Chapter 1
Fluid Mechanics

Textbook:

Fox, McDonald, & Pritchard,

Fluid Mechanics 8ed.

Main Topics

- Definition of a Fluid
- Basic Equations
- Methods of Analysis
- Dimensions and Units
- Analysis of Experimental Error

Definition of Fluid

- Substance: Solid, liquid and gas phases
- A fluid is a substance that deforms 連續變形 continuously under the application of a shear (tangential) stress. 剪應力，切線應力
- No matter how small the shear stress may be, a fluid will deform. 流體是由液態和氣態物質組成

Fluids comprise the liquid and gas phases of matter.

Fluid v.s. Solid (I)

- When a shear stress is applied:
- Fluids continuously deform
- Solids deform or bend

應力與應變關係，可塑性、非可塑性

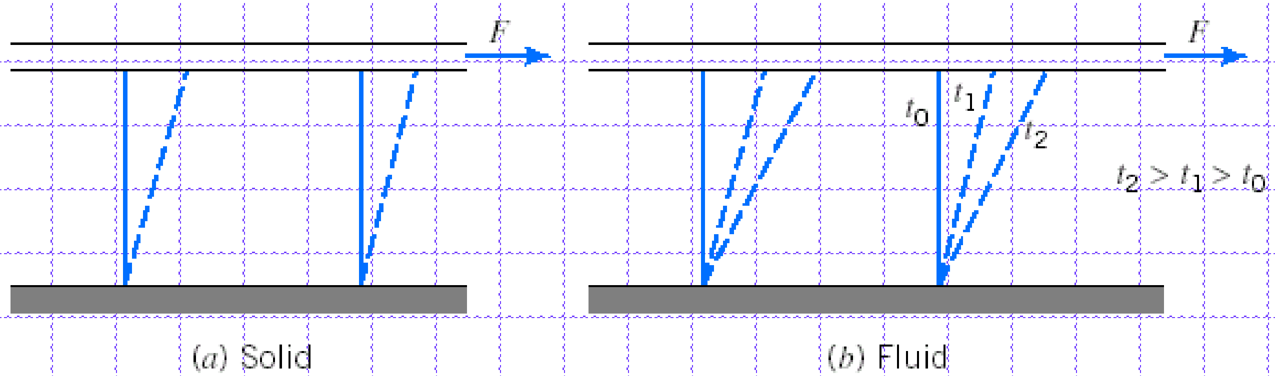


Fig. 1.1 Behavior of a solid and a fluid, under the action of a constant shear force.

Fluid v.s. Solid (II)

$$shear\ stress\ \tau = \frac{F}{A}$$

There is **no slip** at the boundary; the fluid in direct contact with the solid boundary has the same velocity as the boundary itself.

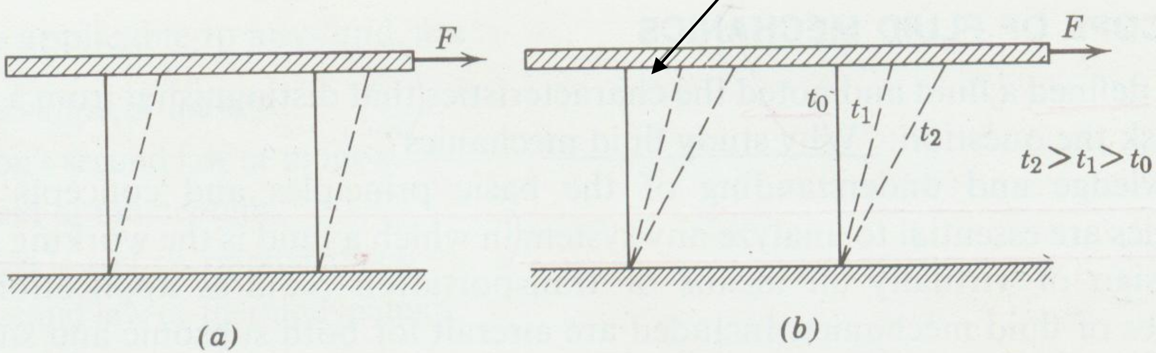


Fig. 1.1 Behavior of (a) solid and (b) fluid, under the action of a constant shear force.

應力與應變關係成線性newtonial fluid ，非線性non-newtonial fluid

No-Slip Condition

http://www.youtube.com/watch?v=cUTkqZeiMow

Ch2 the rate of deformation of fluid– viscosity V

Fluid v.s. Solid (III)

Vague idea:

- Fluid is soft and easily deformed.
- Solid is hard and not easily deformed.

Molecular structure:

- Solid has densely spaced molecules with large intermolecular cohesive force allowed to maintain its shape. 分子內聚力
- Liquid has further apart spaced molecules, the intermolecular forces are smaller than for solids, and the molecules have more freedom of movement.
- Gases have even greater molecular spacing and freedom of motion with negligible cohesive intermolecular forces and as a consequence are easily deformed.

Fluid? Solid ?

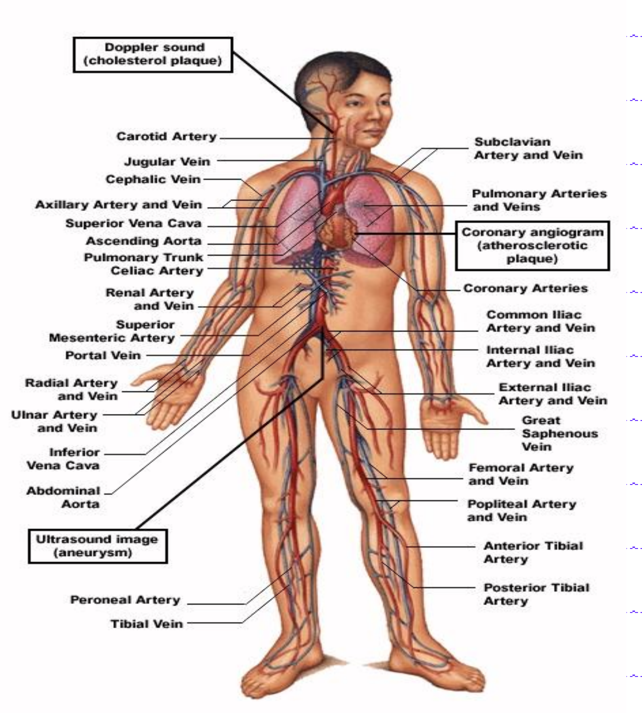
- Some materials, such as slurries, tar, putty, toothpaste, and so on, are not easily classified since they will behave as solid if the applied shearing stress is small, but if the stress exceeds some critical value, the substance will flow. The study of such materials is called *rheology*.
- 某些物質，如泥漿、瀝青、油灰、牙膏等，在承受微小剪應力作用時，特性近似固體，但當剪應力超過某個臨界值以上時，其特性又近似流體。研究此類物質的學科，稱為流變學。

