Fluid Mechanics

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Chapter 1 Introduction

1-1 General Remarks

- Fluid mechanics--- science that deals with the behavior of fluids at rest or in motion, and the interaction of fluids with solids or other fluids at the boundaries.

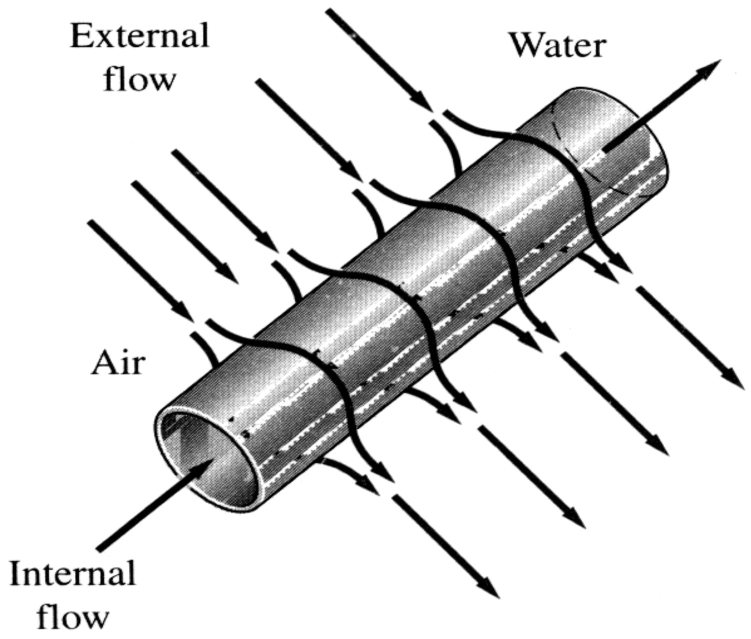
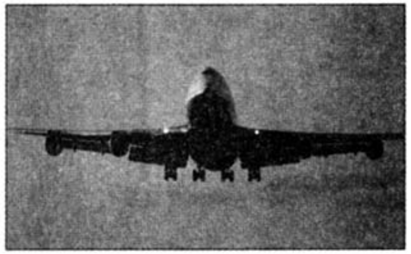


FIGURE 9-1

1-2 Scope of Fluid Mechanics (1)


自然流動氣候


船舶

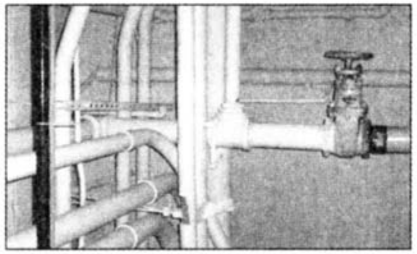

飛機和太空載具

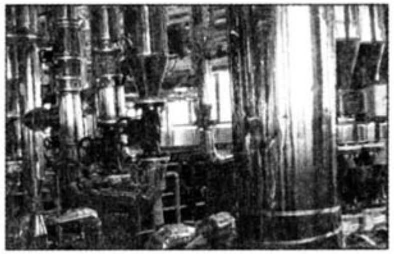

動力廠


人體


汽車


風力渦輪機


管路和水管系統

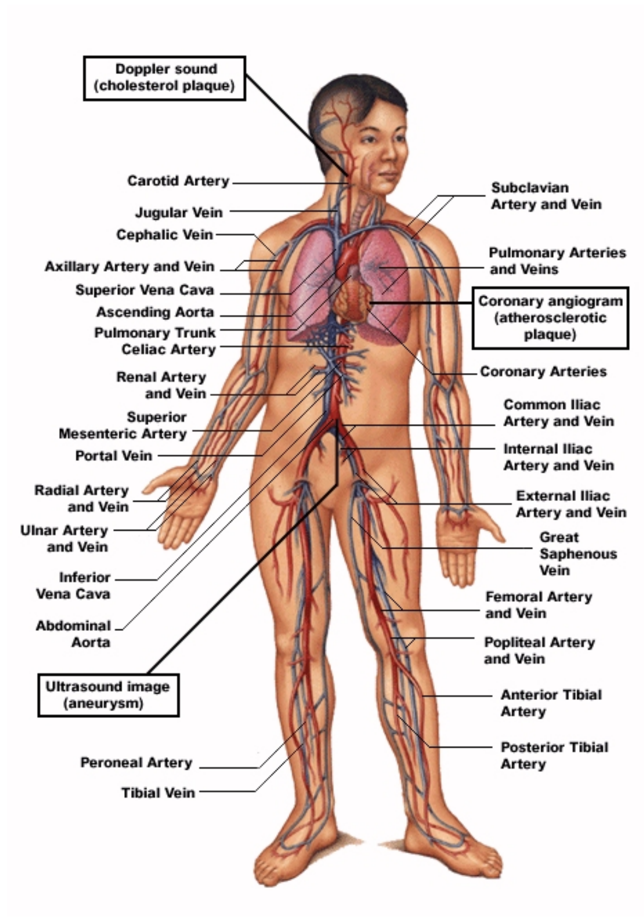

工業應用

1-2 Scope of Fluid Mechanics (2)

