ME 1071: Applied Fluids

Spring 2021

Outlines

- Approaches for Fluid Mechanics
- Continuum Hypothesis
- Properties of Fluids
  - Viscous Flow
- Fluid Statics and Motion
- A Brief Review of Thermodynamics
- Some Aspects of Supersonic Flow: Shock Waves
- Compressible Flow and Hypersonic Flow

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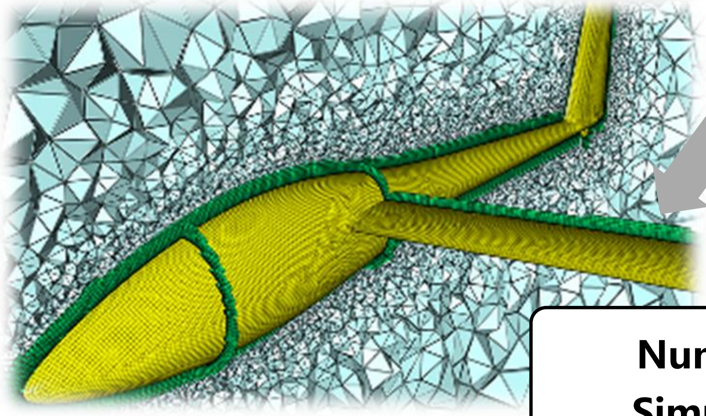
Approaches

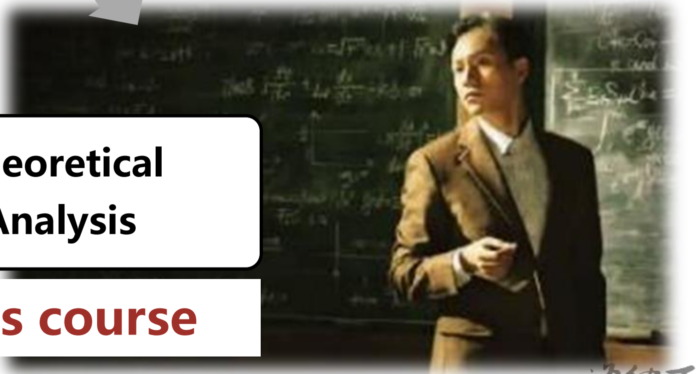
Experimental Measurements

Fluid Mechanics



Numerical Simulation

Theoretical Analysis



This course

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Approaches

Theoretical Analysis

$$\nabla = \frac{\partial}{\partial x}\boldsymbol{i} + \frac{\partial}{\partial y}\boldsymbol{j} + \frac{\partial}{\partial x}\boldsymbol{k}$$

- **Navier-Stokes Equations (the full governing equations)**

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

Mass conservation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0$$

Momentum conservation

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\frac{1}{\rho}\nabla p + \upsilon \Delta \boldsymbol{u} + \frac{1}{3}\upsilon \nabla(\nabla \cdot \boldsymbol{u}) + \boldsymbol{f}$$

Energy conservation

$$\rho \frac{D}{Dt}\left(e + \frac{|\boldsymbol{u}|^2}{2}\right) = \rho \dot{q} - \nabla \cdot (-k\nabla T)$$
$$-\nabla \cdot (p\boldsymbol{u}) + \nabla \cdot (\ddot{\boldsymbol{\tau}} \cdot \boldsymbol{u}) + \rho \boldsymbol{f} \cdot \boldsymbol{u}$$

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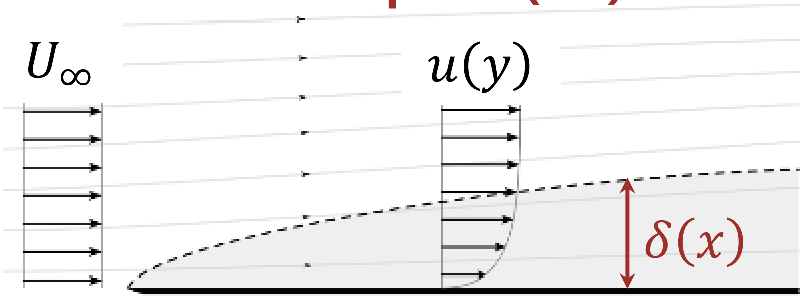
Approaches

Theoretical Analysis

- Model of the physical problem
  - Through appropriate simplification & approximation
- Governing Equations, Initial & Boundary conditions
- Exact solution by using mathematical tools

Boundary layer flow over a flat plate (2D)



✓ All the physics involved in the problem

✓ Direct information on what are the important variables

✓ Simple tools for rapid calculations

× **Only possible for a few simplified cases**

$$
\begin{cases}
\dfrac{\partial u}{\partial x} + \dfrac{\partial v}{\partial y} = 0 \\[2ex]
\dfrac{\partial u}{\partial t} + u\dfrac{\partial u}{\partial x} + v\dfrac{\partial u}{\partial y} = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial x} + \nu\dfrac{\partial^2 u}{\partial y^2} \\[2ex]
\dfrac{\partial p}{\partial y} = 0
\end{cases}
$$

Momentum Equation in y direction

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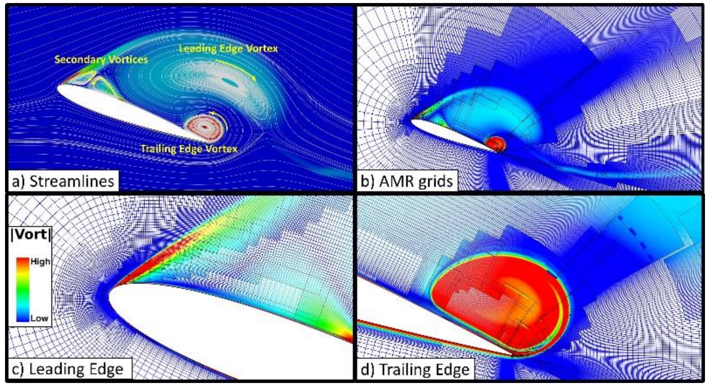
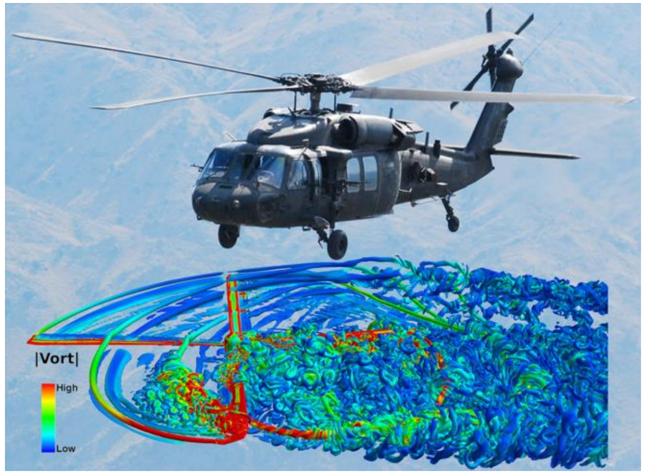
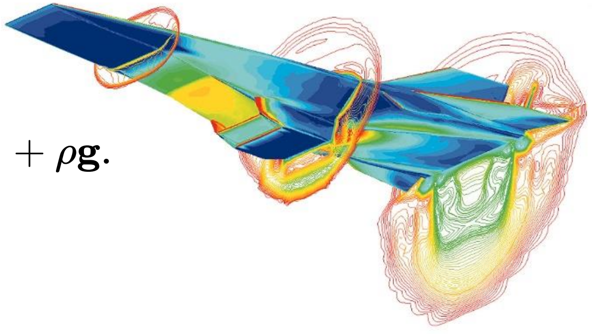
Approaches

- **Computational Fluid Dynamics (计算流体力学，CFD)**
  - A branch of fluid mechanics that uses numerical analysis and data structures to analyze and solve problems that involve fluid flows.
  - CFD deals with computing the equations of fluid flows using numerical methods instead of partial differential equations, represent a continuous flow field by a series of distinct grid points/cells in space.
  - **Finite volume method** (有限体积法, FVM, most common), Finite element method (有限元法, FEM), **Finite difference method** (有限差分法, FDM, historically important), Spectral element method (谱方法, SEM), Lattice Boltzmann method (格子玻尔兹曼, LBM), ……





$$\rho \frac{D\mathbf{u}}{Dt} = \rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = -\nabla\bar{p} + \mu\nabla^2\mathbf{u} + \tfrac{1}{3}\mu\nabla(\nabla\cdot\mathbf{u}) + \rho\mathbf{g}.$$



The Navier-Stokes Equation

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Approaches

Experiment

- Ground test of scaled models in Experimental facilities
- Flight test of the prototype aircraft

✓ Experimental results are reliable and straightforward

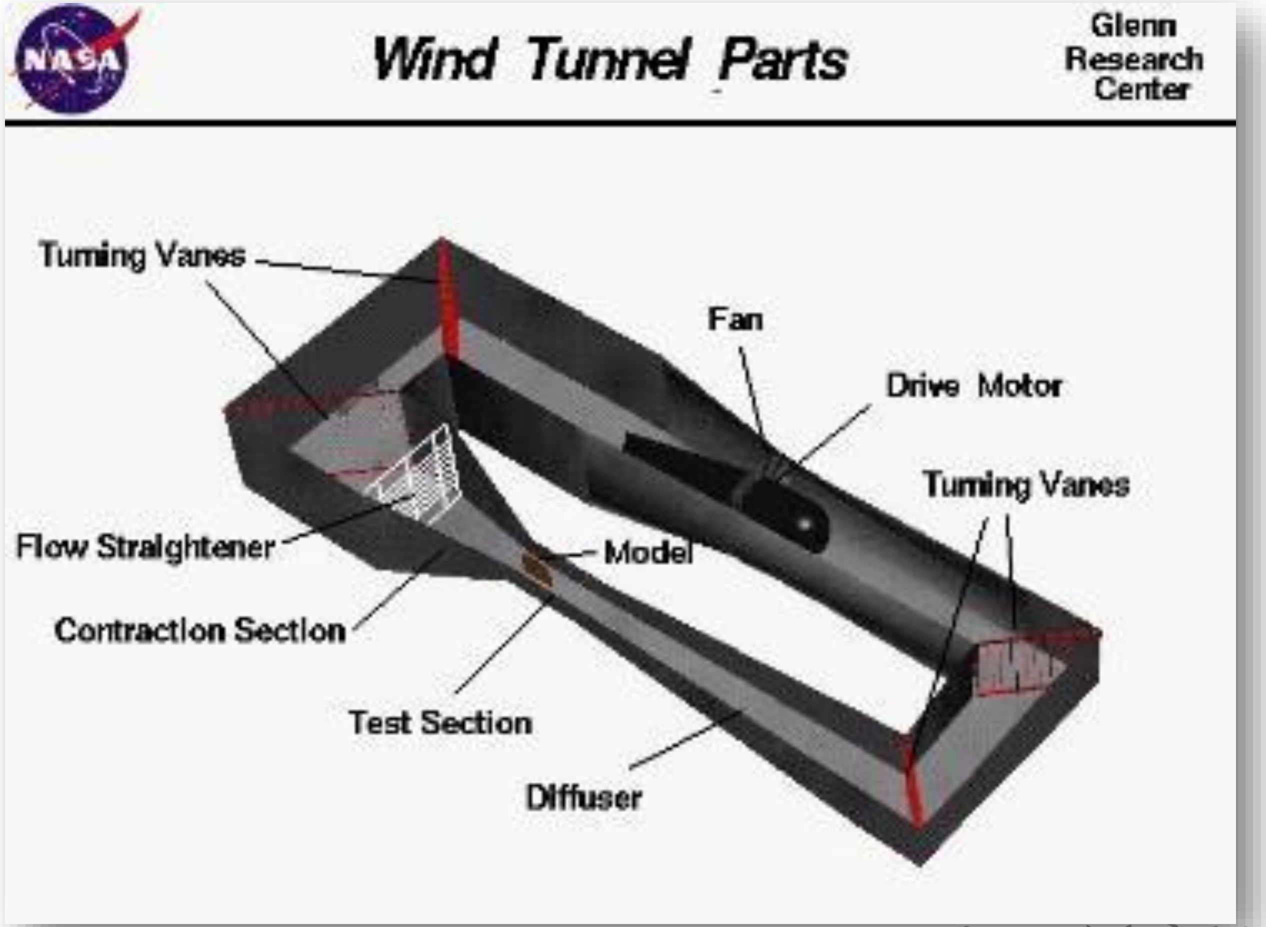
× Scaling issuing

× Cost- and time-consuming

Approaches

Experiment

- Facilities-**Wind Tunnel**



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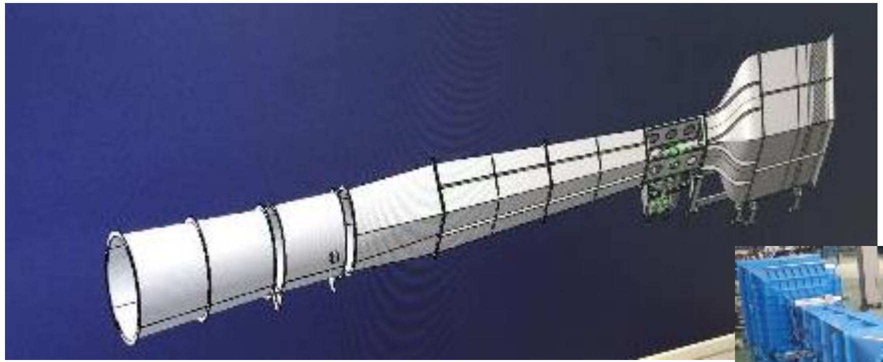
Approaches