Scopes of Fluid Mechanics

- Concept of fluid mechanics are essential to analyze any system in which a fluid is the working medium. For examples:
- Aerospace engineering (aircraft, rocket propulsion).
- Mechanical and Naval engineering (hovercraft, ships, submarines and automobiles combustion, lubrication, pump, ventilation)
- Civil engineering (bridges, buildings, tunnel, power lines)
- Chemical engineering (transport phenomena)
- Biomedical engineering (artificial heart, heart-lung machine, breathing aid, bio-chip).
- Sport engineering (golf ball, baseball, swimming, bicycle and ski racing)

Aerodynamics

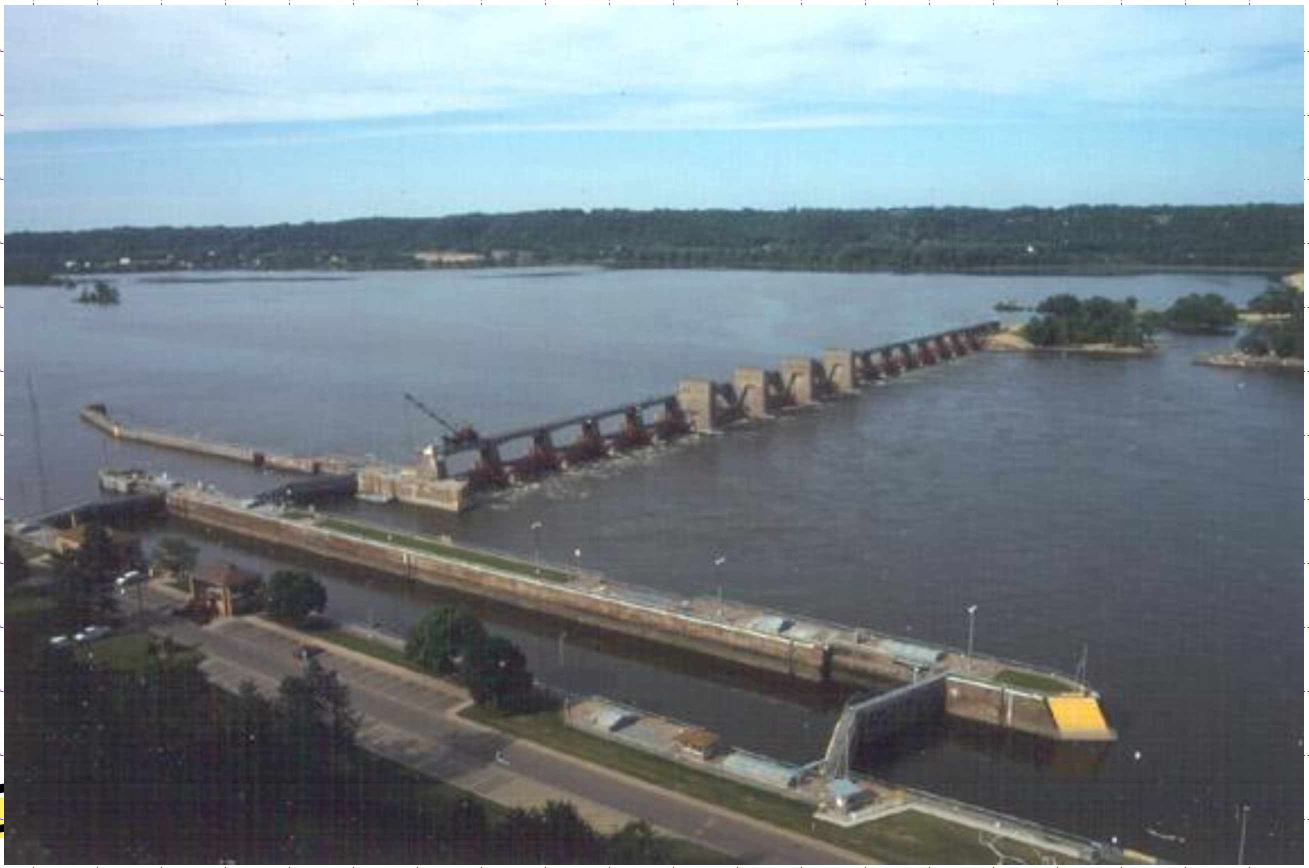
Bioengineering



Geology

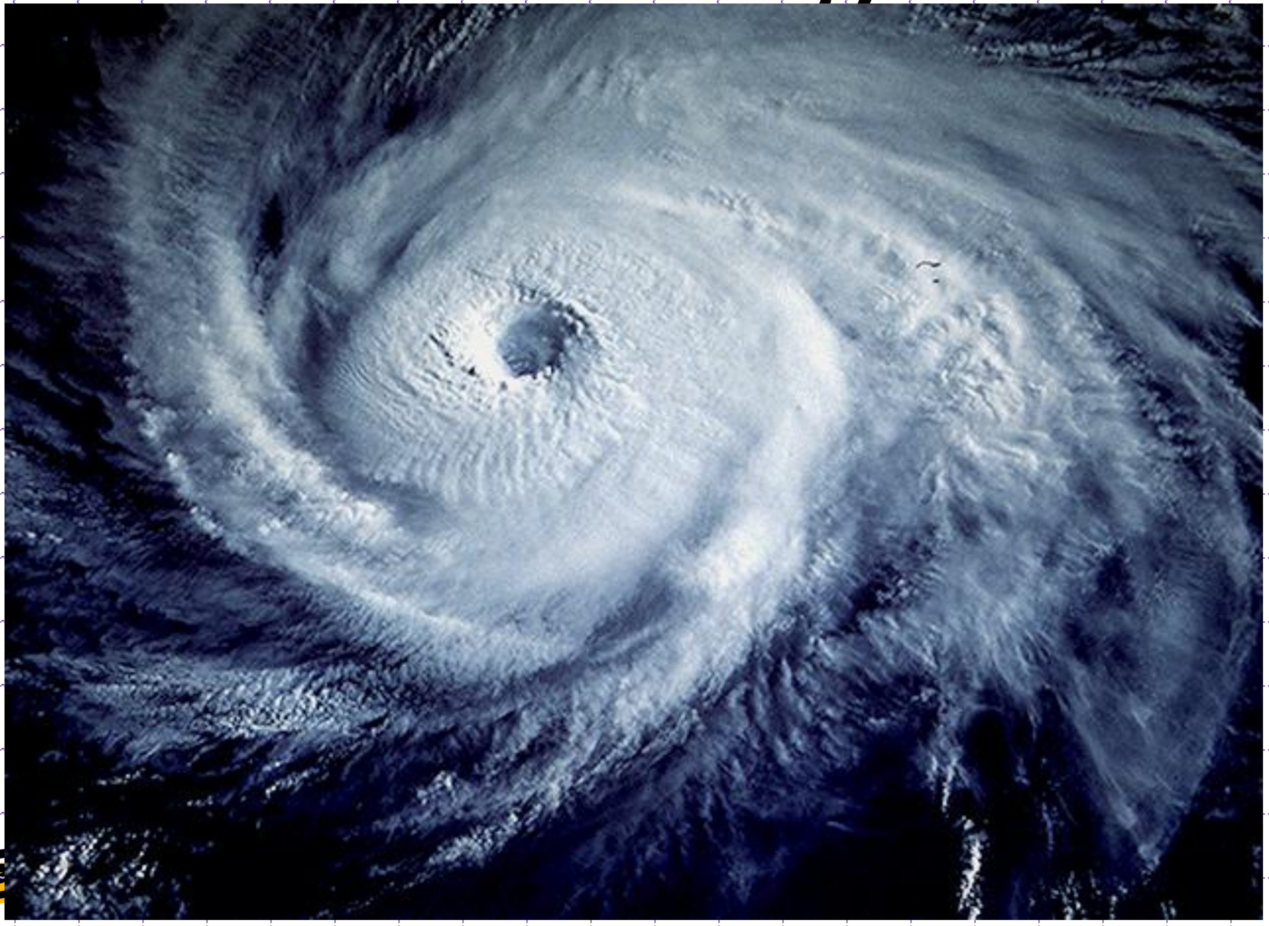
River Hydraulics

Hydraulic Structures

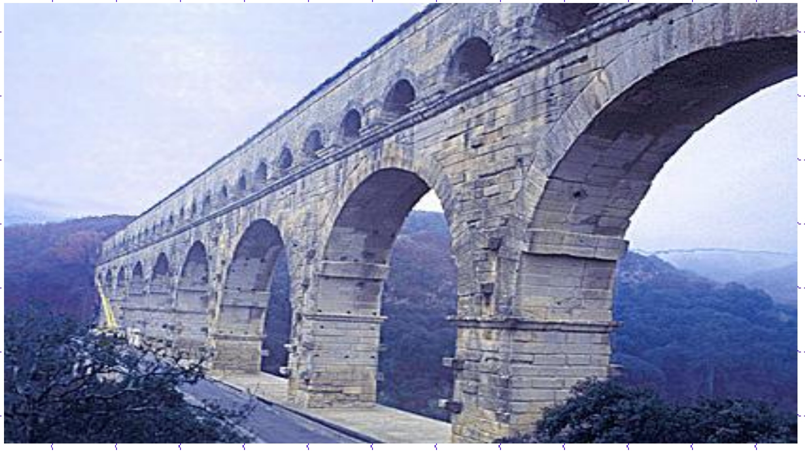


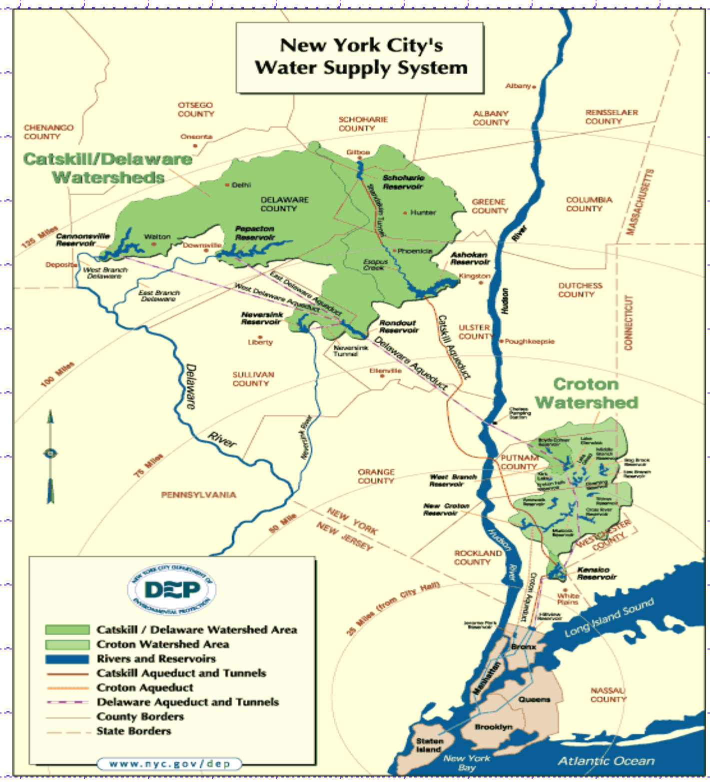
氣象學

Meteorology

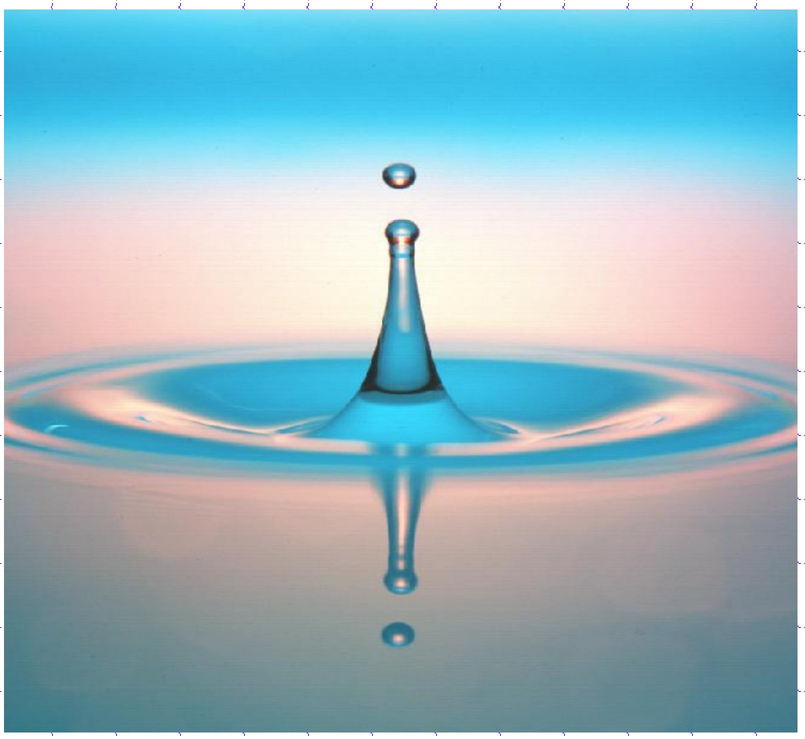


Water Resources





Fluid Mechanics is Beautiful



Tsunamis

- Tsunami: Japanese for “Harbour Wave”
- Created by earthquakes, land slides, volcanoes, asteroids/meteors
