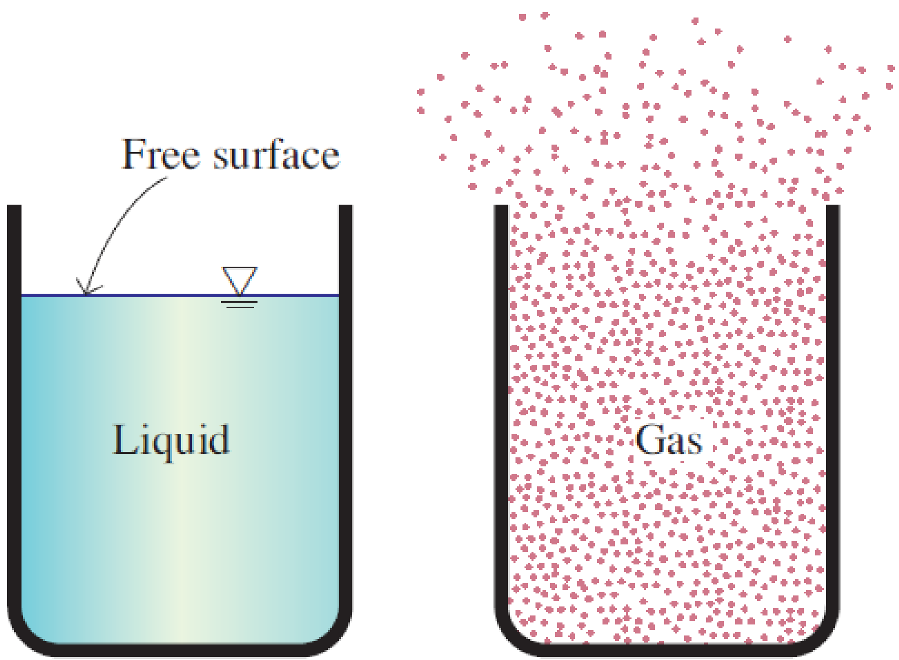
Pressure (压强) **:** The normal stress in a fluid at rest (静止流体).

Zero shear stress: A fluid at rest is at a state of zero shear stress.

引言

In a **liquid (液体)**, groups of molecules can move relative to each other, but the _volume remains relatively constant_ because of the strong cohesive forces (内聚力) between the molecules. As a result, a liquid takes the shape of the container it is in, and it forms a free surface (自由表面) in a larger container in a gravitational field.

A **gas (气体)** expands until it encounters the walls of the container and _fills the entire available space_. This is because the gas molecules are widely spaced, and _the cohesive forces between them are very small_. Unlike liquids, a gas in an open container cannot form a free surface.



与流体不同的是，气体不存在自由表面，气体会填充整个可用空间

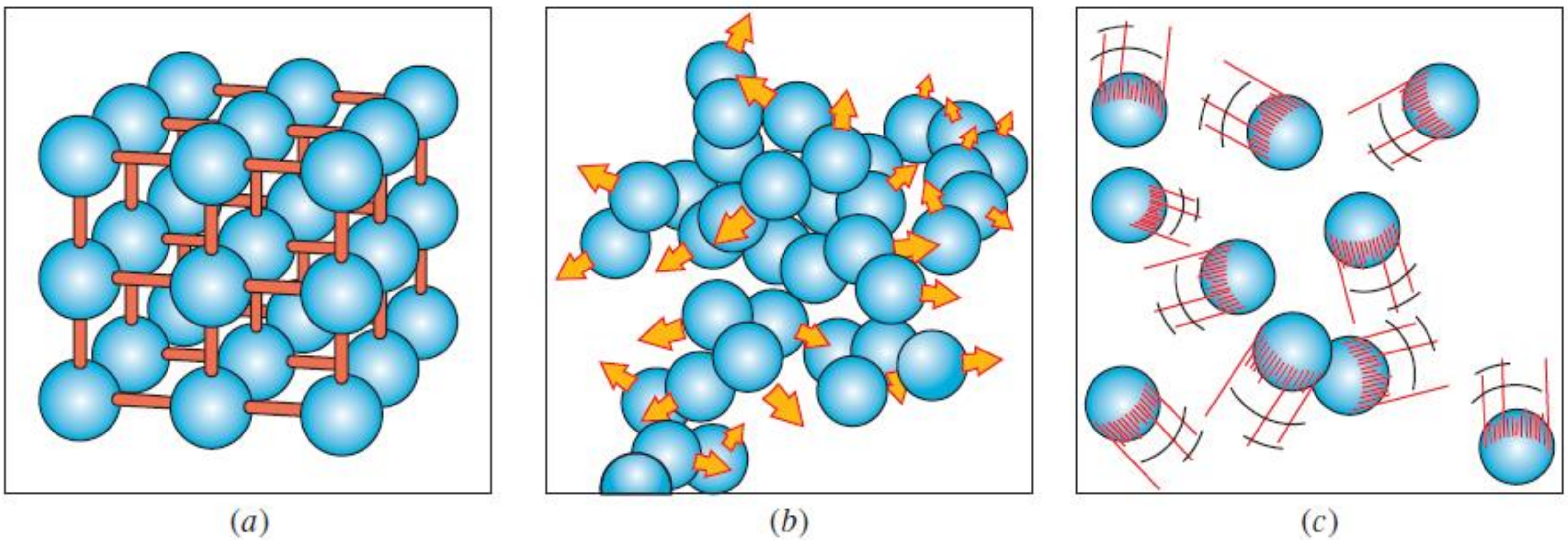
引言

Intermolecular bonds (分子间作用力) *are strongest in solids and weakest in gases.*

Solid (固体): Molecules are arranged in a pattern that is repeated throughout.