Aerodynamics:

1-2 Scope of Fluid Mechanics (3)

Bioengineering:



1-2 Scope of Fluid Mechanics (4)

Energy Generation:

1-2 Scope of Fluid Mechanics (5)

Automobile:

1-2 Scope of Fluid Mechanics (6)

River Hydraulics:

1-2 Scope of Fluid Mechanics (7)

Hydraulic Structure:

1-2 Scope of Fluid Mechanics (8)

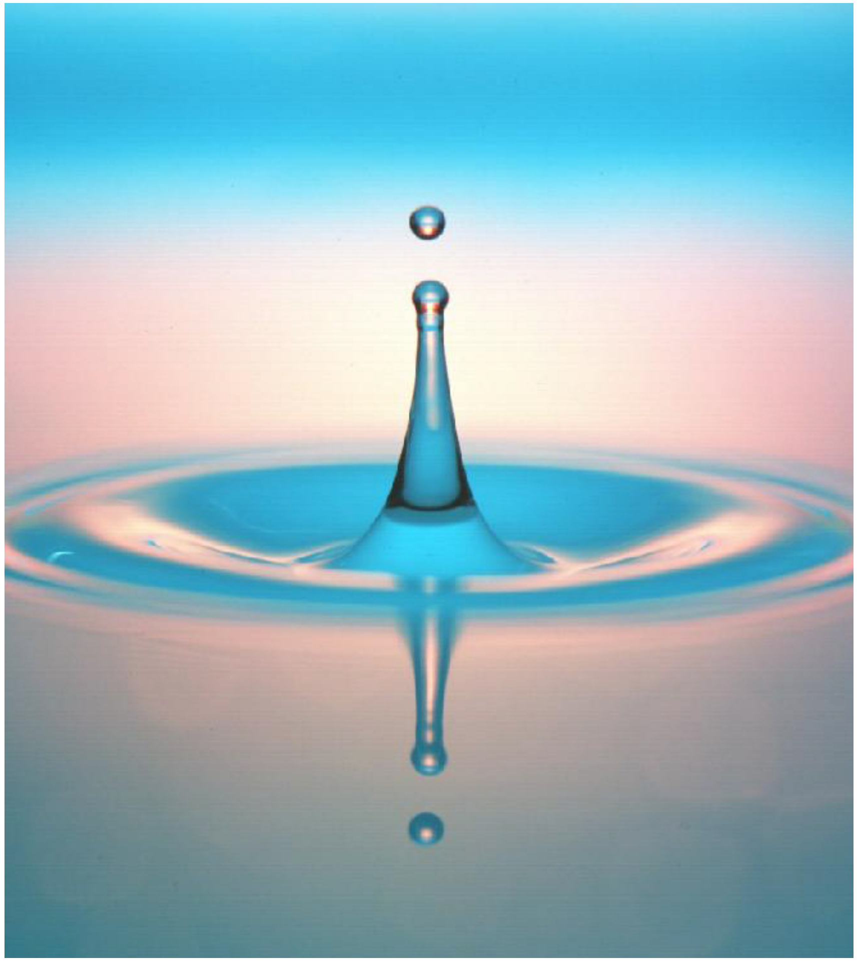
Hydrodynamics:

1-2 Scope of Fluid Mechanics (9)

Water Resources:

1-2 Scope of Fluid Mechanics (10)

Fluid Mechanics is Beautiful:



1-2 Scope of Fluid Mechanics (11)

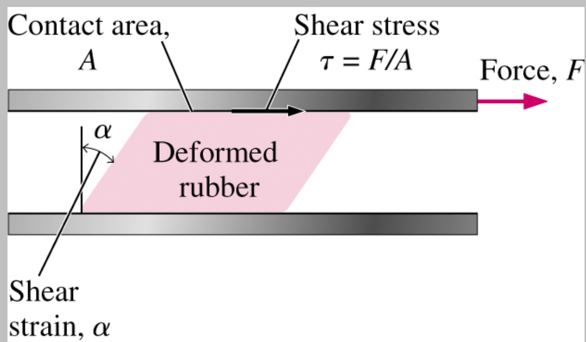
- Tsunami: Japanese for "Harbour Wave"
- Created by earthquakes, land slides, volcanoes, asteroids/meteors
- Pose infrequent but high risk for coastal regions.