Experiment

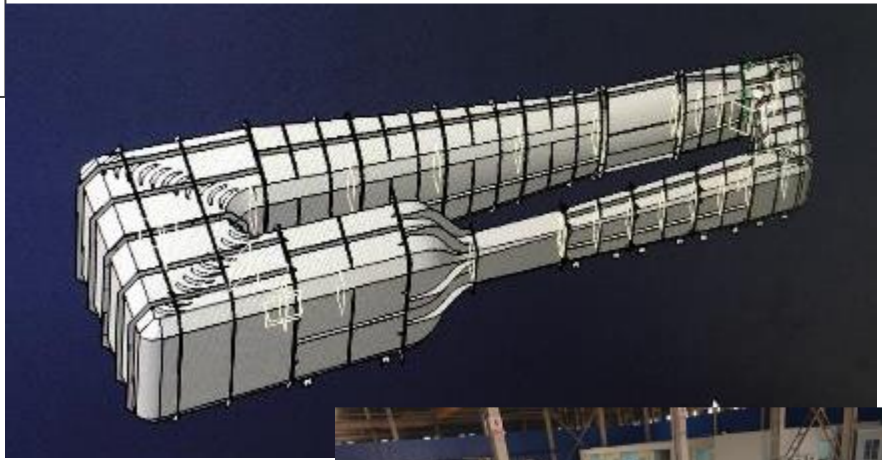
- Facilities-**Wind Tunnel**

School of Aeronautics & Astronautics, Sichuan University



Open return wind tunnel
(低速开口式风洞)

Closed return wind tunnel
(低速闭口式风洞)



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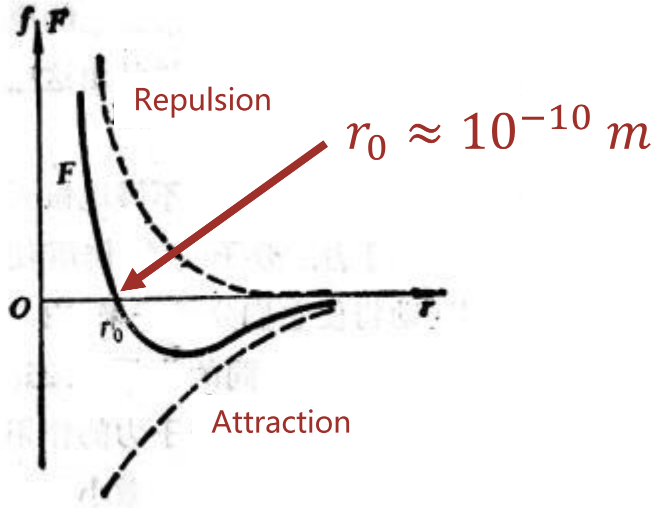
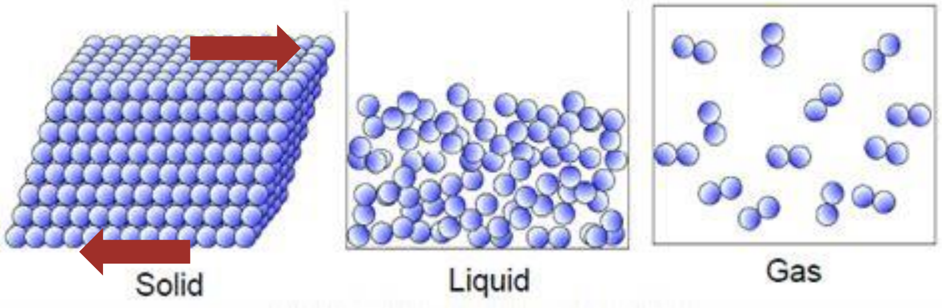
Continuum Hypothesis

The defining property of fluids

- Continuously increasing deformation under the act of tangential shear stress
- the shear stress is proportional to the rate of change of the deformation

Sketch of the force exerted by one (un-ionized) simple molecule on another as a function of the distance r between their centers.





The properties of fluids are directly related to their molecular structure and to the nature of the forces between the molecules

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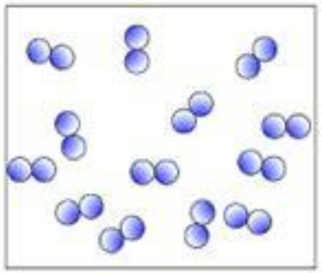
Continuum Hypothesis

On a microscopic scale

- Fluid consists of individual molecules
  - Vacuous regions between molecules of a gas – Mean free path (平均自由程) l
  - In standard atmosphere, $l = 6\times10^{-8}$ m for air
  - Diameter of air molecules $d = 3.7\times10^{-10}$ m

$$\frac{l}{d} \approx 160$$



Gas

- Fluid substance is sparse (稀疏的)
- Its motion is non-uniform (不均匀的), discrete (离散的) and random(随机的)

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Continuum Hypothesis

The Continuum Hypothesis

- **On a macroscopic scale**, the fluid properties (e.g., velocity, pressure, density) are uniform, continuous and definite
- There is huge difference in the length scales of the problem
  - The length scale L in aerodynamics is much larger than the mean free path l

$$\frac{l}{L} \ll 1$$

  - The behavior of individual molecular has no effect on the observed average properties

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Continuum Hypothesis

The Continuum Hypothesis

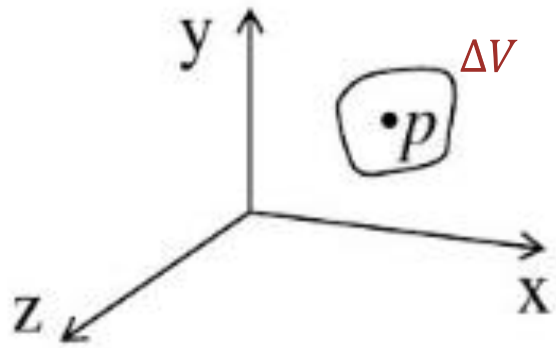
- Considering **the definition of density** as mass per unit volume

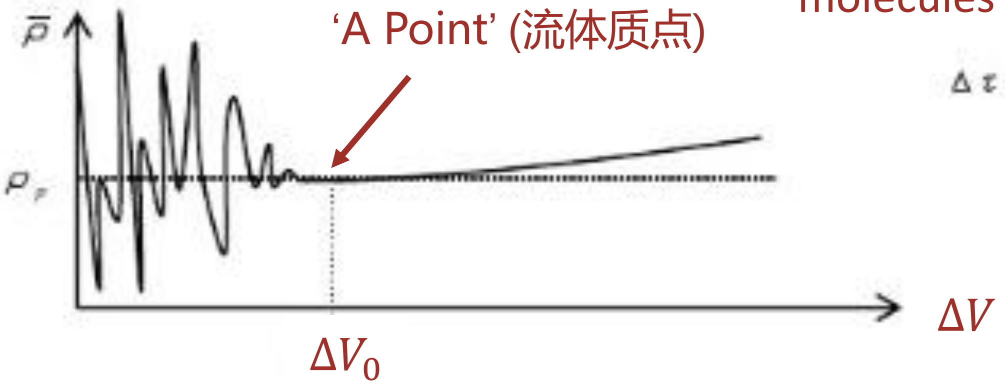
$$\rho_p = \lim_{\Delta V \to 0} \frac{\Delta m}{\Delta V}$$

For Air:

$\Delta V_0 = 10^{-9} m^3$

With about 3×10^7 molecules



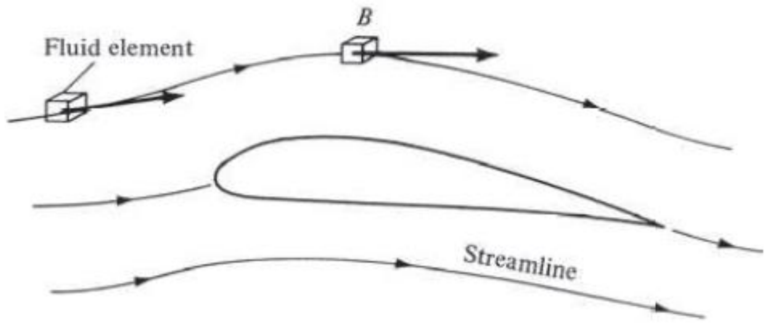


A critical value ΔV_0, below which molecular variations assume importance, and above which one finds a macroscopic variation of density within the region.

Continuum Hypothesis

The Continuum Hypothesis

- **Fluid element** (流体微团): an infinitesimally small element of mass in the gas



- The **velocity** ***U*** of a flowing gas at any fixed-point *B* in space is the velocity of an infinitesimally small fluid element as it sweeps through *B*
  - ***U*** is a vector

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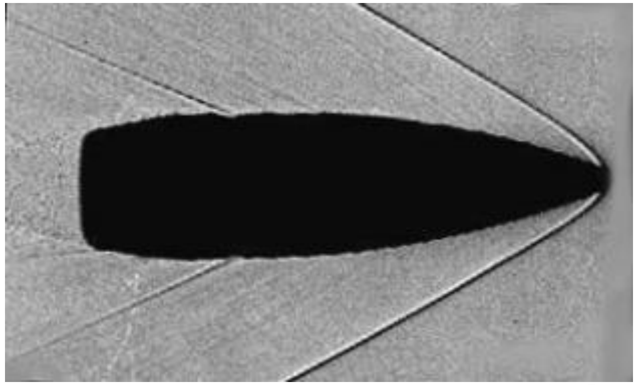
Continuum Hypothesis

- **Knudsen number** $$Kn = \frac{l}{L}$$
  - When $Kn \ll 1$, the continuum hypothesis is satisfied.
  - Named after Danish physicist **Martin Knudsen** (1871–1949).
- Other extreme cases
  - At greater altitudes, $Kn \sim 1$, rarefied gasdynamics
  - Shock wave is typically regarded as a discontinuous surface.