Liquid (液体): Molecules can *rotate and translate* (旋转和平移) freely.

Gas (气体): Molecules are far apart from each other, and molecular ordering is nonexistent (随机无序性).



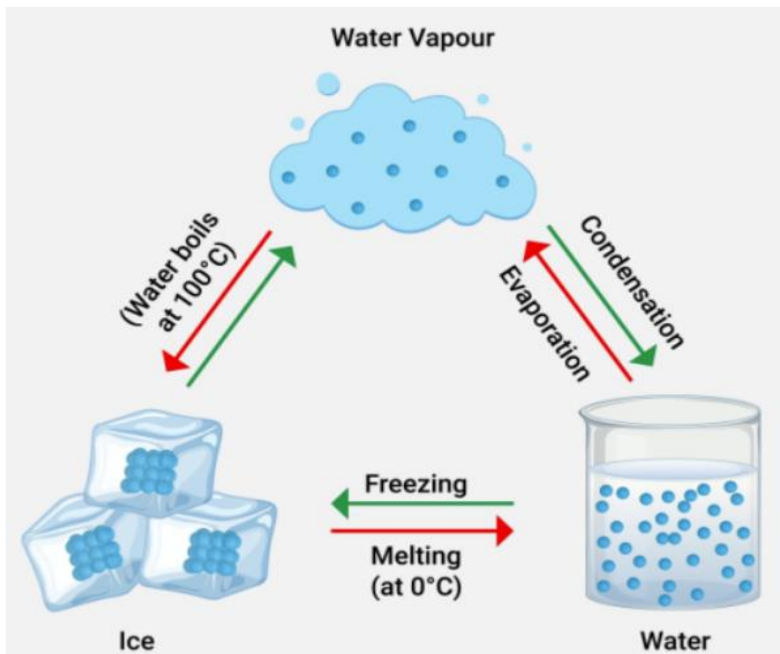
The arrangement of atoms in different phases: (*a*) molecules are at relatively fixed positions in a solid, (*b*) groups of molecules move about each other in the liquid phase, and (*c*) individual molecules move about at random in the gas phase.

引言

***Gas* (气)** and ***vapor* (汽)** are often used as synonymous words.

Gas (气): The vapor phase of a substance is customarily called a *gas* when it is above the critical temperature (临界温度).

Vapor (汽) : Usually implies that the current phase is not far from a state of condensation (冷凝状态).