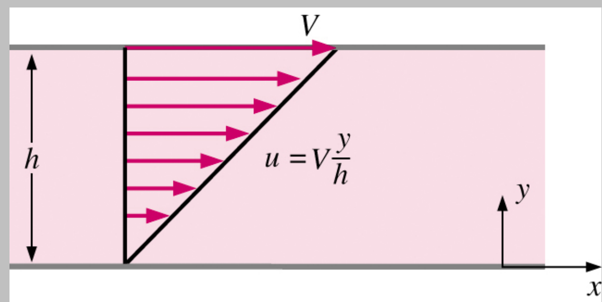
1-3 Definition of a Fluid (1)

- A fluid is a substance in the gaseous or liquid form
- Distinction between solid and fluid?
  - Solid: can resist an applied shear by deforming. Stress is proportional to strain
  - Fluid: deforms continuously under applied shear. Stress is proportional to strain rate

Solid

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



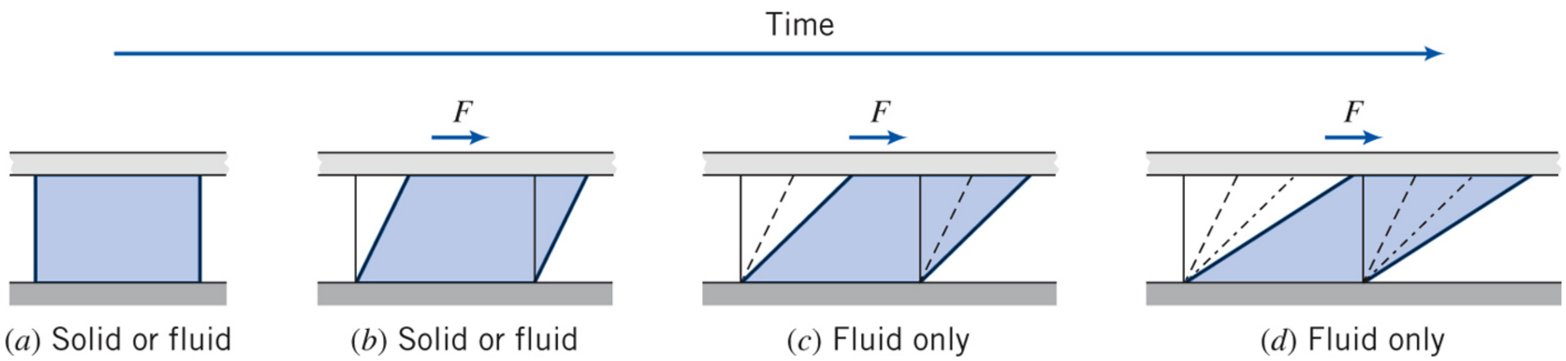


Fluid

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

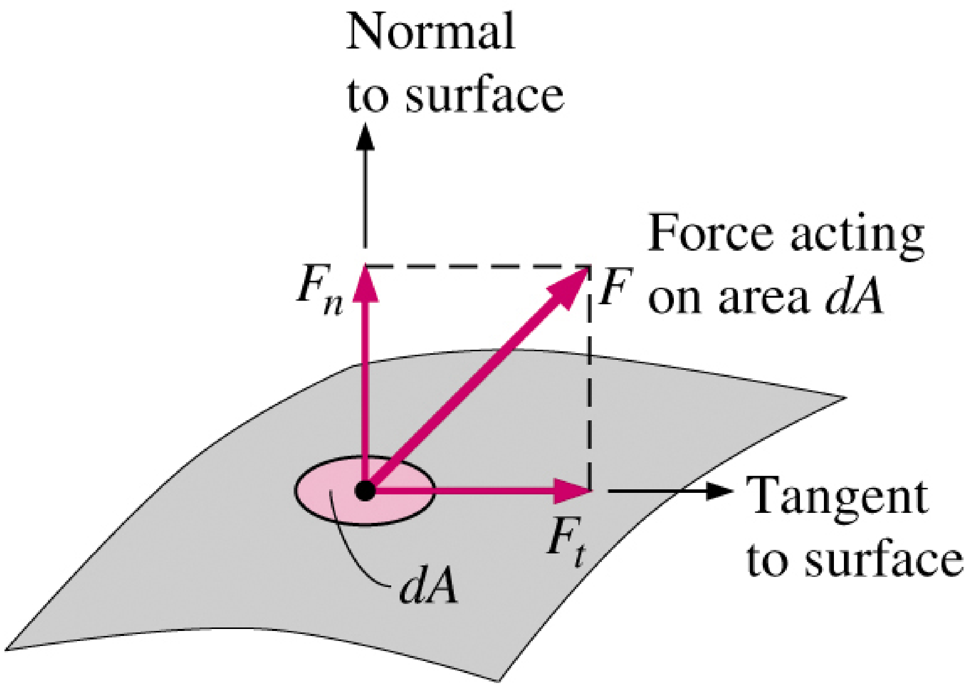
1-3 Definition of a Fluid (2)