- Pose infrequent but high risk for coastal regions.

Racing

Swimming

http://www.youtube.com/watch?v=kmjFdBxbV08

Basic Equations (I)

Analysis of any problem in fluid mechanics necessarily includes statement of the basic laws governing the fluid motion. The basic laws, which applicable to any fluid, are:

- Conservation of mass
- Newton's second law of motion
- Moment of (angular) momentum
- The first law of thermodynamics
- The second law of thermodynamics

Example 1.1

Basic Equations (II)

- **NOT all basic laws are required to solve any one problem.** On the other hand, in many problems it is necessary to bring into the analysis additional relations that describe the behavior of physical properties of fluids under given conditions. For example, **the ideal gas equation of state $p=\rho RT$ is a model that relates density to pressure and temperature for many gases under normal conditions.**
- Many apparently simple problems in fluid mechanics that cannot be solved analytically. **In such cases we must resort to more complicated numerical solutions and/or results of experimental tests.**

CFD and Experimental tests

Mechanics– free body diagram

Methods of Analysis

封閉系統與開放系統

Close system open system , mass flow rate

- System method
  - ✓ In mechanics courses
  - ✓ Dealing with an easily identifiable rigid body
- Control volume method
  - ✓ In fluid mechanics course
  - ✓ Difficult to focus attention on a fixed identifiable quantity of mass
  - ✓ Dealing with the flow of fluids

控制容積

System Method

- A system is defined as a fixed, identifiable quantity of mass
- The boundaries separate the system from the surrounding
- The boundaries of the system may be fixed or movable. No mass crosses the system boundaries

Piston-cylinder assembly:

The gas in the cylinder is the system. If the gas is heated, the piston will lift the weight; The boundary of the system thus move. Heat and work may cross the boundaries, but the quantity of matter remain fixed.

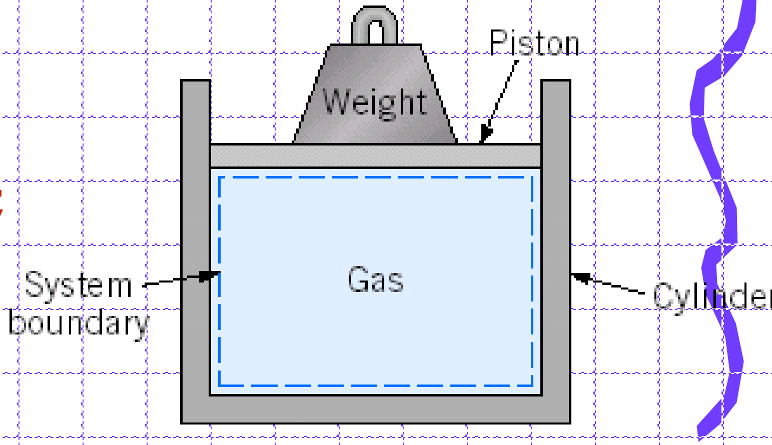


Fig. 1.2 Piston-cylinder assembly.