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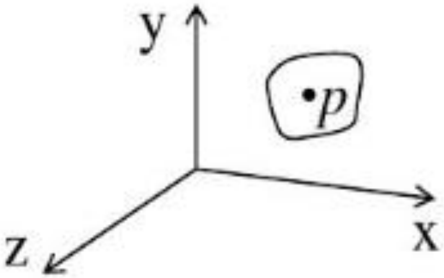
Continuum Hypothesis

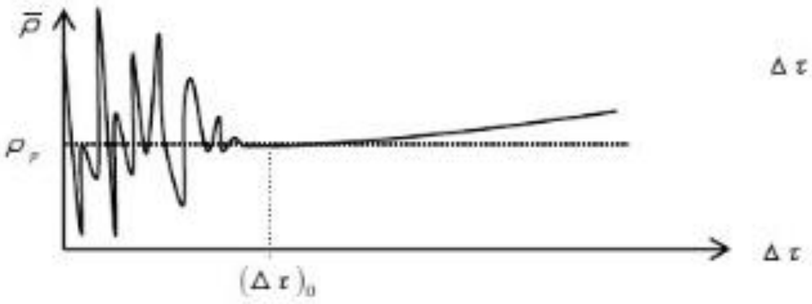
Question

Under the continuum hypothesis, the fluid density is defined as

$$\rho_p = \lim_{\Delta V \to 0} \frac{\Delta m}{\Delta V}$$

Please explain the physical and mathematical meanings of ‘0’ in the limit $\Delta V \to 0$?





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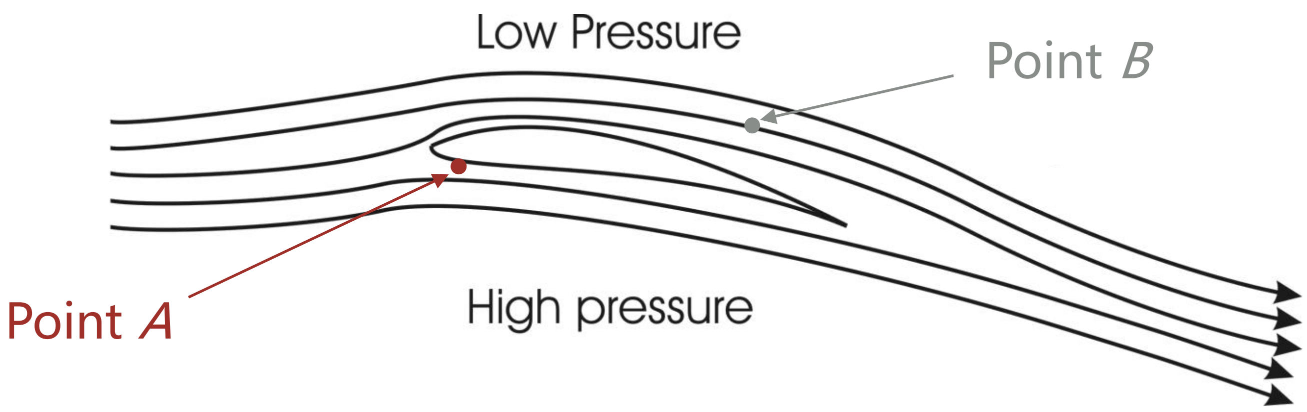
Properties of Fluids

Pressure (压强)

- Normal force per unit area exerted on a surface due to the time rate of change of momentum of the gas molecules impacting on (or crossing) that surface

$$p = \lim_{\Delta A \to 0} \frac{\Delta F}{\Delta A}$$

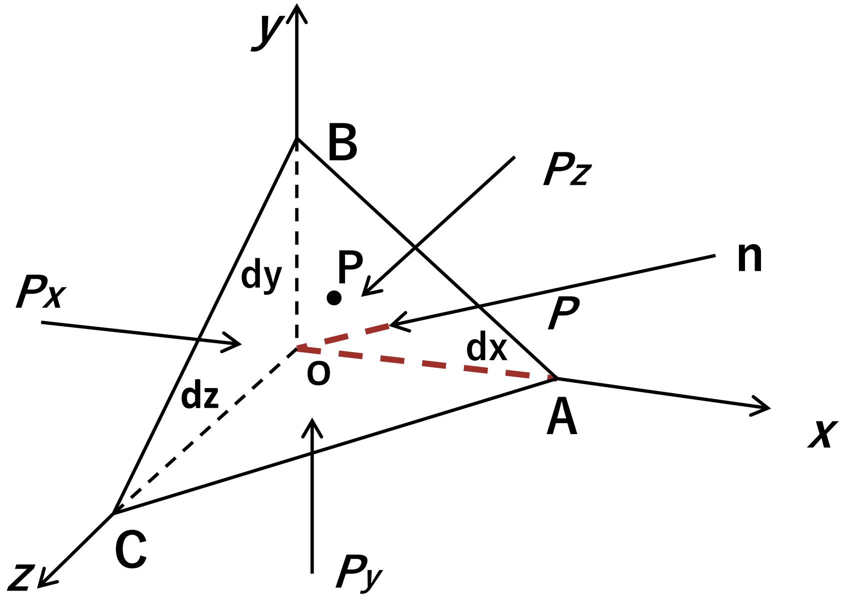


Properties of Fluids

Pressure (压强)

- Dimensions (量纲): force per unit area, or $\{ML^{-1}T^{-2}\}$
- Direction: always acts inward normal to any surface

Question: Does the pressure depend on the direction of the surface on which it acts?



Properties of Fluids

Pressure (压强)

- Dimensions (量纲): force per unit area, or $\{ML^{-1}T^{-2}\}$
- Direction: always acts inward normal to any surface
  - The magnitude of pressure is **independent** of the orientation of the surface on which the pressure acts.
- Pressure is a scalar (point property).

$$p = p(t, x, y, z)$$

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Properties of Fluids

Temperature T

- A measure of the average kinetic energy of the random motion of the molecules of the fluid at a point

$$KE = \frac{3}{2}kT$$

where KE is the mean molecular kinetic energy and k is the Boltzmann constant.

- Temperature is a scalar quantity (magnitude, no direction)
- Unit: **Kelvin (K)**, as an absolute measure of thermal energy

$$T_{(K)} = T_{(°C)} + 273.15$$

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Properties of Fluids

Ideal Gas Law

- The equation of state of a hypothetical ideal gas.
  - R is the specific gas constant

$$p = \frac{\bar{R}}{M}\rho T = \rho R T$$

$\bar{R}$: Universal gas constant (8314 J/mol.K)
M: Molecular weight

- The standard atmospheric condition at sea level

For air, $R = 287.15\, J/(kg \cdot K)$

$$p_s = 1.01325 \times 10^5\ N\, m^{-2} = 1\text{atm} = 0.1\text{MP}$$

$$\rho_s = 1.225\ kg\, m^{-3} \qquad T_s = 288.15\ K = 15°\text{C}$$

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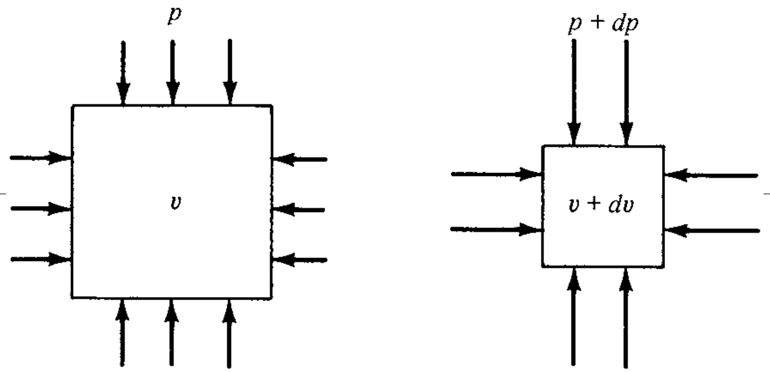
Properties of Fluids



Compressibility (可压缩性)

- A measure of the relative volume change of a fluid as a response to a pressure (or mean stress) change.
  - Specific Volume (比体积): the volume per unit mass

$$v = \frac{1}{\rho} \Rightarrow dv = -\frac{1}{\rho^2} d\rho$$

  - Bulk Modulus (体积弹性模量) determines how compressible a fluid is
    - Higher the value of Bulk Modulus indicates that it is difficult to compress the fluid

$$E_v = -\frac{dp}{dv/v} = \rho \boxed{\frac{dp}{d\rho}}$$

The speed of sound $c^2 = \boxed{\frac{dp}{d\rho}}$

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Properties of Fluids

$$E_v = \rho \frac{dp}{d\rho} \qquad c^2 = \frac{dp}{d\rho}$$

Compressibility (可压缩性)

- Bulk Modulus for different fluids
  - Water: $E_{v\_w} = 2.16 \times 10^9\ N/m^2$
  - Air: $E_{v\_a} = 1.01{\sim}1.42 \times 10^5\ N/m^2$
- Speed of sound for different fluids
  - Water: $c_w \approx 1481\ m/s$
  - Air: $c_a = 340.27\ m/s$

At standard atmospheric condition

- All real substances (fluids or solids) are compressible to some greater or lesser extent

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Properties of Fluids

Compressibility (可压缩性)

- Compressibility of a fluid **flow** (流动的可压缩性)
  - Whether the density ρ can be regarded as a constant in the flow

$$E_v = \rho \frac{dp}{d\rho} \Longrightarrow d\rho = \frac{1}{E_v}\rho dp$$

  - For liquid, E_v is typically very large. Therefore, $d\rho$ will be negligibly small

The flow of a liquid is incompressible

  - For gas, E_v is typically small

  - Mach Number:

$$Ma = \frac{U}{c}$$

High speed flow: dp is large, $d\rho$ can be large — compressible

Low speed flow: $Ma < 0.3$ — dp is small, $d\rho$ can be small, $d\rho/\rho < 5\%$ — incompressible

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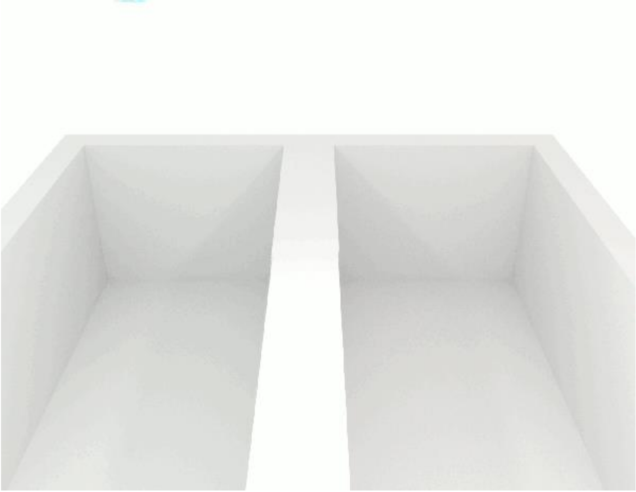
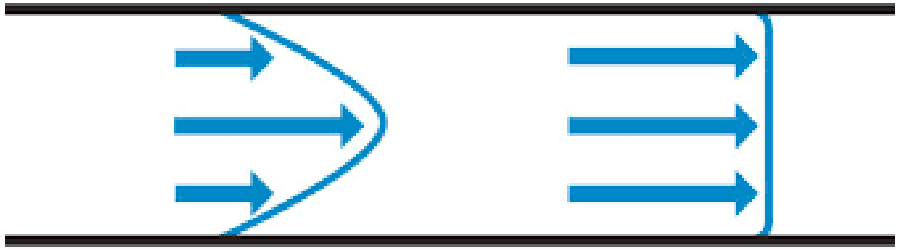
Introduction to Viscous Flow

- **Viscous Flow (黏性流动)**
  - A flow where the effects of viscosity, thermal conduction, and mass diffusion are important, viscous flow are rotational flows.
  - Viscosity: a measure of its resistance to deformation at a given rate.
  - Thermal conduction: the transfer of internal energy by microscopic collisions of particles and movement of electrons within a body or between two bodies in contact.
  - Mass diffusion: the transport of material due to concentration gradients (less considered in this course).