Difference in behavior of a solid and a fluid due to a shear force



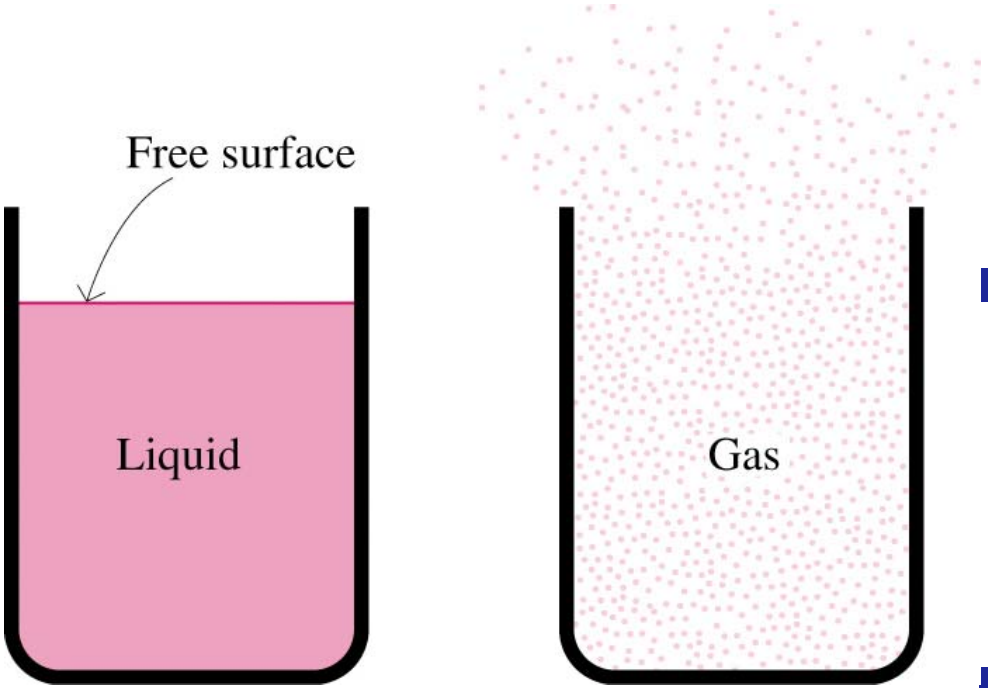
1-3 Definition of a Fluid (3)

Stress:



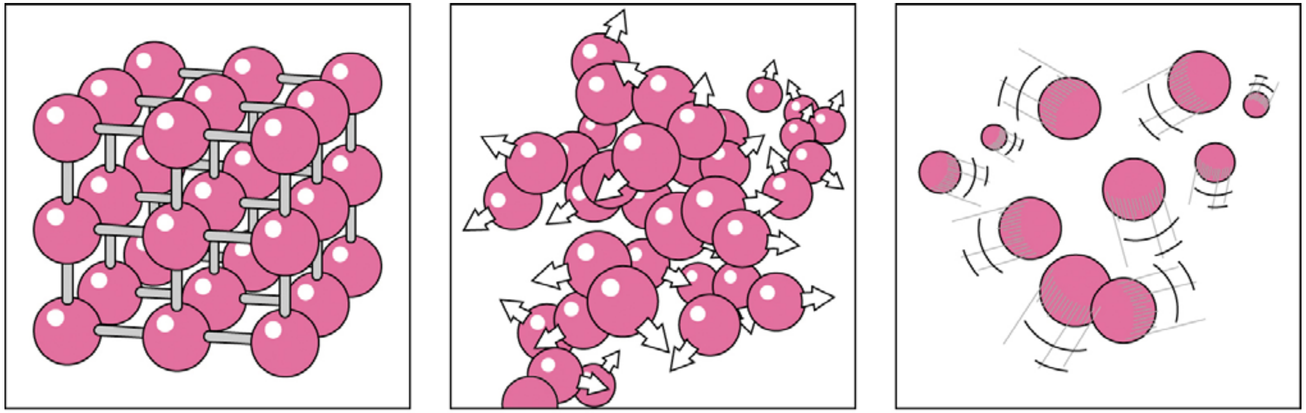
- Stress is defined as the force per unit area.
- Normal component: normal stress
  - In a fluid at rest, the normal stress is called **pressure**
- Tangential component: shear stress

1-3 Definition of a Fluid (4)



- A liquid takes the shape of the container it is in and forms a free surface in the presence of gravity
- A gas expands until it encounters the walls of the container and fills the entire available space. Gases cannot form a free surface
- Gas and vapor are often used as synonymous words

1-3 Definition of a Fluid (5)



(a)