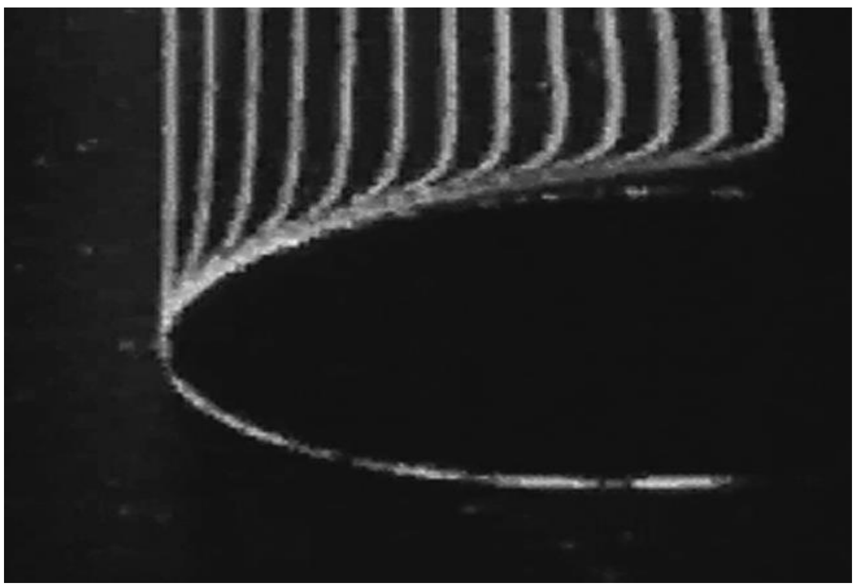


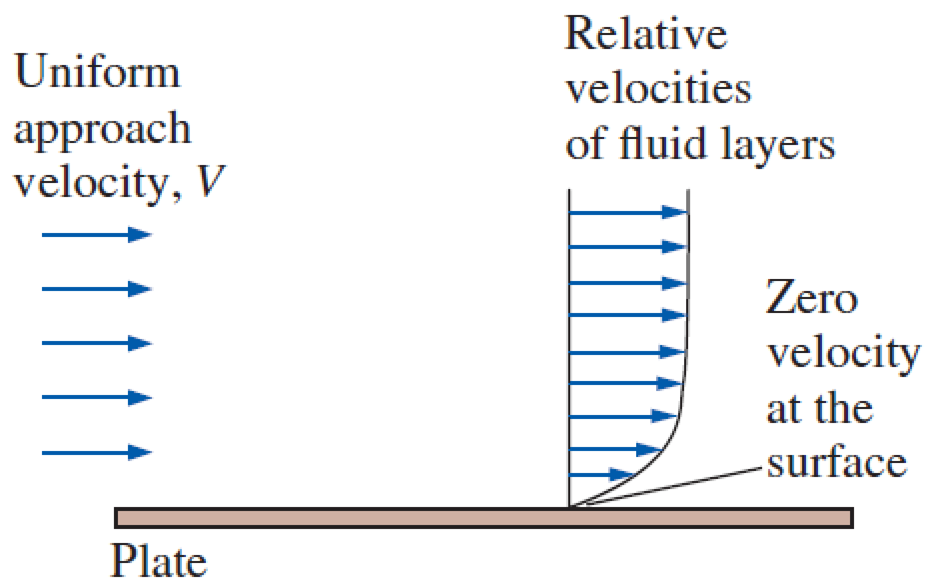
无滑移条件

Consider the flow of a fluid in a stationary pipe (固定管道) or over a solid surface (固体表面) that is nonporous (无空隙无法渗透).

All experimental observations indicate that a fluid in motion comes to a complete stop *at the surface and assumes a zero velocity* relative to the surface. That is, a fluid in direct contact with a solid "sticks" to the surface, and there is no slip. This is known as the no-slip condition (**无滑移条件**).

导致无滑移条件和边界层出现的流体属性是**黏性** (viscosity).



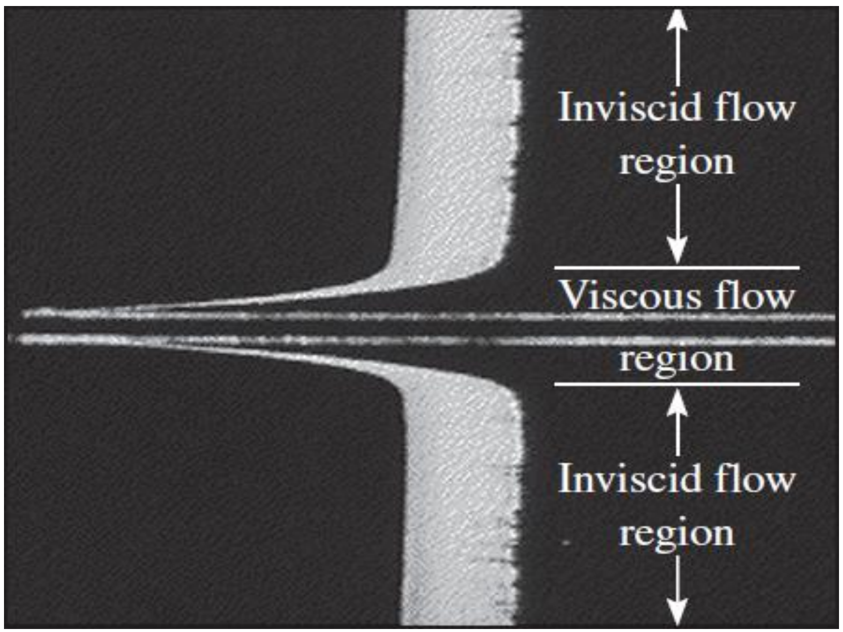


流体流动的分类

Viscous vs Inviscid Regions of Flow

Viscous flows (黏流区): Flows in which the frictional (摩擦力) effects are significant.

Inviscid flow regions (无黏流区): : In many flows of practical interest, there are *regions* (typically regions not close to solid surfaces) where viscous forces (黏性力) are negligibly small compared to inertial or pressure forces (惯性力或压强).



Fundamentals of Boundry Layers, National Committee for Fluid Mechanics Films, © Education Development Center.

For inviscid flows:

$$\rho\left[\frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U}\cdot\nabla)\,\mathbf{U}\right] = -\nabla p + \rho\mathbf{g} + \cancel{\mu\nabla^2\mathbf{U}}^{\,0}$$