Low viscosity vs. high viscosity



High viscosity vs. low viscosity

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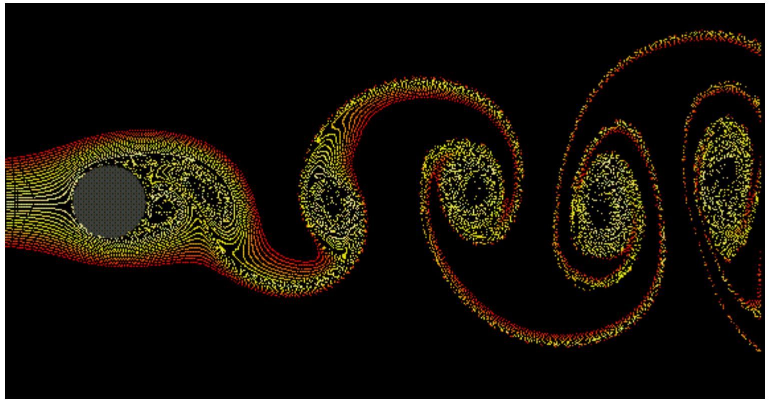
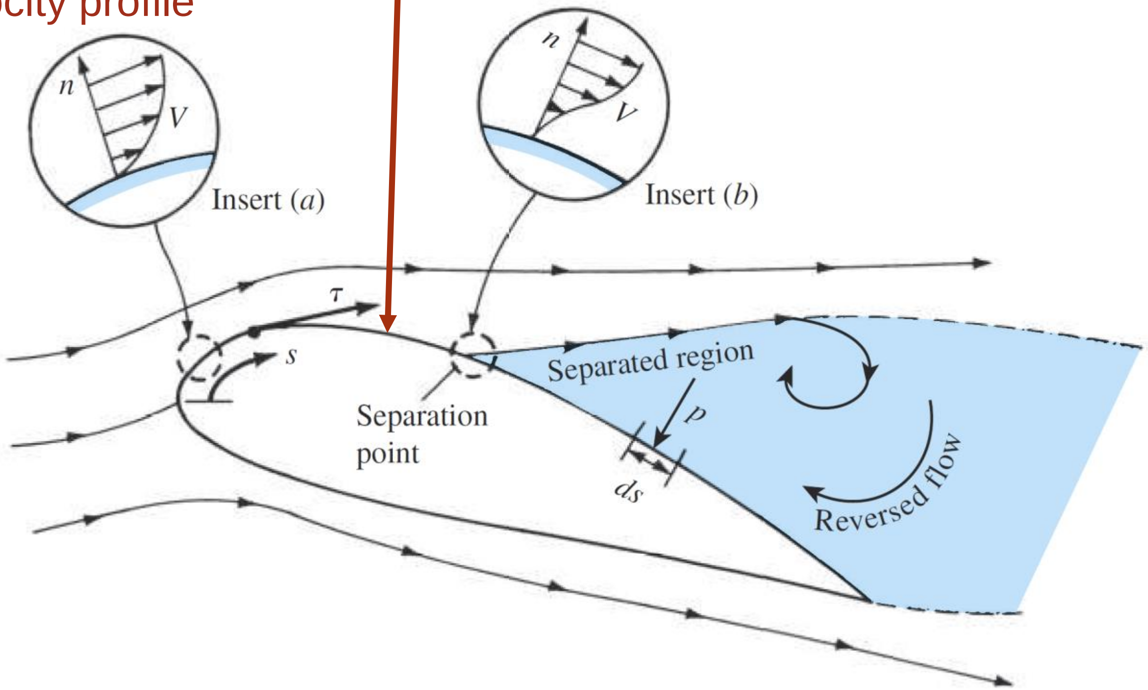
Introduction to Viscous Flow

- **Influence of viscosity**
  - Shear stress τ: tangential 'frictional ' force per unit area.
  - No-slip condition: $V = 0$ at wall surface.
  - Reverse flow cause by adverse pressure gradient.
  - Separated flow: detachment of a boundary layer from a surface into a wake ($\partial V/\partial n = 0$).



The Von Karman vortex street



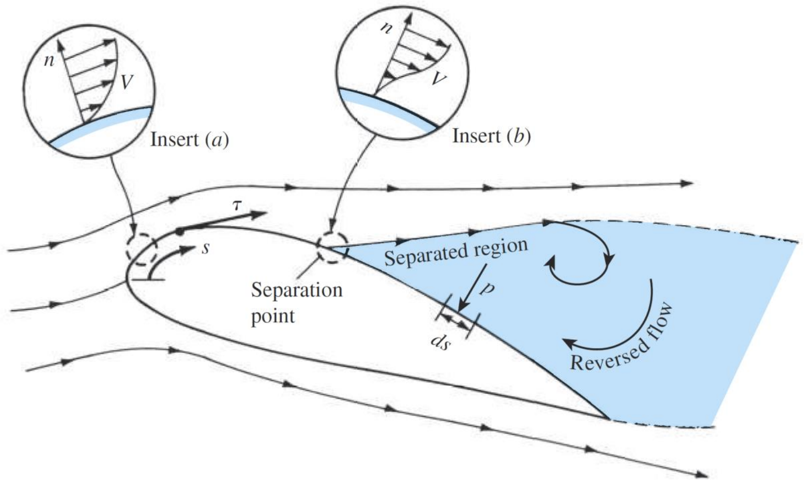
Effect of viscosity on a body in a moving fluid

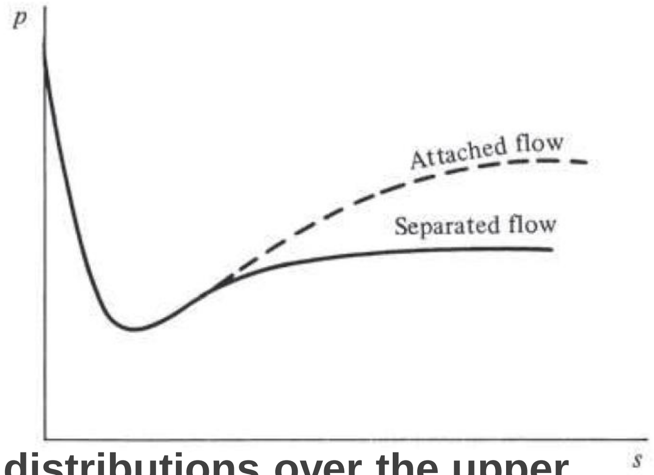
Introduction to Viscous Flow

- **Influence of viscosity**
  - Skin friction drag D_f: the component in the drag direction of the integral of the shear stress τ over the body.
  - Pressure drag due to separation D_p: the component in the drag direction of the integral of the pressure distribution over the body.

$D_p \longrightarrow$ form drag (形状阻力)

$D_f + D_p \longrightarrow$ 2D: profile drag (型阻); 3D: parasite drag (寄生阻力)





The pressure distributions over the upper surface of the body

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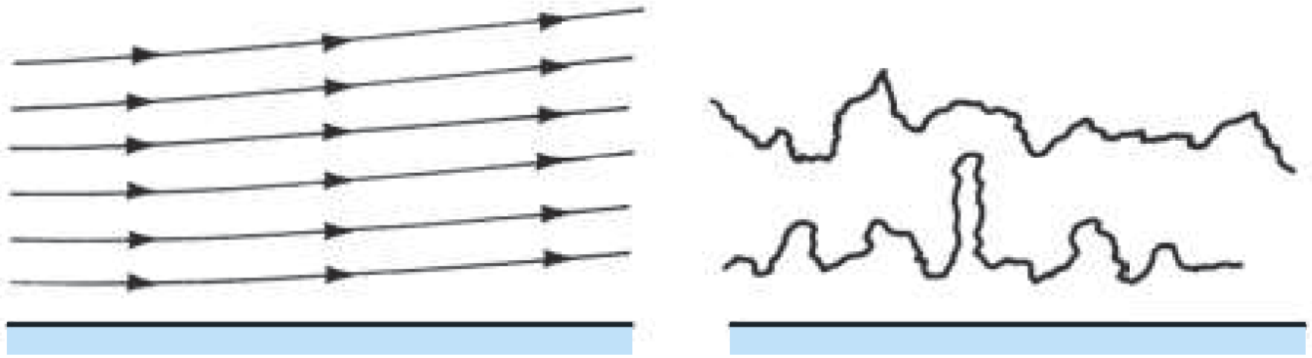
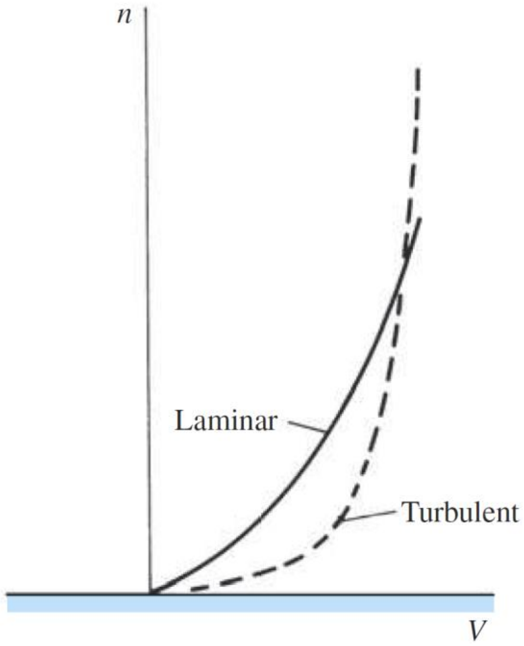
Introduction to Viscous Flow

- **Flow State (流动状态)**
  - Laminar flow: the path lines of various fluid elements are smooth and regular.
  - Turbulent flow: the motion of a fluid element is very irregular (不规则的) and tortuous (弯弯曲曲的).

$$\left[\left(\frac{\partial V}{\partial n}\right)_{n=0}\right]_{\text{turbulent}} > \left[\left(\frac{\partial V}{\partial n}\right)_{n=0}\right]_{\text{laminar}}$$



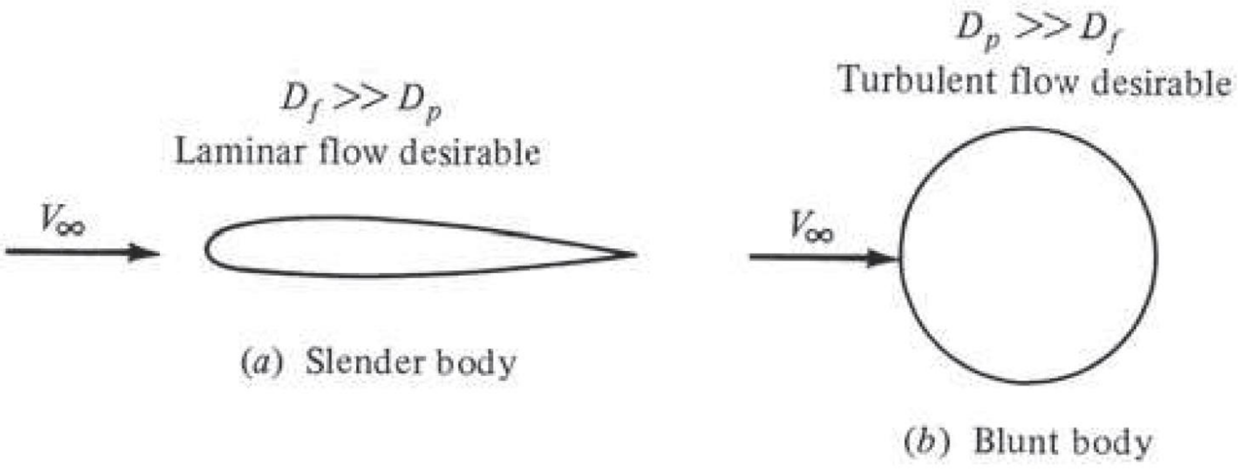
(*a*) Laminar flow (*b*) Turbulent flow



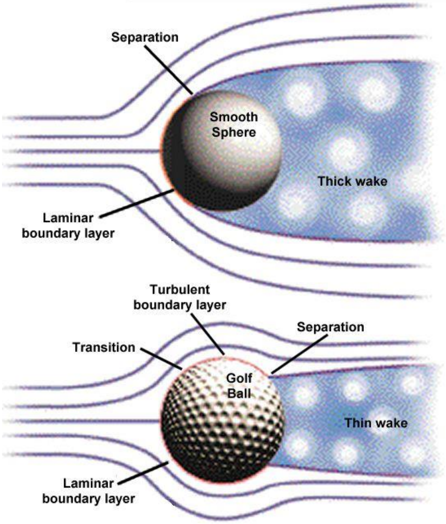
Introduction to Viscous Flow

- **Viscosity flows over different bodies**
  - Laminar flow is preferable for slender bodies (细长体).
  - Turbulent flow is preferable for blunt bodies (钝体)

$$\boxed{D = D_f + D_p}$$



Why there are dimples on the golf ball?