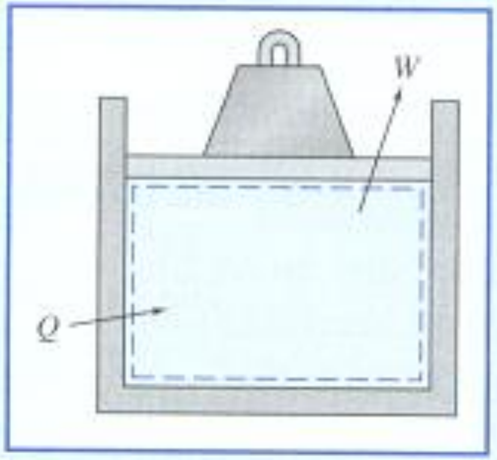
EXAMPLE 1.1 First Law Application to Closed System

A piston-cylinder device contains 0.95 kg of oxygen initially at a temperature of 27°C and a pressure due to the weight of 150 kPa (abs). Heat is added to the gas until it reaches a temperature of 627°C. Determine the amount of heat added during the process.

EXAMPLE PROBLEM 1.1

GIVEN: Piston-cylinder containing O_2, $m = 0.95$ kg.

$$T_1 = 27°C \qquad T_2 = 627°C$$



FIND: $Q_{1\to 2}$.

SOLUTION:

p = constant = 150 kPa (abs)

We are dealing with a system, $m = 0.95$ kg.

Governing equation: First law for the system, $Q_{12} - W_{12} = E_2 - E_1$

Assumptions: (1) $E = U$, since the system is stationary
(2) Ideal gas with constant specific heats

Under the above assumptions,

$$E_2 - E_1 = U_2 - U_1 = m(u_2 - u_1) = mc_v(T_2 - T_1)$$

The work done during the process is moving boundary work

$$W_{12} = \int_{V_1}^{V_2} p\, dV = p(V_2 - V_1)$$

For an ideal gas, $pV = mRT$. Hence $W_{12} = mR(T_2 - T_1)$. Then from the first law equation,

$$Q_{12} = E_2 - E_1 + W_{12} = mc_v(T_2 - T_1) + mR(T_2 - T_1)$$

$$Q_{12} = m(T_2 - T_1)(c_v + R)$$

$$Q_{12} = mc_p(T_2 - T_1) \qquad \{R = c_p - c_v\}$$

From the Appendix, Table A.6, for O_2, $c_p = 909.4$ J/(kg · K). Solving for Q_{12}, we obtain

$$Q_{12} = 0.95\ \text{kg} \times 909\ \frac{\text{J}}{\text{kg} \cdot \text{K}} \times 600\ \text{K} = 518\ \text{kJ} \longleftarrow \underline{Q_{12}}$$

This problem:

- ✓ Was solved using the nine logical steps discussed earlier.
- ✓ Reviewed use of the ideal gas equation and the first law of thermodynamics for a system.

System v.s. Control volume

- A system is defined as a fixed, identifiable quantity of mass
- The system boundaries separate the system from the surroundings
- The boundaries of system may be fixed or movable; however, there is no mass transfer across the system boundaries

Control Volume Method

- Control Volume (CV) is an arbitrary volume in space through which the fluid flows
- The geometric boundary of the control volume is called the Control Surface (CS)

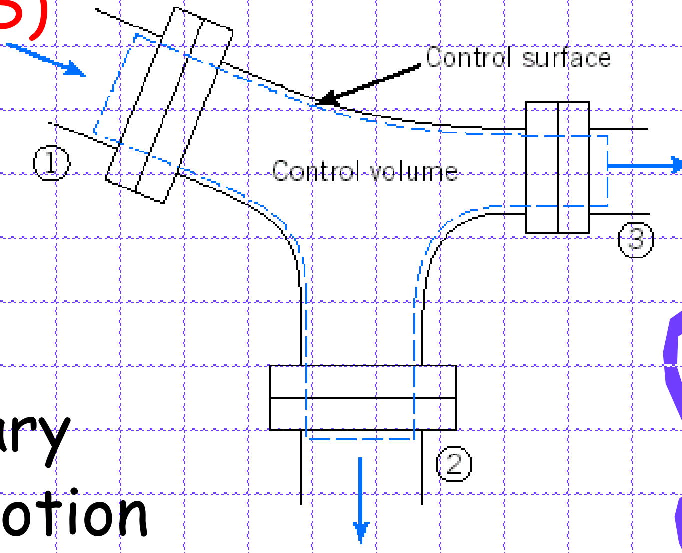
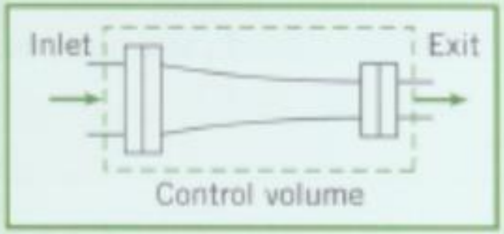


Fig. 1.3 Fluid flow through a pipe junction.

- The CS may be real or imaginary
- The CV may be at rest or in motion

EXAMPLE 1.2 Mass Conservation Applied to Control Volume

A reducing water pipe section has an inlet diameter of 5 cm and exit diameter of 3 cm. If the steady inlet speed (averaged across the inlet area) is 2.5 m/s, find the exit speed.



GIVEN: Pipe, inlet $D_i = 5$ cm, exit $D_e = 3$ cm
Inlet speed, $V_i = 2.5$ m/s

FIND: Exit speed, V_e

SOLUTION:

Assumption: Water is incompressible (density ρ = constant)

The physical law we use here is the conservation of mass, which you learned in thermodynamics when studying turbines, boilers, and so on. You may have seen mass flow at an inlet or outlet expressed as either $\dot{m} = VA/v$ or $\dot{m} = \rho VA$ where V, A, v, and ρ are the speed, area, specific volume, and density, respectively. We will use the density form of the equation. Hence the mass flow is:

$$\dot{m} = \rho VA$$

Applying mass conservation, from our study of thermodynamics,

$$\rho V_i A_i = \rho V_e A_e$$

(Note: $\rho_i = \rho_e = \rho$ by our first assumption)
(Note: Even though we are already familiar with this equation from thermodynamics, we will derive it in Chapter 4.)