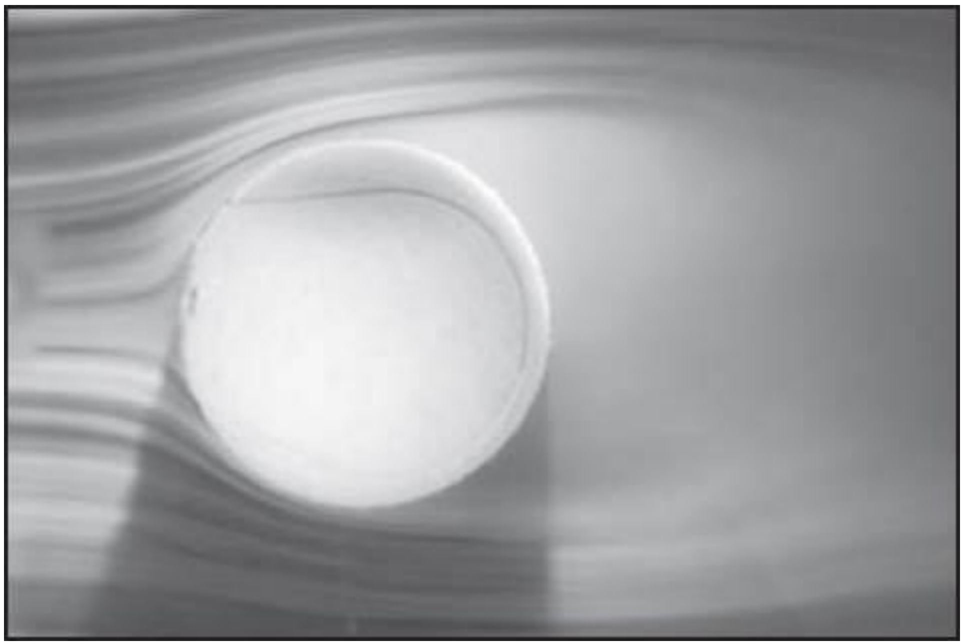
The flow of an originally uniform fluid stream over a flat plate, and the regions of viscous flow (next to the plate on both sides) and inviscid flow (away from the plate).

流体流动的分类

Internal vs External Flow

External flow (外流): 不受限制的流体在物面上方的流动（如平板，球表面流等）.

Internal flow (内流) : 流体在管道内的流动（流体完全受到固体表面的限制）.



External flow over a tennis ball, and the turbulent wake (湍流尾迹) region behind.

Water flow in a pipe is internal flow (内流), and airflow over a ball is external flow (外流).

The flow of liquids in a duct is called *open-channel flow (明渠流动)* if the duct is only partially filled with the liquid and there is a free surface (自由表面).

流体流动的分类

Compressible vs Incompressible Flow

Incompressible flow (不可压缩流动):
If the *density* of flowing fluid remains *nearly constant* throughout (e.g., liquid flow).

Compressible flow (可压缩流动): If the *density* of fluid *changes* during flow (e.g., high-speed gas flow)

分析高速气体流动时 (如火箭，战斗机等), 流速通常表示为无量纲马赫数 **Mach number** (马赫数)

$$\mathrm{Ma} = \frac{V}{c} = \frac{\text{Speed of flow}}{\text{Speed of sound}}$$

Ma = 1	**Sonic flow (声速)**
Ma < 1	**Subsonic flow (亚声速)**
Ma > 1	**Supersonic flow (超声速)**
Ma >> 1	**Hypersonic flow (高超声速)**