Answer: To delay the flow separation so to reduce the pressure drag

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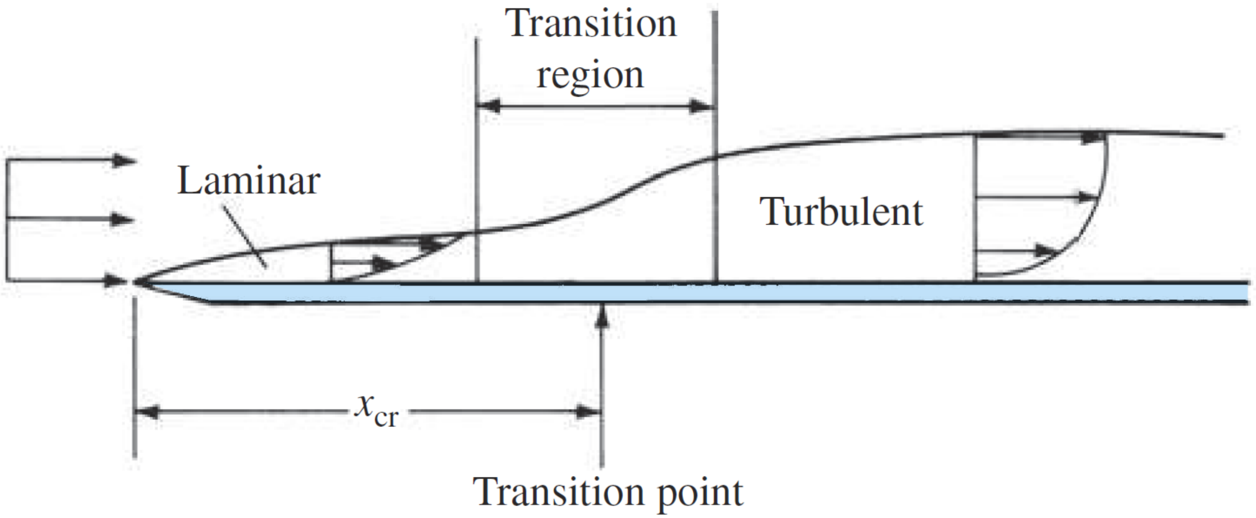
Introduction to Viscous Flow

- **Transition from laminar to turbulent flow (how to control?)**
  - Increased surface roughness (表面粗糙度).
  - Increased turbulence in the freestream.
  - Adverse pressure gradients.
  - Heating of the fluid by the surface.



For practical aerodynamic applications,

$$Re_{cr} = \frac{\rho_\infty V_\infty x_{cr}}{\mu_\infty} \longrightarrow \begin{cases} < 500{,}000\text{: laminar} \\ > 500{,}000\text{: turbulent} \end{cases}$$

Critical Reynolds Number

For pipe flow (管流),

$$Re_{cr} = \frac{\rho VD}{\mu} \longrightarrow \begin{cases} < 2{,}000\text{: laminar} \\ > 5{,}000\text{: turbulent} \end{cases}$$

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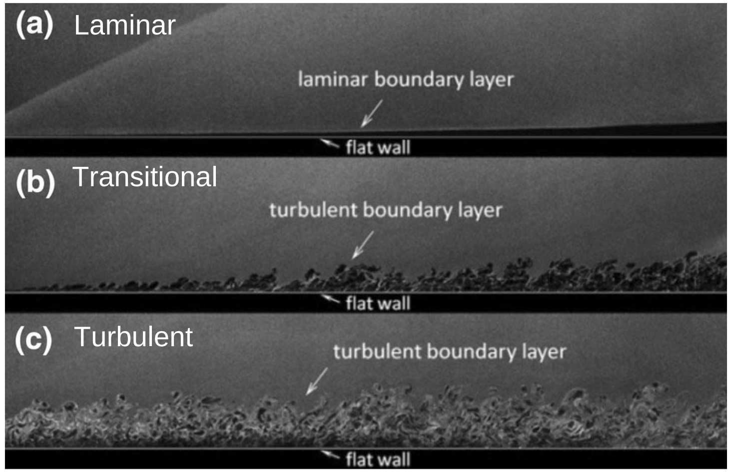
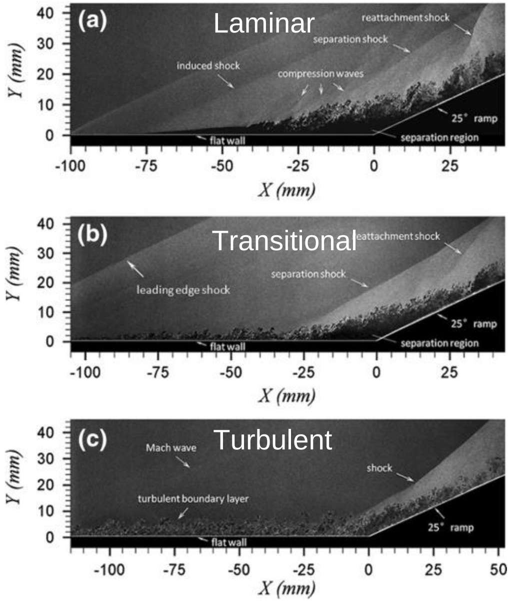
Introduction

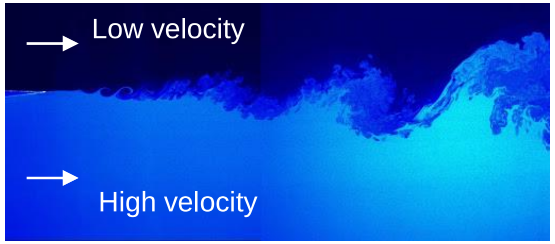
- **Boundary Layer**
  - The thin region of flow adjacent to a surface, where the flow is retarded by the influence of friction between a solid surface and the fluid.

- **Shear Layer**
  - A layer of flow where a shear or velocity gradient exists. Boundary layer is also a form of shear layer, but shear layer is often used in fluid-fluid interactions.



Different boundary layers.

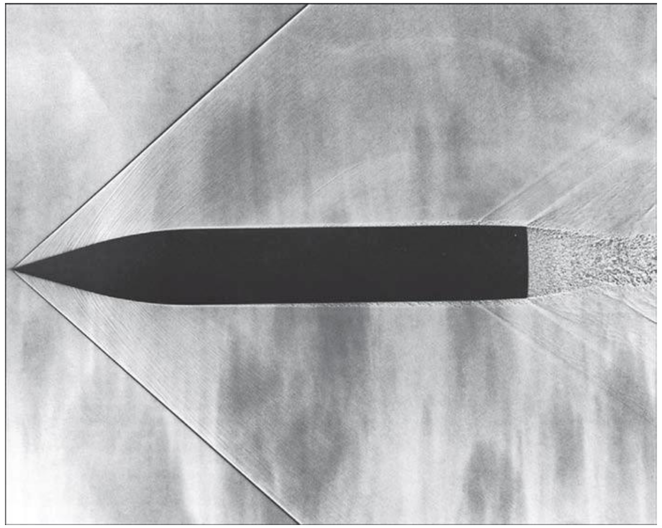




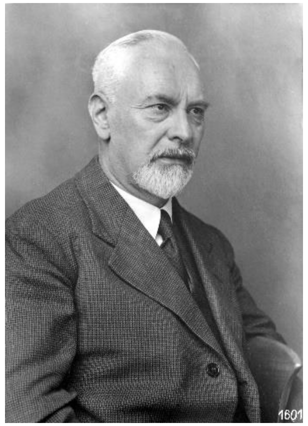
An example of shear layer.

Introduction

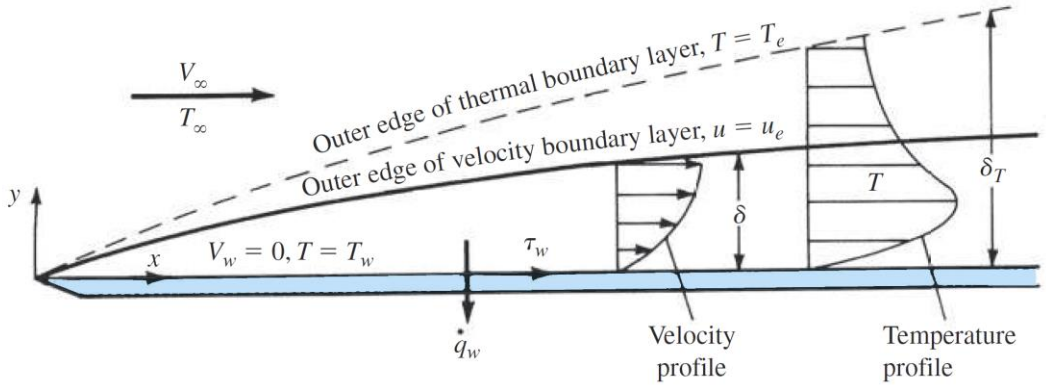
- **Boundary Layer**
  - Using Prandtl's concept of a boundary layer adjacent to an aerodynamic surface, the Navier-Stokes equations can be reduced to a more tractable (容易处理的) form called the boundary-layer equations.
  - Prandtl's boundary-layer concept was an advancement in the science of fluid mechanics of the caliber of a Nobel prize, although he never received that honor.



Boundary layer on an aerodynamic body.



Ludwig Prandtl



Boundary layer on a flat plate.

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Outlines

- Approaches for Fluid Mechanics
- Continuum Hypothesis
- Properties of Fluids
  - Viscous Flow
- **Fluid Statics and Motion**
- A Brief Review of Thermodynamics
- Some Aspects of Supersonic Flow: Shock Waves
- Compressible Flow and Hypersonic Flow

Fluid Statics

The type of forces

- The forces that could act on fluid elements are be divided into two categories

Forces

Surface Force	Body Force
Pressure, Shear Stress, etc.	Gravity, inertia, electromagnetic forces, etc.