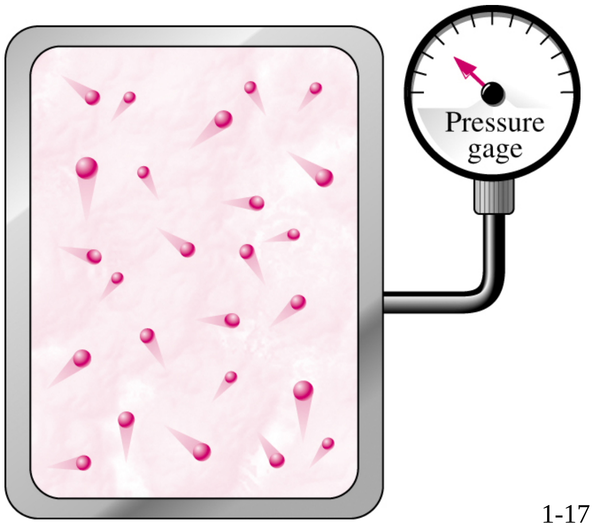
solid

(b)

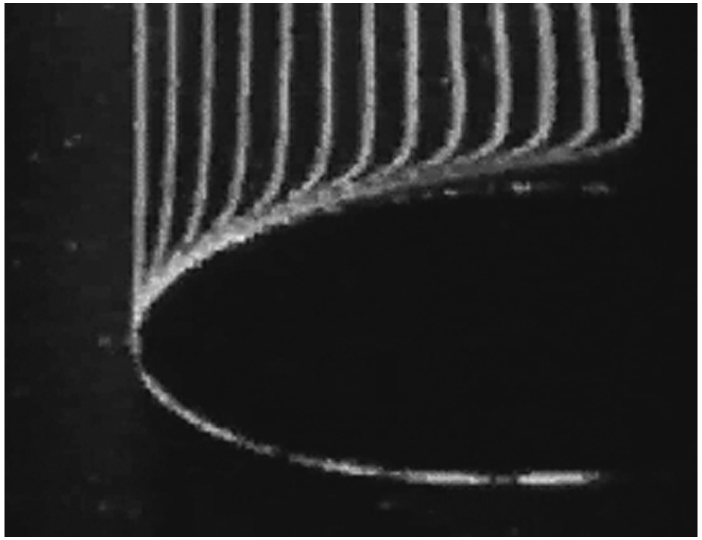
liquid

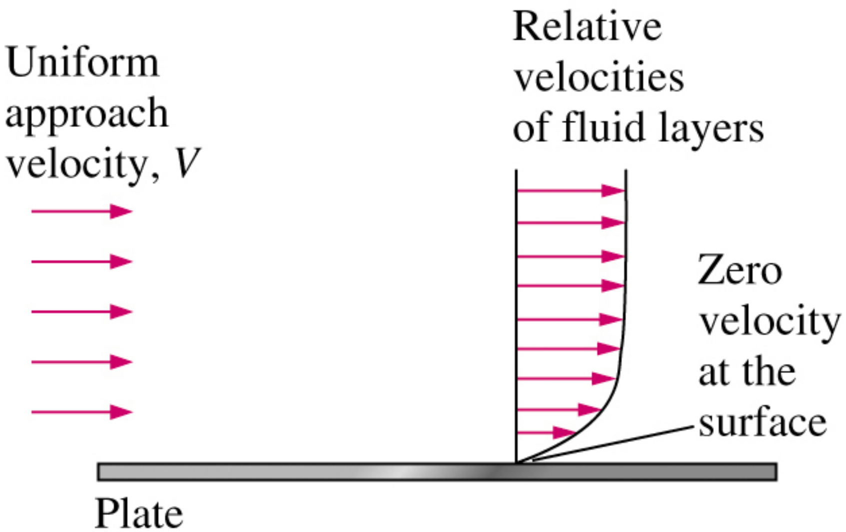
(c)

gas



1-3 Definition of a Fluid (6)





No-Slip Condition:

- No-slip condition: A fluid in direct contact with a solid "sticks" to the surface due to viscous effects
- Responsible for generation of wall shear stress t_w, surface drag D= $\int t_w\, dA$, and the development of the boundary layer
- The fluid property responsible for the no-slip condition is **viscosity**
- Important boundary condition in formulating initial boundary value problem (IBVP) for analytical and computational fluid dynamics analysis

1-4 Classification of Flows (1)

- We classify flows as a tool in making simplifying assumptions to the governing partial-differential equations, which are known as the Navier-Stokes equations
  - Conservation of Mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0$$