Solving for V_e,

$$V_e = V_i \frac{A_i}{A_e} = V_i \frac{\pi D_i^2/4}{\pi D_e^2/4} = V_i \left(\frac{D_i}{D_e}\right)^2$$

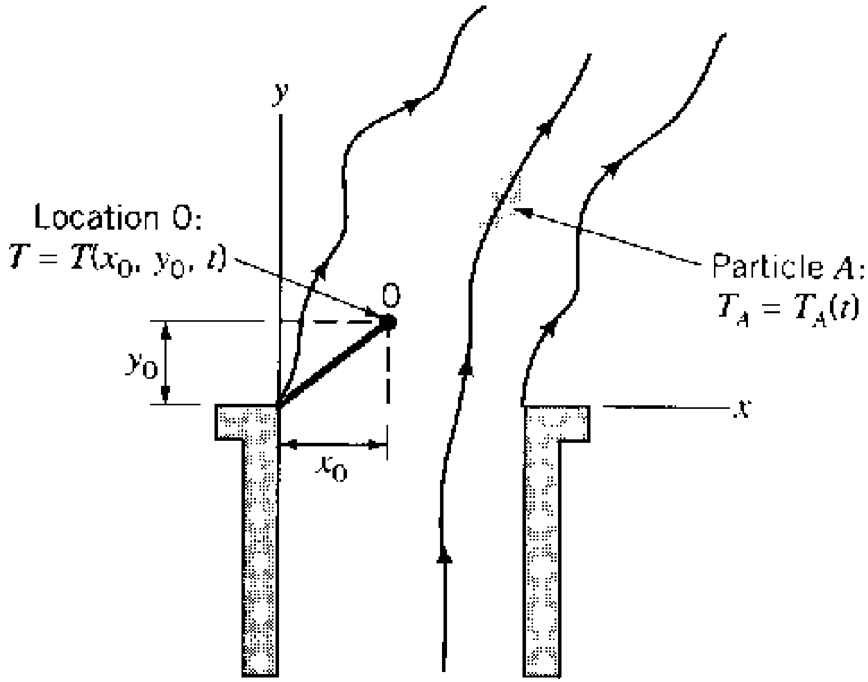
$$V_e = 2.7 \frac{\text{m}}{\text{s}} \left(\frac{5}{3}\right)^2 = 7.5 \frac{\text{m}}{\text{s}}$$ ← V_e

Differential versus Integral Approach

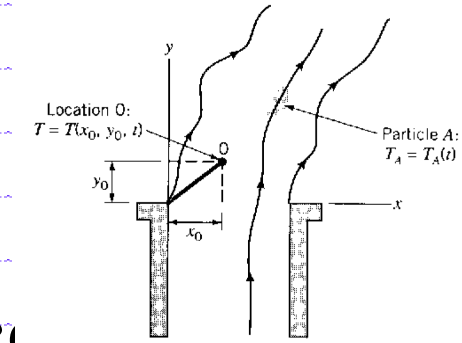
- The basic law can be formulated in terms of infinitesimal systems
  - Resulting differential equations
- The basic law can be formulated in terms of control volume
  - Resulting integral equations

Methods of Description

- Lagrangian method = System method
- Eulerian method = Control volume method



Lagrangian Method



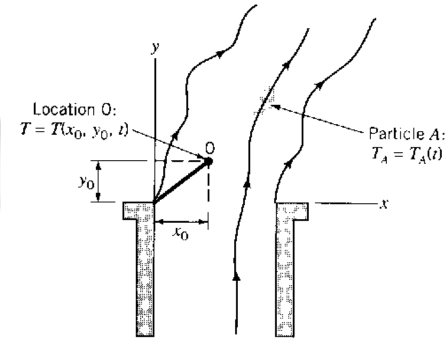
- Following individual fluid particles as they
- The fluid particles are tagged or identifie
- Determining how the fluid properties associated with these particles change as a function of time

❖ **Example:** one attaches the temperature-measuring device to a particular fluid particle A and record that particle's temperature as it moves about. $T_A = T_A(t)$ The use of may such measuring devices moving with various fluid particles would provide the temperature of these fluid particles as a function of time.

Identifiable elements of mass

將注意力集中在各流體質點上，以觀測物理性質隨時間之變化。

Eulerian Method



- Using the field concept
- The fluid motion is given by completely prescribing the necessary properties as a functions of space and time
- Obtaining information about the flow in terms of what happens at fixed points in space as the fluid flows past those points

❖ **Example:** one attaches the temperature-measuring device to a particular point (x,y,z) and record the temperature at that point as a function of time.

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

Control volume analysis, field

將注意力集中且固定在空間中某特定範圍，以觀測物理性質隨時間及位置之變化。

應該是關於流體力學的描述
尤拉描述物體是以"相對的"概念去描述
即相對於自身，物體是以XYZ三維及時間相對多少
取一函數H
H=H(X，Y，Z，T)
微分式省略

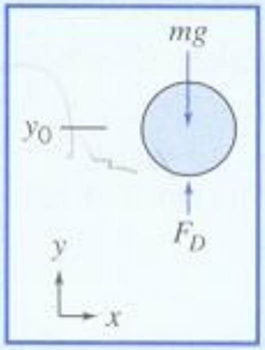
拉格倫菊，描述物體只與時間有關
H=H(T)
微分式省略

如果H(T)=H(X，Y，Z，T)
微分式為
dH/dT=PH/PX*dX+.....類推YZT
P=partial
整理過後會得到『DH/DT=(V向量‧旋度)H+PH/PT』---------◎

整個式子在流體力學中又稱為Material Derivative或Subs tantial Derivative
中文又翻作"實質導函數"或是"隨物微分"理論
我個人比較偏向使用隨物微分
簡單的說
如果H換成速度v
◎左式對t微分就變成加速度a
在◎右式就變成uvw向量+時間項

The air resistance (drag force) on a 200g ball in free flight is given by $F_D = 2\times10^{-4}\ V^2$, where F_D is in Newtons and V is in meters per second. If the ball is dropped from rest 500m above the ground, determine the speed at which it hits the ground. What percentage of the terminal speed in the result?