- **Surface forces** are exerted to the surface of an object
  - Brought about by contact of fluid with another fluid or a solid body
- **Body forces** are distributed on every portion of the body they act on
  - Depend upon the mass of the substance

Fluid Statics

Hydrostatic equation

- Application: **U-Tube Manometer**

$$p + \rho g h = Const. \qquad (1.54)$$

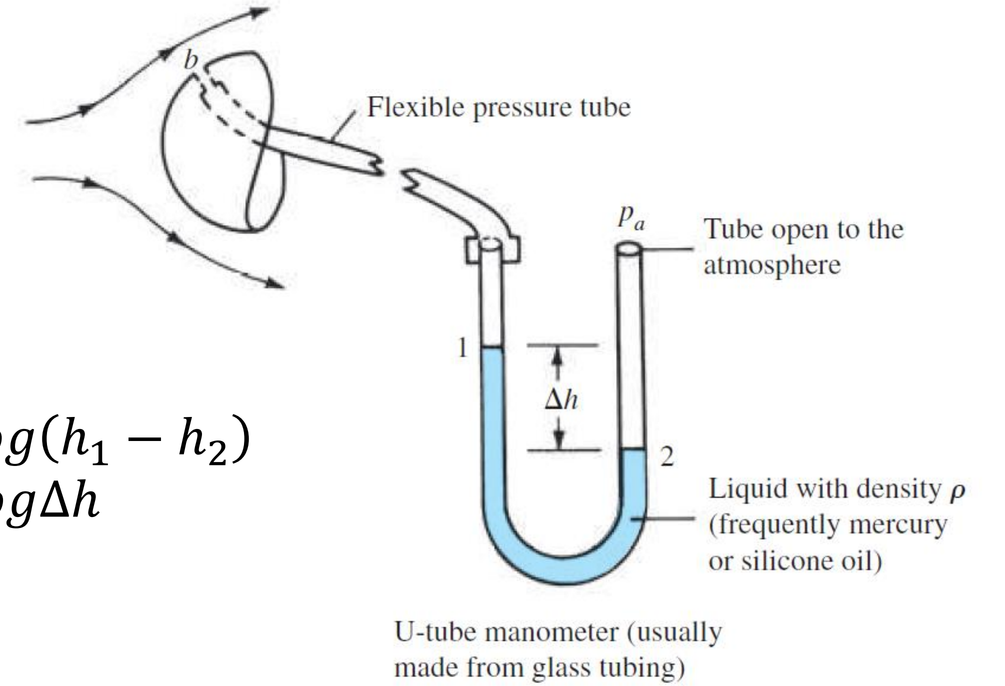
★ $p_1 + \rho g h_1 = p_2 + \rho g h_2$

$\Longrightarrow$ $p_1 = p_2 - \rho g(h_1 - h_2)$

★ $p_1 \approx p_b; p_2 \approx p_a$

(because $\rho_{air} \ll \rho_{liquid}$)

$$p_b = p_a - \rho g(h_1 - h_2) = p_a - \rho g \Delta h$$



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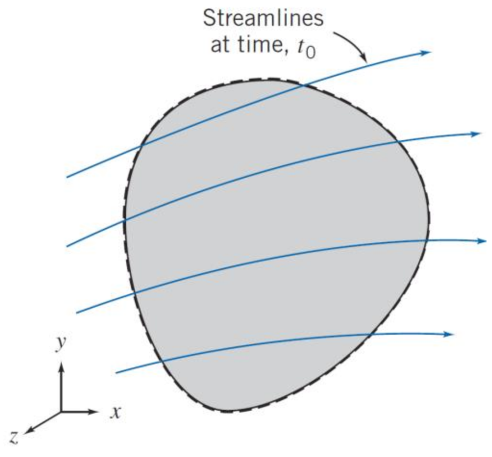
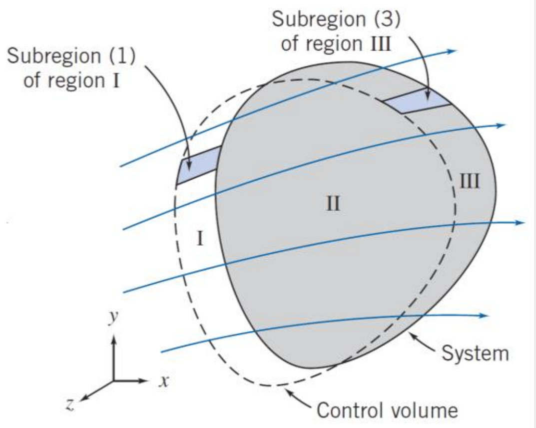
Fluid Motion

- Conservation of Mass
  - Uniform Flow Through a Control Volume
  - Non-uniform Flow Through a Control Volume
- Linear Momentum
  - Forces Acting on a Flow Through a Control Volume
  - Differential Analysis and the Bernoulli Equation
  - Constant Velocity Through a Control Volume
- Principle of Angular Momentum
  - Fixed Control Volume
- Moving Control Volume
  - Constant Velocity
  - Acceleration



(a) Time, t_0



(b) Time, $t_0 + \Delta t$

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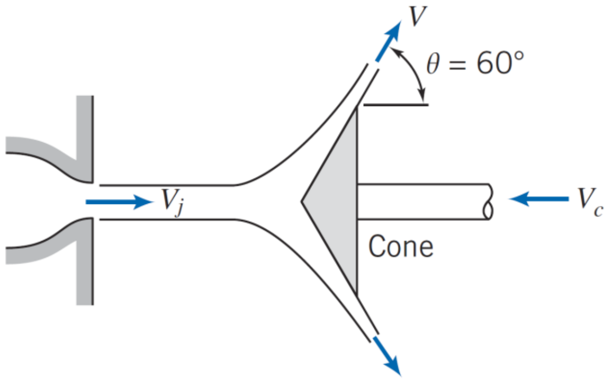
Fluid Motion

Question 1

Water moving at 30 m/s from a 100 mm jet is deflected by a cone moving at 14 m/s. Find the thickness of the jet at a distance of 230 mm from the center of the cone and the force to move the cone.

- Hint : mass conservation

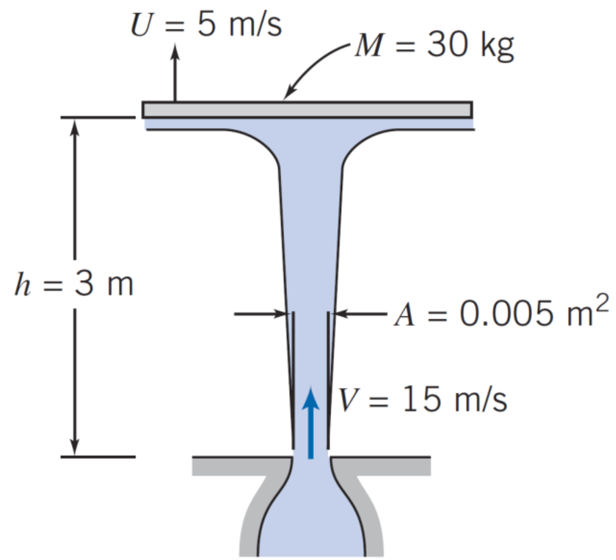


Fluid Motion

Question 2

Water from a jet hits a horizontal disk that will be moving upward at 5 m/s when it is 3 m above the nozzle exit. What is the vertical acceleration of the disk at this point?

- Hint 1: proper selection of control volume
- Hint 2: Bernoulli's Equation
- Hint 3: mass conservation
- Newton's second law and momentum equation



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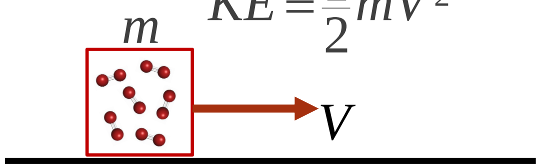
A Brief Review of Thermodynamics

- Perfect gas
  - A gas which the intermolecular forces are neglected
  - Equation of state $\boxed{p=\rho RT,\ R=287\ \mathrm{J/(kg{\cdot}K)}}$

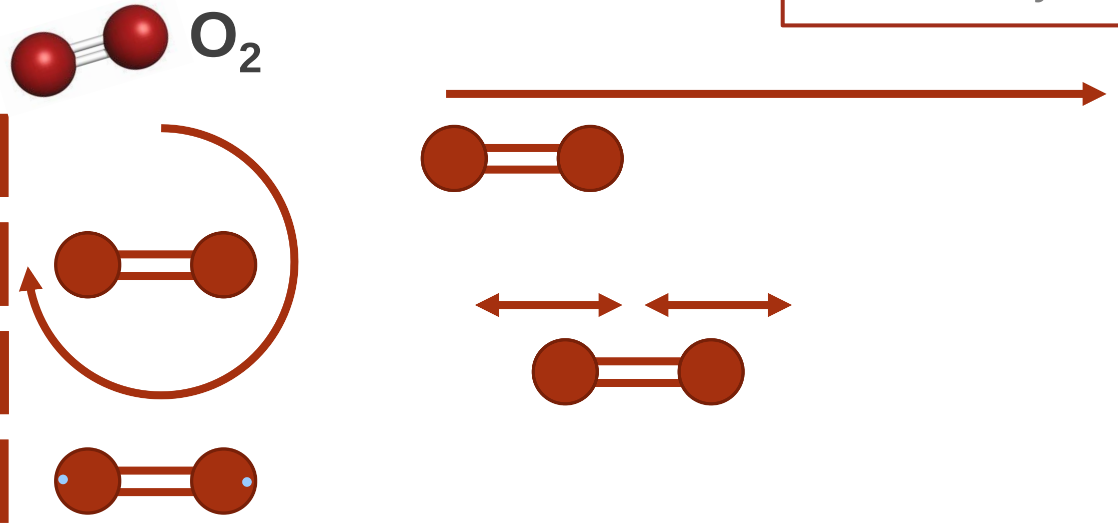
$$KE=\frac{1}{2}mV^2$$



- Internal energy (e)
  - Summation of the energies of all molecules (in random motions) in a system.

- Kinetic energy 动能
  - Macro system motions

Internal energy
- Translational 平移
- Rotational 旋转
- Vibrational 振动
- Electronical 电子运动



A Brief Review of Thermodynamics

- Enthalpy
  - The sum of the system's internal energy and the product of its pressure and volume.

$$\boxed{h = e + pv}$$

  - For a perfect gas, both e and h are functions of temperature only

$$e = e(T) = c_v T \qquad h = h(T) = c_p T$$

  - Calorically perfect gas: a perfect gas where c_v and c_p are constant.
  - Mayer’s relation for ideal gas: $\boxed{c_p - c_v = R}$
  - Heat capacity ratio: $\gamma \equiv c_p / c_v$

$$\boxed{c_p = \frac{\gamma R}{\gamma - 1}} \qquad \boxed{c_v = \frac{R}{\gamma - 1}}$$

  - For air at standard conditions (1 atm, 25 ℃), γ = 1.4.

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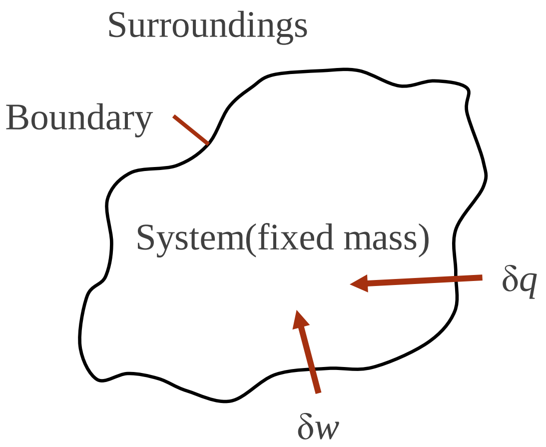
A Brief Review of Thermodynamics

- **First law of thermodynamics**



δq : An incremental amount of heat added to the system across the boundary

δw : The work done on the system by the surroundings

de : The change in energy of the system

$$\boxed{de = \delta q + \delta w = \delta q - p\,dv}$$

- Adiabatic process
  - No heat is added to or taken away from the system.
- Reversible process
  - No dissipative phenomena (effects of viscosity, thermal conductivity and mass diffusion) occur.
- Isentropic process
  - Both adiabatic and reversible.

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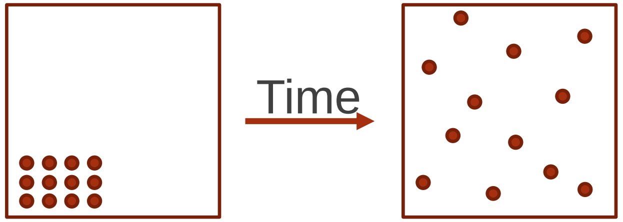
A Brief Review of Thermodynamics

- **Entropy**
  - The degree of randomness
  - The change in entropy (ideal) $ds = \frac{\delta q_{\text{rev}}}{T}$
  - δq_{rev} requires the difference in temperature between the heat source and the system has to approach zero, i.e., the transfer would have to occur infinitely slowly (quasi-statically).

$$\boxed{ds = \frac{\delta q}{T} + ds_{\text{irrev}}, \quad ds_{\text{irrev}} \geq 0}$$

- **Second law of thermodynamics**
  - The total entropy of an isolated system can never decrease over time, and is constant if and only if all processes are reversible.



$$\boxed{ds \geq 0}$$

- **Third law of thermodynamics**
  - The entropy of a system approaches a constant value as its temperature approaches absolute zero.