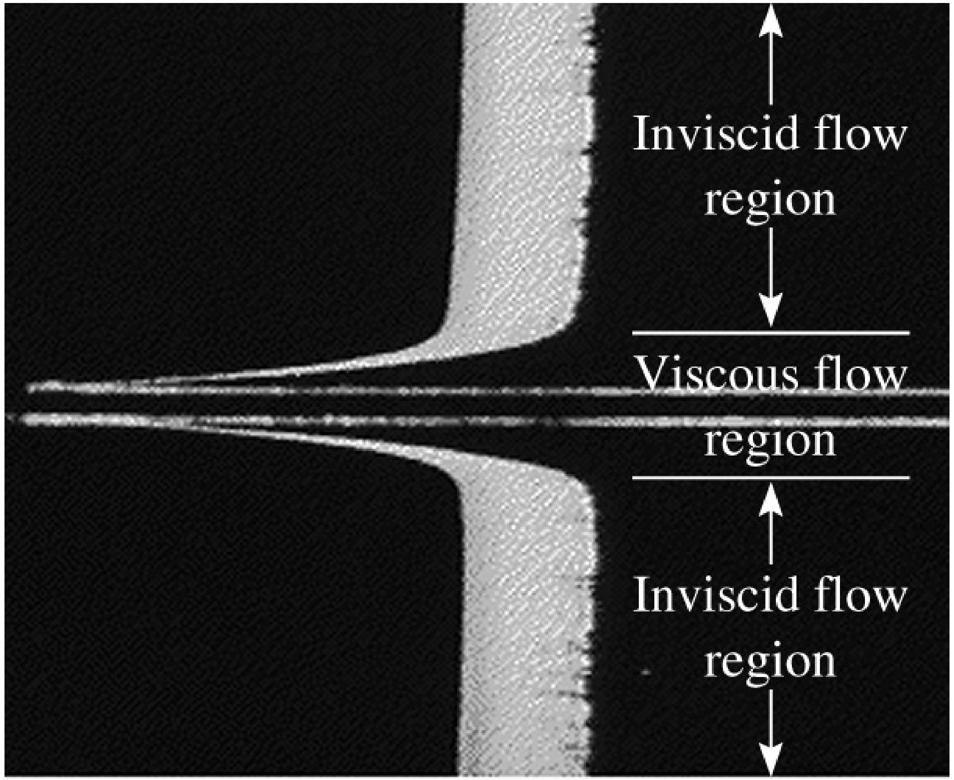
  - Conservation of Momentum

$$\rho \frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U} \cdot \nabla)\mathbf{U} = -\nabla p + \rho \mathbf{g} + \mu \nabla^2 \mathbf{U}$$

1-4 Classification of Flows (2)

Viscous vs. Inviscid Regions of Flow:

- Regions where frictional effects are significant are called viscous regions. They are usually close to solid surfaces.
- Regions where frictional forces are small compared to inertial or pressure forces are called inviscid



For inviscid flows:

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

1-4 Classification of Flows (3)

Viscous versus Inviscid Flow

(1) when two fluid layers move to each other, a friction force develops between them

(2) viscosity--- a measure of internal stickiness of fluid

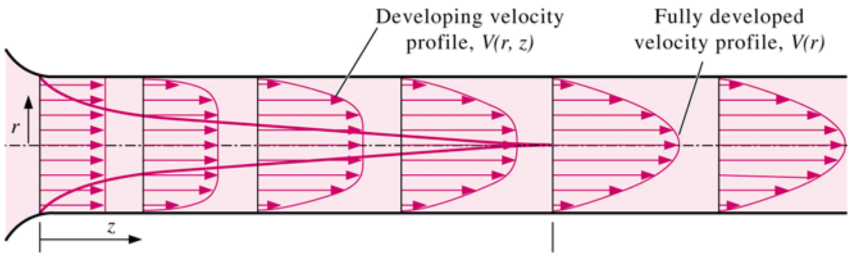
(3) viscosity caused by the cohesive forces between molecules in liquids and by molecular collisions in gases

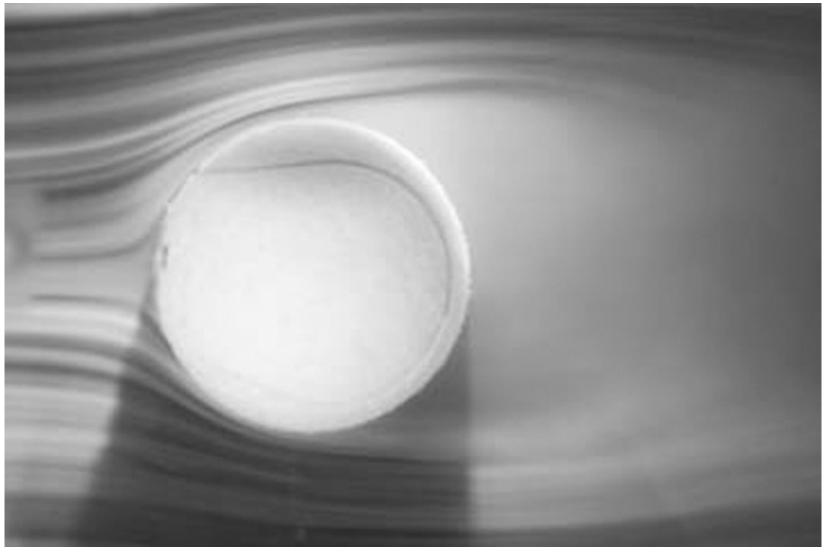
(4) viscous flows--- flows in which the effects of viscosity are significant

(5) inviscid (or frictionless) flows--- zero-viscosity fluids (idealized flows)

1-4 Classification of Flows (4)

Internal vs. External Flow:





- Internal flows are dominated by the influence of viscosity throughout the flowfield
- For external flows, viscous effects are limited to the boundary layer and wake.