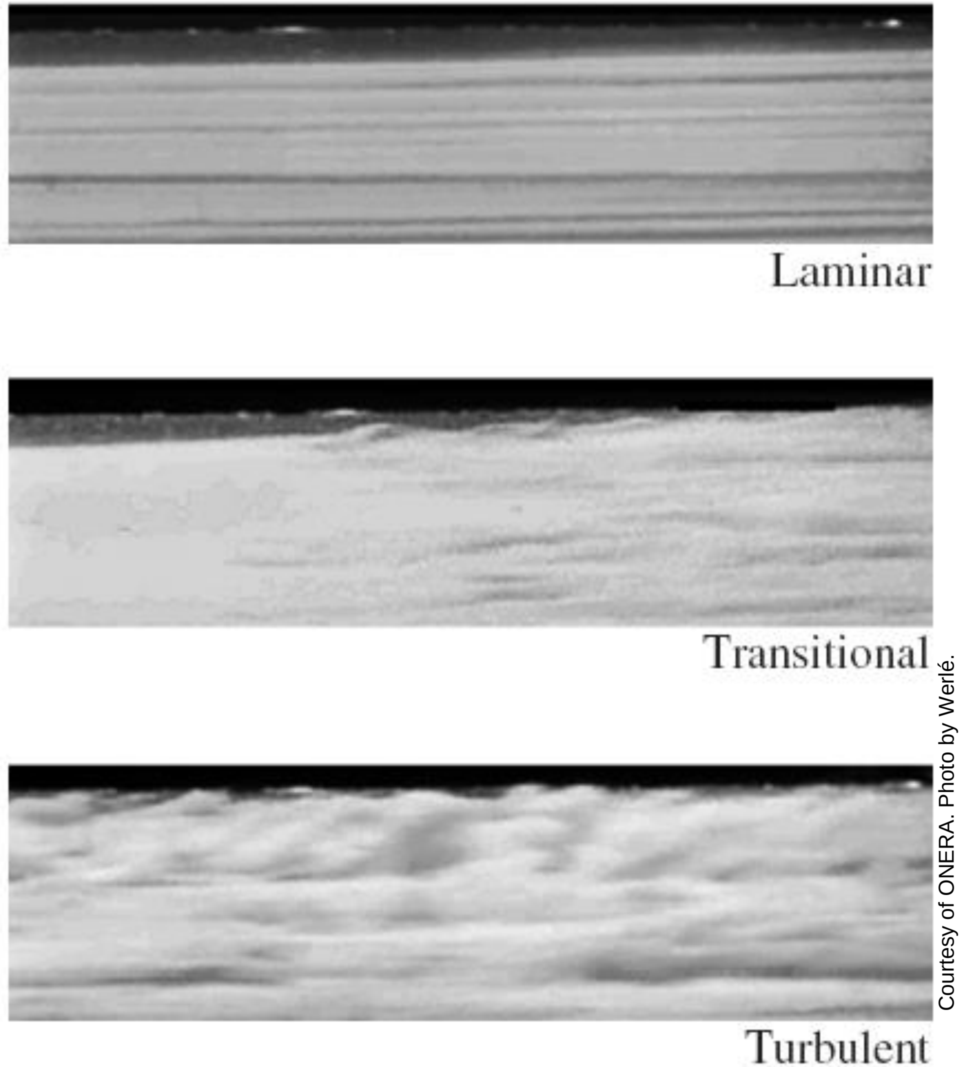
流体流动的分类

Laminar vs Turbulent Flow

Laminar flow (层流) : The highly ordered (高度有序) fluid motion characterized by smooth layers of fluid. The flow of high-viscosity fluids such as oils at low velocities is typically laminar.

Turbulent flow (湍流) : The highly disordered (高度无序) fluid motion that typically occurs at high velocities and is characterized by velocity fluctuations. The flow of low- viscosity fluids such as air at high velocities is typically turbulent.

Transitional flow (过渡流) : A flow that alternates between being laminar and turbulent.



Laminar, transitional, and turbulent flows over a flat plate

流体流动的分类

Natural (or Unforced) vs Forced Flow

Forced flow (强制流动) : A fluid is forced to flow over a surface or in a pipe by external means (外部手段) such as *a pump* or a fan.

Natural flow (自然流动) : Fluid motion is due to natural means (自然手段) such as the buoyancy effect etc (浮力效应).

流体流动的分类

Steady vs Unsteady Flow

The term **steady** implies *no change at a point with time* **(定常流动).**

$$\frac{\partial \mathbf{U}}{\partial t} = \frac{\partial \rho}{\partial t} = 0$$

The opposite of steady is **unsteady (非定常流动).**

In fluid mechanics, *unsteady is the most general term that applies to any flow that is not steady.*

The term **uniform** implies *no change with location* over a specified region **(均匀流).**

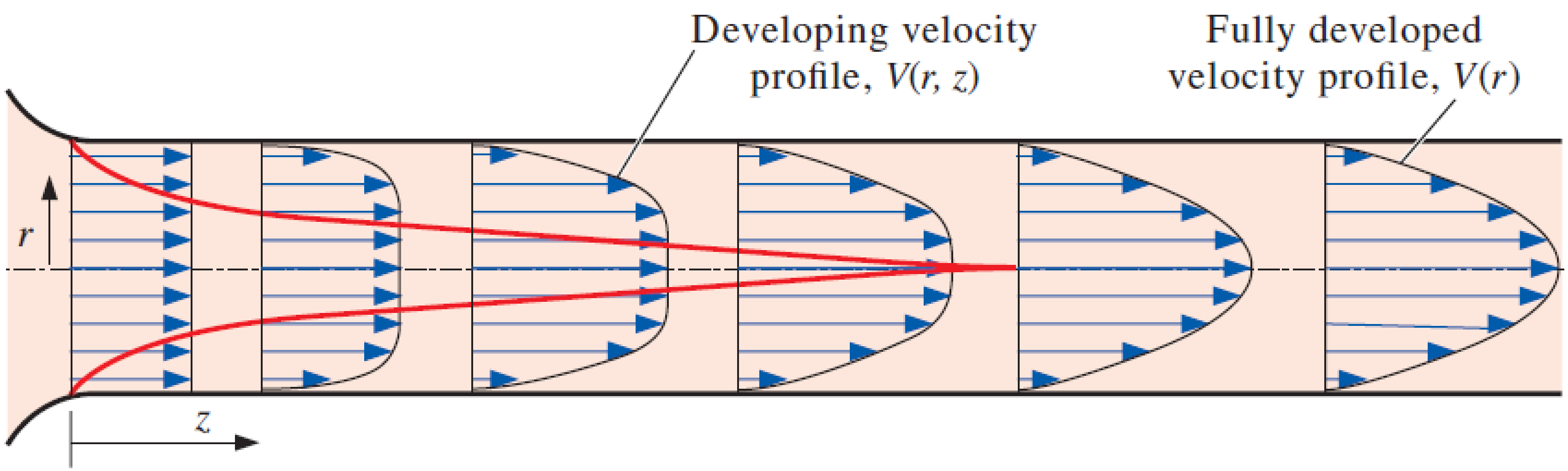
流体流动的分类

一维流动、二维流动和三维流动

A flow field **(流场)** is best characterized by its velocity distribution (速度分布).

A flow is said to be one-, two-, or three-dimensional if the *flow velocity* varies in one, two, or three dimensions , respectively.