Disorder is more probable than order.

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A Brief Review of Thermodynamics

- **Isentropic relations**
  - Isentropic process is a process that is both adiabatic and reversible.

$$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1} = 0 \qquad s_2 - s_1 = c_v \ln \frac{T_2}{T_1} - R \ln \frac{v_2}{v_1} = 0$$

$$\frac{p_2}{p_1} = \left(\frac{\rho_2}{\rho_1}\right)^{\gamma} = \left(\frac{T_2}{T_1}\right)^{\gamma/(\gamma-1)}$$

  - A large amount of practical compressible flow problems can be considered as isentropic.
  - The flow outside the boundary layer can be assumed to be isentropic.
  - Within the boundary layer, entropy increases due to strong dissipative mechanisms of viscosity, thermal conduction and diffusion.
- **Third law of thermodynamics**
  - The entropy of a system approaches a constant value as its temperature approaches absolute zero.

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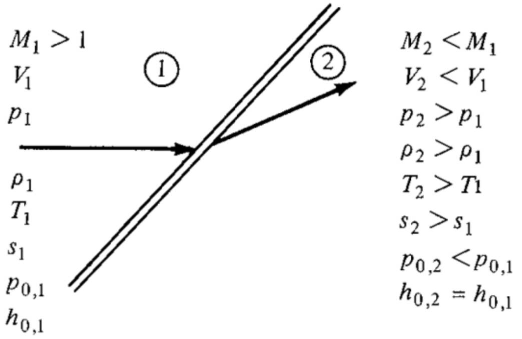
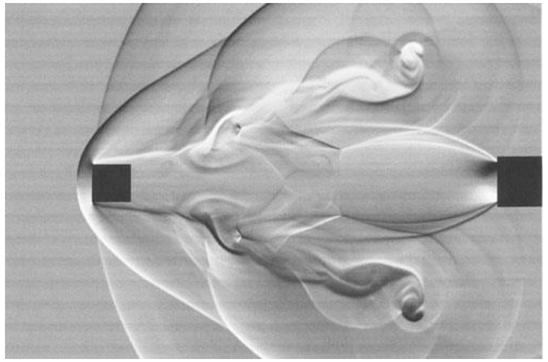
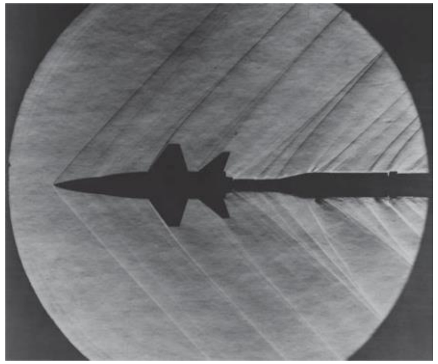
Some Aspects of Supersonic Flow: Shock Waves

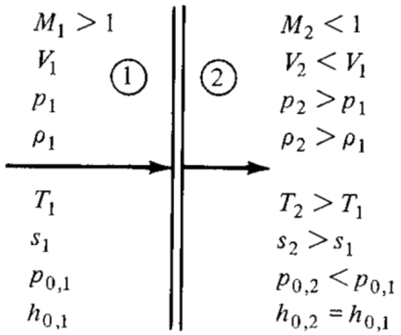
- Shock Wave
  - A type of propagating disturbance that moves faster than the local speed of sound in the medium.



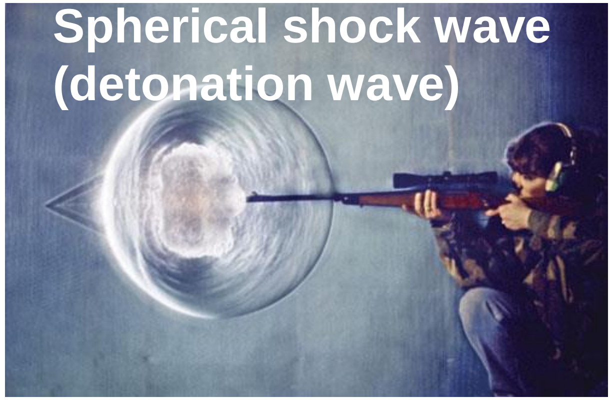
Oblique shock wave







Normal shock wave



Spherical shock wave (detonation wave)

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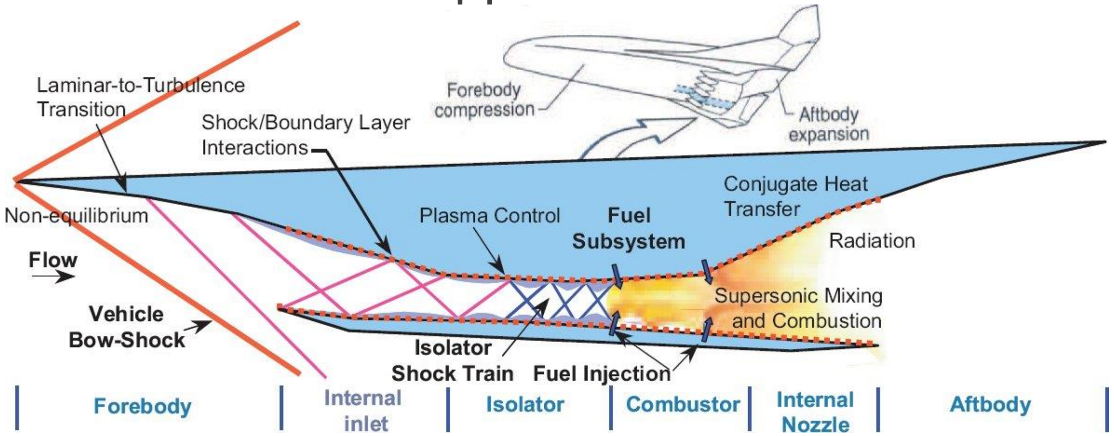
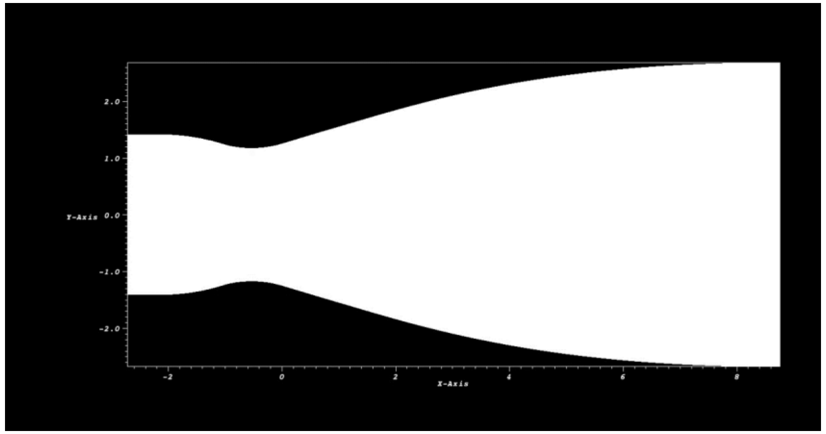
Some Aspects of Supersonic Flow: Shock Waves

- Shock waves in applications



Scramjet

Shock diamond



Startup of a rocket engine

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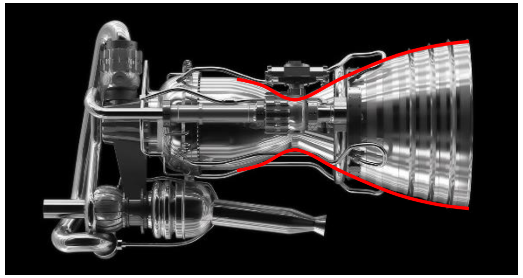
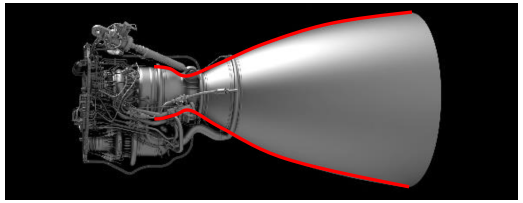
Compressible Flow and Hypersonic Flow

- **Compressible Flow Through Ducts (槽道)**
  - Nozzle (喷管): A duct to increase the flow velocity in the expense of pressure or internal energy.
  - Diffuser (扩压器): A duct to decrease the flow velocity.
  - Wind tunnel (风洞): combination of nozzles and diffusers to provide uniform supersonic flow for testing.
  - Quasi-one-dimensional flow (准一维流动): one with varied cross-sectional area in which all variables vary primarily along one direction.

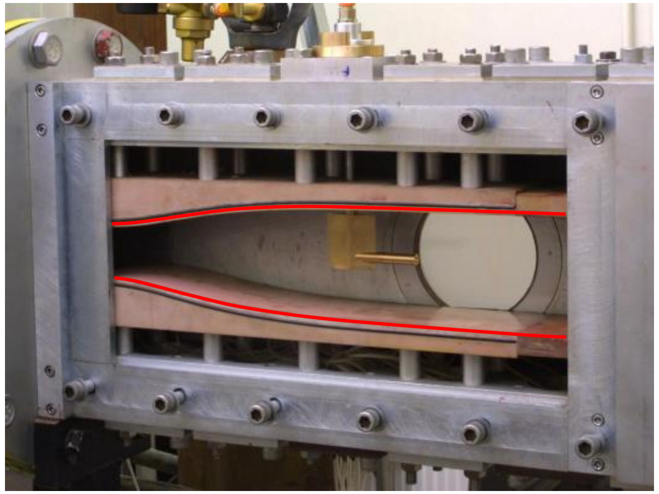
SpaceX's Merlin Engines in Falcon Heavy



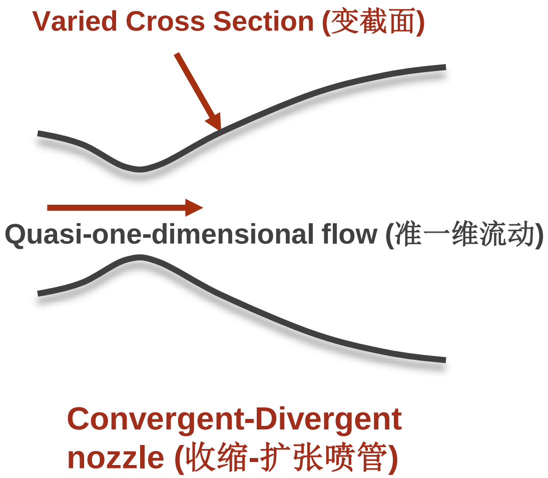
SpaceX's Merlin Engine



SpaceX's Raptor Engine



Supersonic Wind Tunnel of Imperial College London



Compressible Flow and Hypersonic Flow

- **Hypersonic Flow (高超音速流动)**
  - In aerodynamics, a hypersonic speed is one that greatly exceeds the speed of sound, often stated as starting at speeds of Mach 5 and above.
  - Classified as hypersonic aerodynamics.
  - Atmospheric reentry (to Earth, 地球大气再入), atmospheric entry (space exploration, 太空探索的大气进入), military applications
  - New phenomena arise when Mach number is sufficiently high.