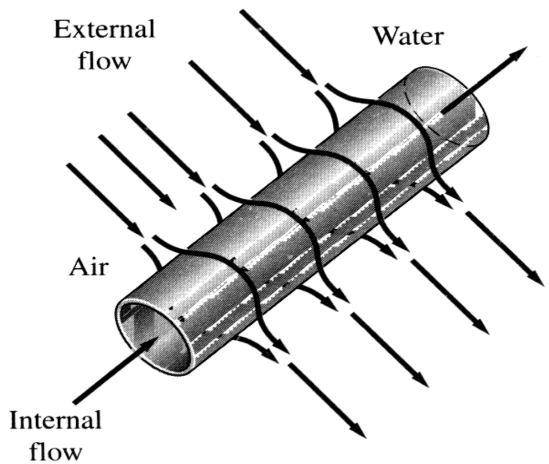


FIGURE 9-1

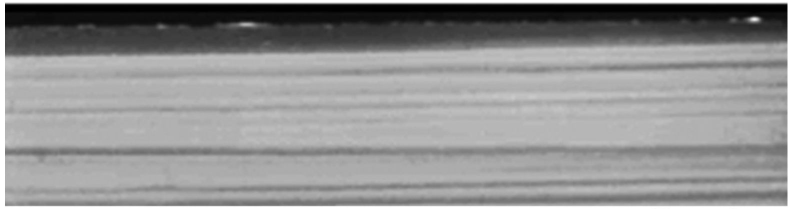
Compressible vs. Incompressible Flow:

- A flow is classified as incompressible if the density remains nearly constant.
- Liquid flows are typically incompressible.
- Gas flows are often compressible, especially for high speeds.
- Mach number, Ma = V/c is a good indicator of whether or not compressibility effects are important.
  - Ma < 0.3 : Incompressible
  - Ma < 1 : Subsonic
  - Ma = 1 : Sonic
  - Ma > 1 : Supersonic
  - Ma >> 1 : Hypersonic

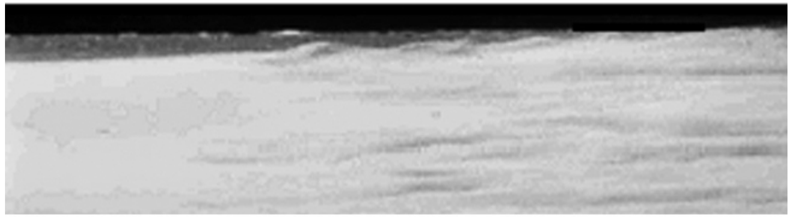
1-4 Classification of Flows (6)

Laminar vs. Turbulent Flow:

- Laminar: highly ordered fluid motion with smooth streamlines.
- Turbulent: highly disordered fluid motion characterized by velocity fluctuations and eddies.
- Transitional: a flow that contains both laminar and turbulent regions
- Reynolds number, Re= ρ UL/ μ is the key parameter in determining whether or not a flow is laminar or turbulent.



Laminar



Transitional

Turbulent

1-4 Classification of Flows (7)

Steady vs. Unsteady Flow:

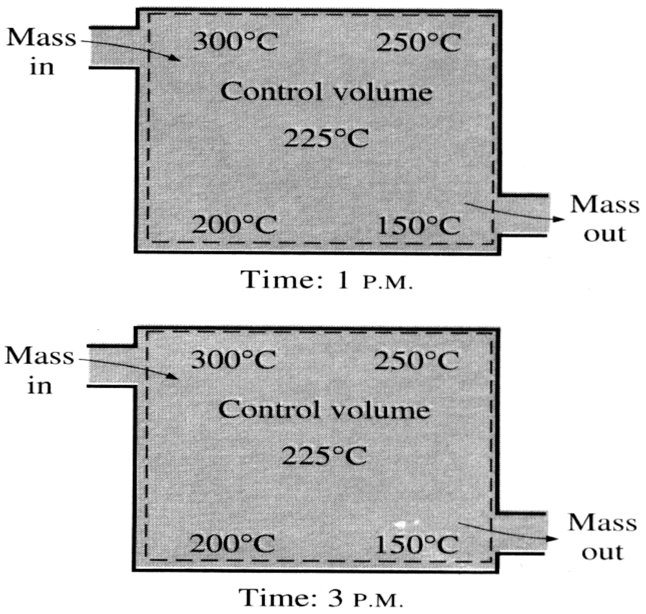


FIGURE 9-3

- Steady implies no change at a point with time. Transient terms in N-S equations are zero