但某些方向相对于其他方向的速度变化很小时可以忽略不计



The development of the velocity profile in a circular pipe. V = V(r, z) and thus the flow is *two-dimensional in the entrance region*, and *becomes one-dimensional* downstream when the velocity profile fully develops and remains unchanged in the flow direction, V = V(r).

体系和控制体

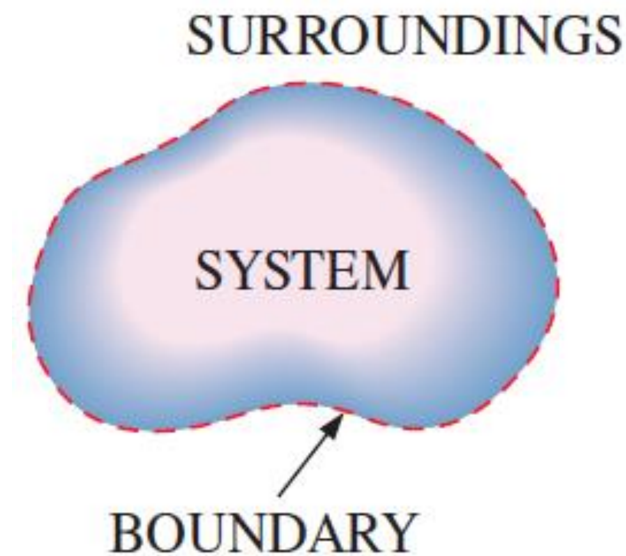
System (体系): A quantity of matter or a region in space chosen for study.

Surroundings (环境): The mass or region outside the system

Boundary (边界): The real or imaginary surface that separates the system from its surroundings.

The boundary of a system can be *fixed* or *movable*.

Systems (体系) may be considered to be *closed* or *open* (封闭或开放体系).

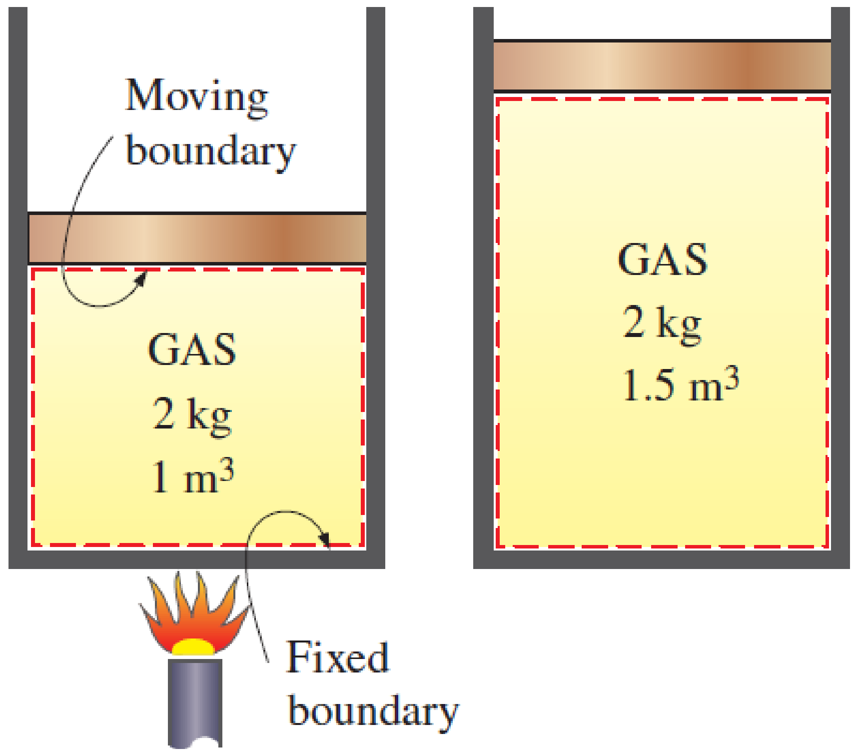


System, surroundings, and boundary

体系和控制体

Closed system (封闭体系):

A fixed amount of mass, and *no mass can cross* its boundary.



A closed system with a moving boundary.

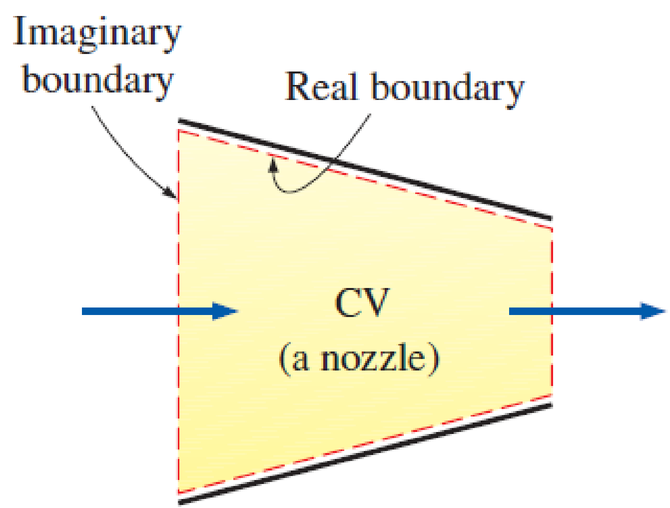
体系和控制体

Open system (**control volume, 控制体**): A properly selected region in space.