EXAMPLE PROBLEM 1.2 Free-Fall of Ball in Air



GIVEN: Ball, $m = 0.2$ kg, released from rest at $y_0 = 500$ m
Air resistance, $F_D = kV^2$, where $k = 2 \times 10^{-4}\ \text{N} \cdot \text{s}^2/\text{m}^2$

Units: F_D(N), V(m/s)

FIND: (a) Speed at which the ball hits the ground.
(b) Ratio of speed to terminal speed.

SOLUTION:

Governing equation: $\sum \vec{F} = m\vec{a}$

Assumption: (1) Neglect buoyancy force.

The motion of the ball is governed by the equation

$$\sum F_y = ma_y = m\frac{dV}{dt}$$

Since $V = V(y)$, we write $\sum F_y = m\frac{dV}{dy}\frac{dy}{dt} = mV\frac{dV}{dy}$ Then,

$$\sum F_y = F_D - mg = kV^2 - mg = mV\frac{dV}{dy}$$

Separating variables and integrating,

$$\int_{y_0}^{y} dy = \int_0^V \frac{mV\,dV}{kV^2 - mg}$$

$$y - y_0 = \left[\frac{m}{2k}\ln(kV^2 - mg)\right]_0^V = \frac{m}{2k}\ln\frac{kV^2 - mg}{-mg}$$

Taking antilogarithms, we obtain

$$kV^2 - mg = -mg\, e^{\left[\frac{2k}{m}(y-y_0)\right]}$$

Solving for V gives

$$V = \left\{\frac{mg}{k}\left(1 - e^{\left[\frac{2k}{m}(y-y_0)\right]}\right)\right\}^{1/2}$$

Substituting numerical values with $y = 0$ yields

$$V = \left\{0.2\text{kg} \times 9.81\,\frac{\text{m}}{\text{s}^2} \times \frac{\text{m}^2}{2\times10^{-4}\,\text{N}\cdot\text{s}^2} \times \frac{\text{N}\cdot\text{s}^2}{\text{kg}\cdot\text{m}}\left(1 - e^{\left[\frac{2\times2\times10^{-4}}{0.2}(-500)\right]}\right)\right\}^{1/2}$$

$V = 78.7$ m/s $\longleftarrow$ V

At terminal speed, $a_y = 0$ and $\Sigma F_y = 0 = kV_t^2 - mg$

Then, $V_t = \left[\frac{mg}{k}\right]^{1/2} = \left[0.2\text{ kg} \times 9.81 \frac{\text{m}}{\text{s}^2} \times \frac{\text{m}^2}{2 \times 10^{-4}\text{N} \cdot \text{s}^2} \times \frac{\text{N} \cdot \text{s}^2}{\text{kg} \cdot \text{m}}\right]^{1/2} = 99.0 \text{ m/s}.$

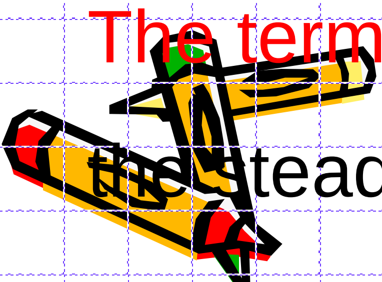
The ratio of actual speed to terminal speed is

$$\frac{V}{V_t} = \frac{78.7}{99.0} = 0.795, \text{ or } 79.5\% \longleftarrow \frac{V}{V_t}$$

This problem:

- ✓ Reviewed the methods used in particle mechanics.
- ✓ Introduced a variable aerodynamic drag force.

Try the *Excel* workbook for this Example Problem for variations on this problem.



The terminal speed: $m\frac{dV}{dt} = mg - kV^2 = 0$ $\quad V_t = \sqrt{\frac{mg}{k}}$

the steady speed a falling body eventually attains.

Field Representation of Flow

- At a given instant in time, any fluid property (such as **density**, **pressure**, **velocity**, and **acceleration**) can be described as a functions of the fluid's location.This representation of fluid parameters as functions of the spatial coordinates is termed a ***field representation of flow***.
- The specific field representation may be different at different times, so that to describe a fluid flow we must determine the various parameter not only as functions of the spatial coordinates but also as a function of time.
- EXAMPLE: **Temperature field** $T = T(x, y, z, t)$
- EXAMPLE: **Velocity field**

$$\overline{V} = u(x,y,z,t)\overline{i} + v(x,y,z,t)\overline{j} + w(x,y,z,t)\overline{k}$$

Dimensions and Units

Qualitative aspect

- Identify the nature, or type, of the characteristics (such as length, time, stress, and velocity) .
- 基本量
  Given in terms of certain **primary quantities**, such as **Length, L, time, T, mass, M, and temperature, θ.** The primary quantities are also referred to as basic dimensions.
- Given in terms of other **secondary quantity**, for example, **area ≒ L^2, velocity ≒ LT^{-1} , density ≒ ML^{-3}**.導出量

Quantitative aspect

Provide a numerical measure of the characteristics.

Requires both a number and a standard, Such standards are called units.

System of Dimensions

- Mass[M], Length[L], time[t], and Temperature[T] ...MLtT system
- Force[F], Length[L], time[t], and Temperature[T] ...FLtT system
- Force[F], Mass[M], Length[L], time[t], and Temperature[T] ...FMLtT

System of Units (I)

- British Gravitational System: B.G.
- International Standard: S.I.
- English Engineering: E.E.