Supersonic Vehicle: Chengdu J20

Hypersonic Vehicles: DF-17 missiles and hypersonic transportation concepts

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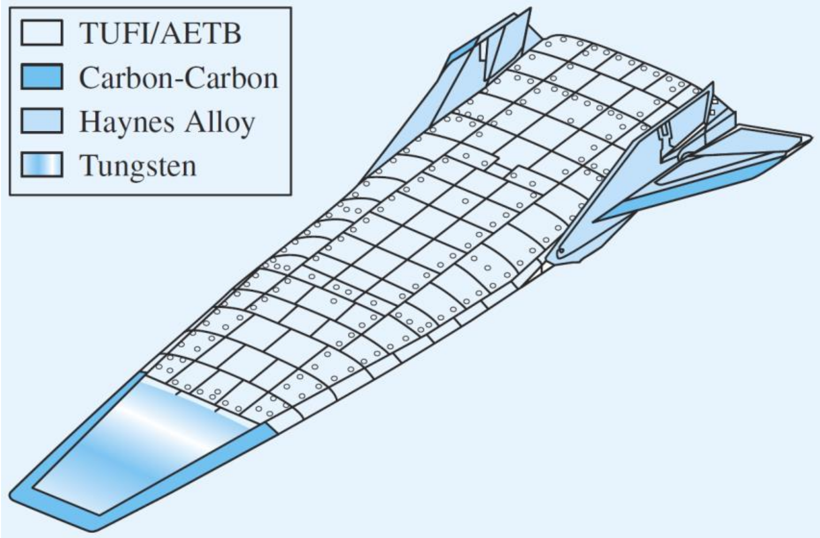
Compressible Flow and Hypersonic Flow

- **Hypersonic Vehicle: X-43 (NASA)**
  - An experimental unmanned (无人操纵的) hypersonic aircraft with multiple planned scale variations meant to test various aspects of hypersonic flight.
  - It was part of the X-plane series and specifically of NASA's Hyper-X program.
  - Rocket engine boosted and scramjet engine propelled.
  - The X-43 is the fastest aircraft on record at approximately Mach 9.6.

Supersonic Vehicle: NASA X-43



氧化铝增强热障 1500℃
碳碳复合材料 2600℃
海恩斯合金 1200℃
钨 1650℃

Thermal protection system of X-43

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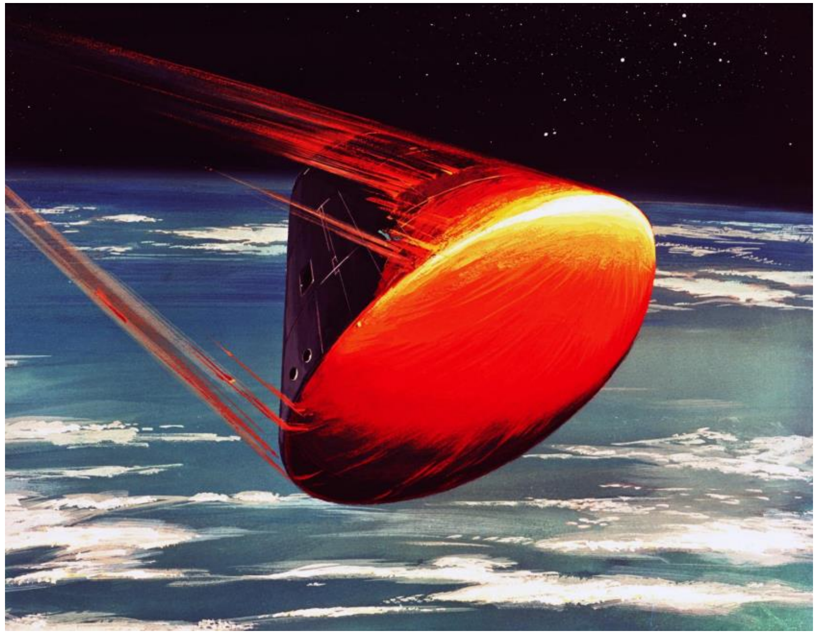
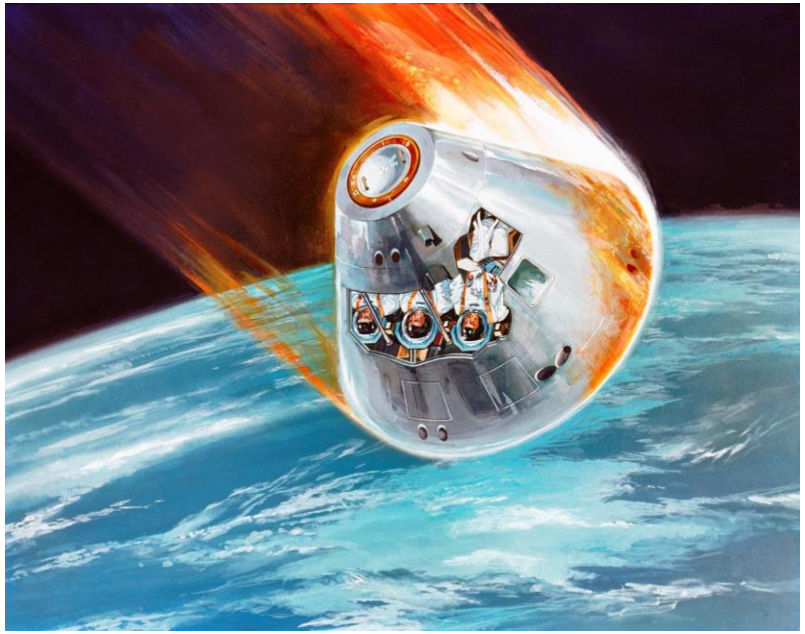
Compressible Flow and Hypersonic Flow

- **Hypersonic Vehicle: Atmospheric Reentry of Apollo 11**
  - On July 24, 1969, Apollo 11 splashed down in Earth’s oceans, successfully completing the return trip from moon with human beings (1969 crewed lunar mission, 载人登月任务).
  - Reentering the atmosphere at Mach 36.





The reentry of Apollo 11 (artwork)

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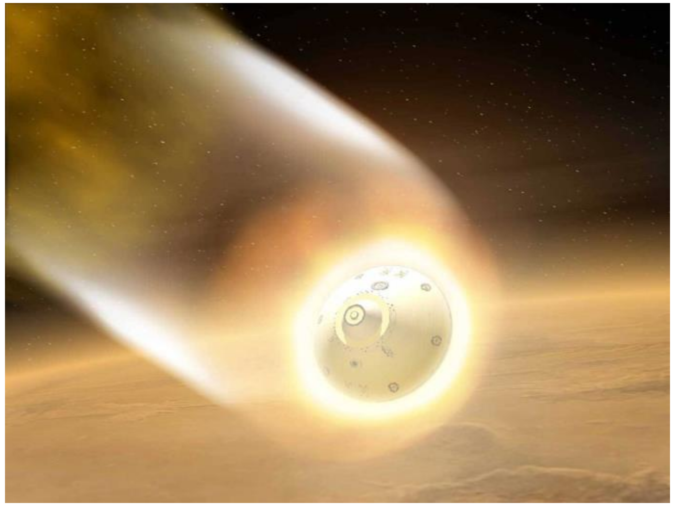
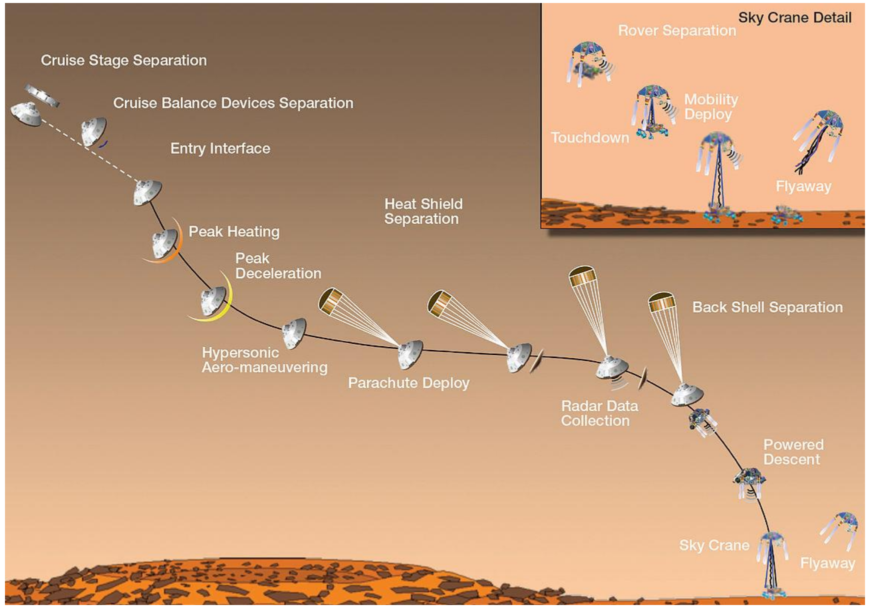
Compressible Flow and Hypersonic Flow

- **Hypersonic Vehicle: Atmospheric Entry of Space Exploration Probe/Rover (太空探索探测器/探测车)**
  - Curiosity Rover landed on Mars on August 2012.
  - Galileo Jupiter Atmospheric Probe entered Jupiter on December 1995.



The entry of Mars CO_2-N_2 atmosphere (artwork)

The entry of Jupiter H_2-Ne-CH_4-NH_3 atmosphere (artwork)



The entry of Curiosity Rover into Mars

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Question 3

Which would you prefer for our class?

1. More lecture, homework is assigned after class;

2. Less lecture, in-class homework.

Fluid Motion

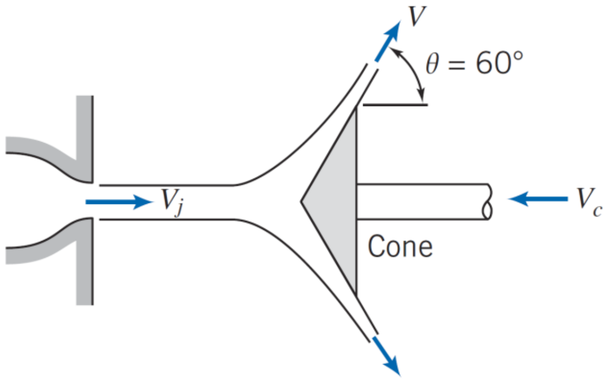
Question 1

Water moving at 30 m/s from a 100 mm jet is deflected by a cone moving at 14 m/s. Find the thickness of the jet at a distance of 230 mm from the center of the cone and the force to move the cone.

$$\rho V_1 A_1 = \rho V_2 A_2$$

$$\rho (V_j + V_c) \frac{\pi D_j^2}{4} = \rho (V_j + V_c)(2\pi R t)$$

$$t = \frac{D_j^2}{8R} = \frac{100}{8 \cdot 230} = 5.435 \text{ mm}$$

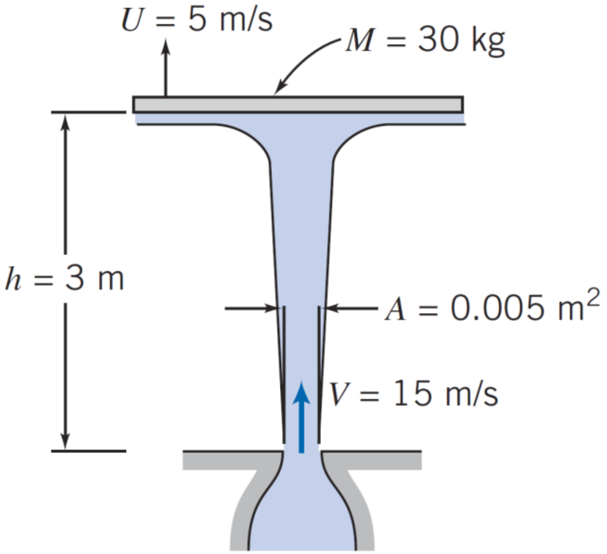


Fluid Motion

Question 2

Water from a jet hits a horizontal disk that will be moving upward at 5 m/s when it is 3 m above the nozzle exit. What is the vertical acceleration of the disk at this point?

$$\frac{p_0}{\rho}+\frac{V_0^2}{2}+gz_0=\frac{p_1}{\rho}+\frac{V_1^2}{2}+gz_1 \qquad V_1=12.9\,\mathrm{m/s}$$



$$\text{momentum equation: } \dot{m}_2 U-\dot{m}_1 V_1=F=-Mg-Ma$$

$$\text{mass conservation: } \dot{m}_1=\dot{m}_2=\rho(V_1-U)A_1,\ \rho V_1 A_1=\rho VA$$

$$a=\frac{\rho(V_1-U)A_1(V_1-U)-Mg}{M}=2.29\ \mathrm{m/s^2}$$

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