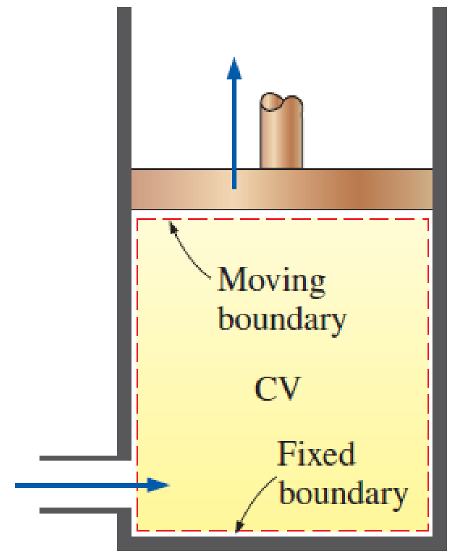
It usually encloses a device that involves mass flow such as a compressor, turbine, or nozzle.

Both mass and energy can cross the boundary of a control volume.

Control surface (控制面): The boundaries of a control volume. It can be real or imaginary.



(*a*) A control volume (CV) with real and imaginary boundaries



(*b*) A control volume (CV) with fixed and moving boundaries as well as real and imaginary boundaries

量纲和单位的重要性

Any physical quantity can be characterized by **dimensions (量纲)**.

The magnitudes assigned to the dimensions are called **units**.

Some basic dimensions such as mass *m*, length *L*, time *t*, and temperature *T* are selected as **primary** or **fundamental dimensions** (基本量纲), while others such as velocity *V*, energy *E*, and volume *V* are expressed in terms of the primary dimensions and are called **secondary dimensions**, or **derived dimensions** (导出量纲).

Metric SI system (国际单位制)**:** A simple and logical system based on a decimal relationship between the various units.

English system (英制)**:** It has no apparent systematic numerical base, and various units in this system are related to each other rather arbitrarily.

TABLE 1–1
The seven fundamental (or primary) dimensions and their units in SI

Dimension	Unit
Length	meter (m)
Mass	kilogram (kg)
Time	second (s)
Temperature	kelvin (K)
Electric current	ampere (A)
Amount of light	candela (cd)
Amount of matter	mole (mol)

TABLE 1–2
Standard prefixes in SI units

Multiple	Prefix
10^{24}	yotta, Y
10^{21}	zetta, Z
10^{18}	exa, E
10^{15}	peta, P
10^{12}	tera, T
10^{9}	giga, G
10^{6}	mega, M
10^{3}	kilo, k
10^{2}	hecto, h
10^{1}	deka, da
10^{-1}	deci, d
10^{-2}	centi, c
10^{-3}	milli, m
10^{-6}	micro, μ
10^{-9}	nano, n
10^{-12}	pico, p
10^{-15}	femto, f
10^{-18}	atto, a
10^{-21}	zepto, z
10^{-24}	yocto, y

一些SI和英制单位

1 lbm = 0.45359 kg

1 ft = 0.3048 m

Work = Force × Distance

1 J = 1 N·m

1 cal = 4.1868 J

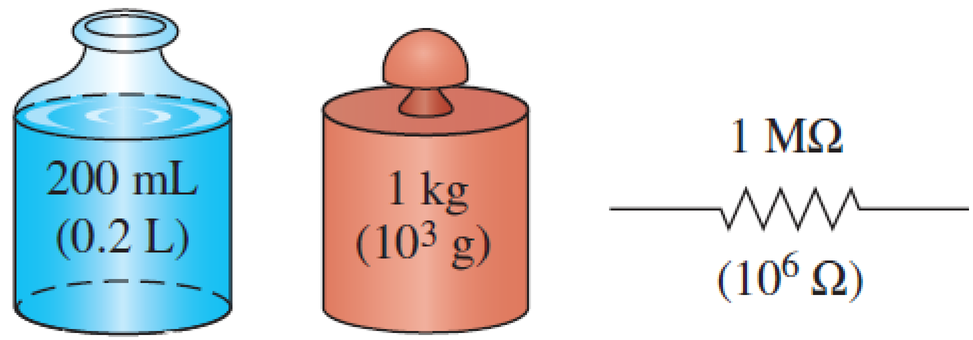
1 Btu = 1.0551 kJ

Force = (Mass) (Acceleration)