System of Units (II)

- MLtT
  - ✓SI (kg, m, s, K)
- FLtT
  - ✓British Gravitational (lbf, ft, s, °R)
- FMLtT
  - ✓English Engineering (lbf, lbm, ft, s, °R)

System of Dimensions	Unit System	Force F	Mass M	Length L	Time t	Temperature T
a. MLtT	Système International d'Unités (SI)	(N)	kg	m	s	K
b. FLtT	British Gravitational (BG)	lbf	(slug)	ft	s	°R
c. FMLtT	English Engineering (EE)	lbf	lbm	ft	s	°R

British Gravitational System

- Length: ft
- Time: second
- Force: lbf
- Temperature: ^{O}F or ^{O}R $^{O}R = {^{O}F} + 459.67$
- Mass:slug ; $1\ lbf = 1\ slug \times 1\ ft / sec^2$
- $g = 32.2\ ft / sec^2$
- $w\ (lbf) = m\ (slug) \times g\ (ft / sec^2)$

International Standard

- Length: m
- Time: second
- Mass: Kg
- Temperature: $^{\circ}K$; $^{\circ}K = {^{\circ}C} + 273.15$
- Force: Newton $1\ N = 1\ Kg \times 1\ m / sec^2$
- Work: Joule (J) ; $J = 1\ N \times m$
- Power: Watt (W) ; $W = J / sec = N \times m/sec$
- $g = 9.807\ m / sec^2$

English Engineering

- Mass: lbm
- Force: lbf
- Length: ft
- Time: second
- Temperature: °R (absolute temperature)

$F = ma / g_c$; g_c : the constant of proportionality

1 lbf = $(\text{lbm} \times 32.2\ \text{ft} / \text{sec}^2) / g_c$

$g_c = 32.2\ \text{ft} / \text{sec}^2$

In E.E., the relationship between weight and mass :

$W = mg / g_c$

Therefore, 1 slug = 32.2 lbm (when $g=g_c$)

Preferred Systems of Units

- SI (kg, m, s, K)

$$1\ \text{N} = 1\ \text{kg} \times 1\ \text{m} / \text{sec}^2$$

- British Gravitational (lbf, ft, s, ^{o}R)

$$1\ \text{lbf} = 1\ \text{slug} \times 1\ \text{ft} / \text{sec}^2$$

- English Engineering (lbf, lbm, ft, s, ^{o}R)

$$1\ \text{lbf} = (\text{lbm} \times 32.2\ \text{ft} / \text{sec}^2) / g_c$$

$$g_c = 32.2\ \text{ft} / \text{sec}^2$$

EXAMPLE 1.4 Use of Units

The label on a jar of peanut butter states its net weight is 510 g. Express its mass and weight in SI, BG, and EE units.

GIVEN: Peanut butter "weight," $m = 510$ g

FIND: Mass and weight in SI, BG, and EE units

SOLUTION:

This problem involves unit conversions and use of the equation relating weight and mass:

$$W = mg$$

The given "weight" is actually the mass because it is expressed in units of mass:

$$m_{SI} = 0.510 \text{ kg} \qquad \longleftarrow m_{SI}$$

Using the conversions of Table G.2 (Appendix G),

$$m_{EE} = m_{SI}\left(\frac{1 \text{ lbm}}{0.454 \text{ kg}}\right) = 0.510 \text{ kg}\left(\frac{1 \text{ lbm}}{0.454 \text{ kg}}\right) = 1.12 \text{ lbm} \qquad \longleftarrow m_{EE}$$

Using the fact that 1 slug = 32.2 lbm,

$$m_{BG} = m_{EE}\left(\frac{1 \text{ slug}}{32.2 \text{ lbm}}\right) = 1.12 \text{ lbm}\left(\frac{1 \text{ slug}}{32.2 \text{ lbm}}\right) = 0.0349 \text{ slug} \qquad \longleftarrow m_{BG}$$

To find the weight, we use

$$W = mg$$

In SI units, and using the definition of a newton,

$$W_{SI} = 0.510 \text{ kg} \times 9.81 \frac{\text{m}}{\text{s}^2} = 5.00\left(\frac{\text{kg}\cdot\text{m}}{\text{s}^2}\right)\left(\frac{\text{N}}{\text{kg}\cdot\text{m/s}^2}\right) = 5.00 \text{ N} \qquad \longleftarrow W_{SI}$$

In BG units, and using the definition of a slug,

$$W_{BG} = 0.0349 \text{ slug} \times 32.2 \frac{\text{ft}}{\text{s}^2} = 1.12 \frac{\text{slug}\cdot\text{ft}}{\text{s}^2} = 1.12\left(\frac{\text{slug}\cdot\text{ft}}{\text{s}^2}\right)\left(\frac{\text{s}^2\cdot\text{lbf/ft}}{\text{slug}}\right) = 1.12 \text{ lbf} \qquad \longleftarrow W_{BG}$$

In EE units, we use the form $W = mg/g_c$, and using the definition of g_c,

$$W_{EE} = 1.12 \text{ lbm} \times 32.2 \frac{\text{ft}}{\text{s}^2} \times \frac{1}{g_c} = \frac{36.1}{g_c}\frac{\text{lbm}\cdot\text{ft}}{\text{s}^2} = 36.1\left(\frac{\text{lbm}\cdot\text{ft}}{\text{s}^2}\right)\left(\frac{\text{lbf}\cdot\text{s}^2}{32.2 \text{ ft}\cdot\text{lbm}}\right) = 1.12 \text{ lbf} \qquad \longleftarrow W_{EE}$$

Dimensional Consistency of Equation

- In a correct equation or formula, each term in an equation, and both side of the equation, should be reducible to the same dimensions. For example, the Bernoulli equation

$$\frac{p_1}{\rho g} + \frac{V_1}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{V_2}{2g} + z_2$$

where relates the pressure p, velocity V and elevation z between points 1 and 2 along a streamline for a steady, frictionless incompressible flow.

- This equation is dimensionally consistent because each term in the equation can be reduced to dimension of L. Therefore, Three terms in Bernoulli equation are usually called as pressure head, velocity head and elevation head respectively.

Analysis of Experimental Error

EER= cooling rate/ electrical input

Analysis of Experimental Error

-→

Engineers performing experiments must not just data but also the uncertainties in their measurements.