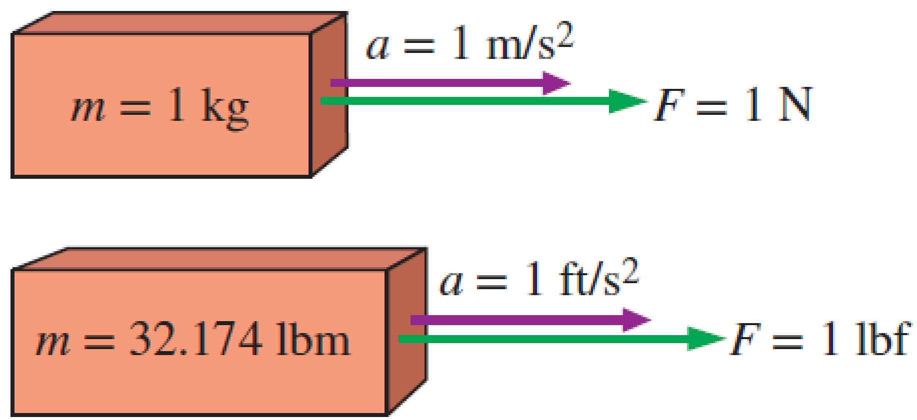
$F = ma$

1 N = 1 kg·m/s^2

1 lbf = 32.174 lbm·ft/s^2



The SI unit prefixes are used in all branches of engineering.



The definition of the force units.

练习1-1

通过单位分析获得公式

空气作用于汽车的阻力取决于无量纲阻力系数、空气密度、汽车车速和汽车迎风面积。也就是说，$F_D = F_D(C_D, A_{Front}, \rho, V)$。仅基于单位分析，求阻力的关系式。

【解】：力F的单位是 N，N相当于kg·m/s²。因此，应该采用基本物理量(基本量)，从而使最后得到的阻力单位是 kg·m/ s² 。考虑到上述信息，得到

$$F_D\left[\mathrm{kg}\cdot\frac{m}{s^2}\right] = f\left(C_D[1], A_{Front}[m^2], \rho\left[\frac{\mathrm{kg}}{m^3}\right], V[m/s]\right)$$

显然，要使最后得到的阻力单位是"kg·m/s²"，只能将密度乘以速度的二次方再乘以迎风面积，最后乘以阻力系数作为比例系数。

因此，关系式是 $F_D = C_D A_{Front} \rho V^2$

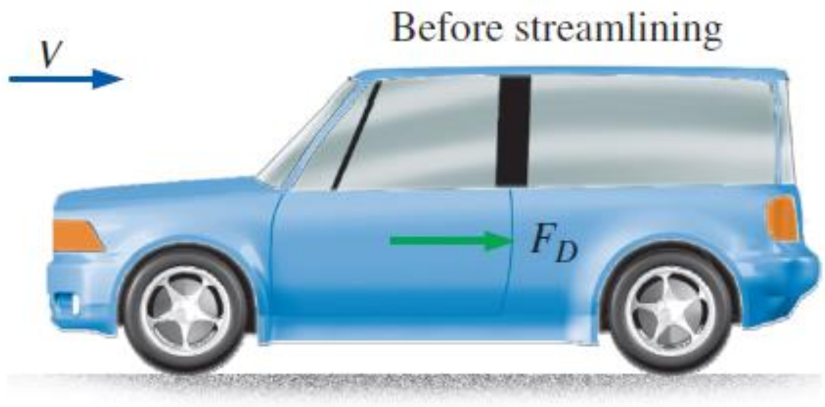
【注意】阻力系数是无量纲的，所以我们不确定它应该在分子上还是在分母上，或者是否有指数等。不过，常识告诉我们阻力应该线性正比于阻力系数。

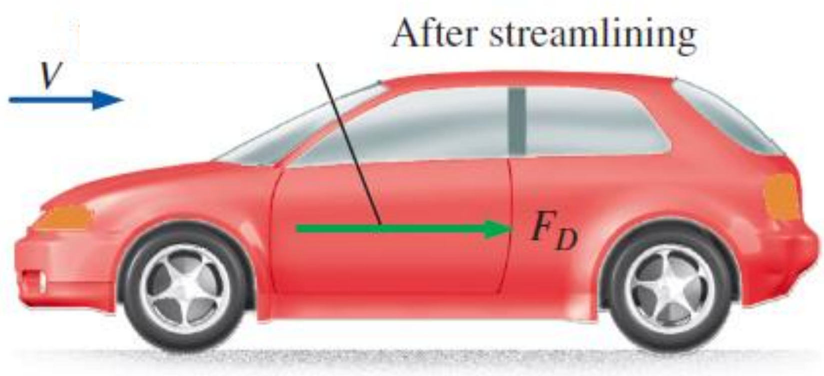
工程问题的建模

An engineering device or process can be studied either *experimentally* (testing and taking measurements) or *analytically* (by analysis or calculations).

The experimental approach (实验方法) has the advantage that we deal with the actual physical system, and the desired quantity is determined by measurement, within the limits of experimental error. However, this approach is expensive, time-consuming, and often *impractical*.

The analytical approach (分析方法、包括数值方法) has the advantage that it is *fast and inexpensive*, but the results obtained are subject to the accuracy of the assumptions, approximations, and idealizations made in the analysis.





The results obtained from an engineering analysis must be checked for reasonableness.

Summary

- Introduction (引 言)
- The No-Slip Condition (无滑移条件)
- Classification of Fluid Flows (流动的分类)
- System and Control Volume (体系和控制体)
- Dimensions and Units (量纲和单位)
- Modeling in Engineering (工程问题的建模)