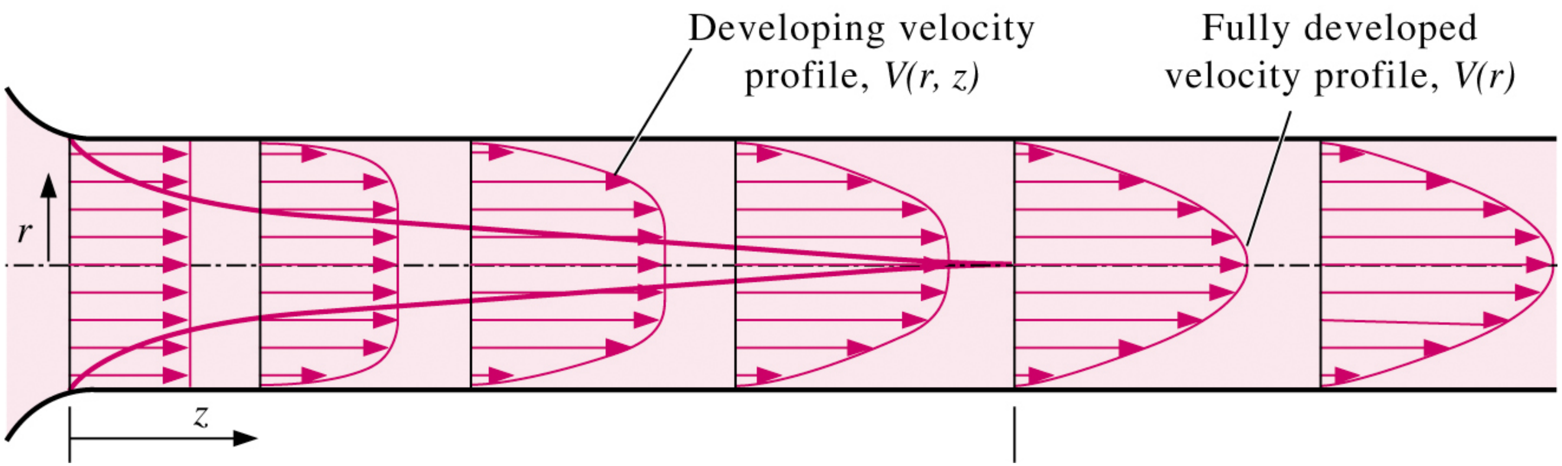
$$\frac{\partial \mathbf{U}}{\partial t} = \frac{\partial \rho}{\partial t} = 0$$

- Unsteady is the opposite of steady.
  - Transient usually describes a starting, or developing flow.
  - Periodic refers to a flow which oscillates about a mean.
- Unsteady flows may appear steady if "time-averaged"

1-4 Classification of Flows (8)

One-, Two-, and Three-Dimensional Flows:

- N-S equations are 3D vector equations.
- Velocity vector, $\mathbf{U}(x,y,z,t) = [U_x(x,y,z,t), U_y(x,y,z,t), U_z(x,y,z,t)]$
- Lower dimensional flows reduce complexity of analytical and computational solution
- Change in coordinate system (cylindrical, spherical, etc.) may facilitate reduction in order.
- Example: for fully-developed pipe flow, velocity $V(r)$ is a function of radius r and pressure $p(z)$ is a function of distance z along the pipe.



1-4 Classification of Flows (9)

- National (or unforced) versus Forced Flow

  (1) forced flow--- a fluid is forced to flow over a surface or in a pipe by external means such as a pump or a fan

  (2) natural flow--- any fluid motion is due to natural means such as buoyancy effect

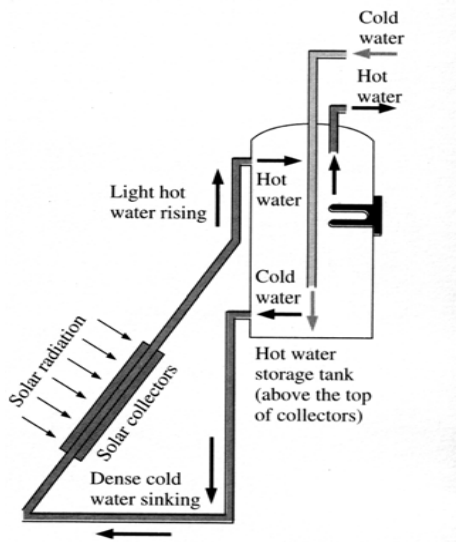
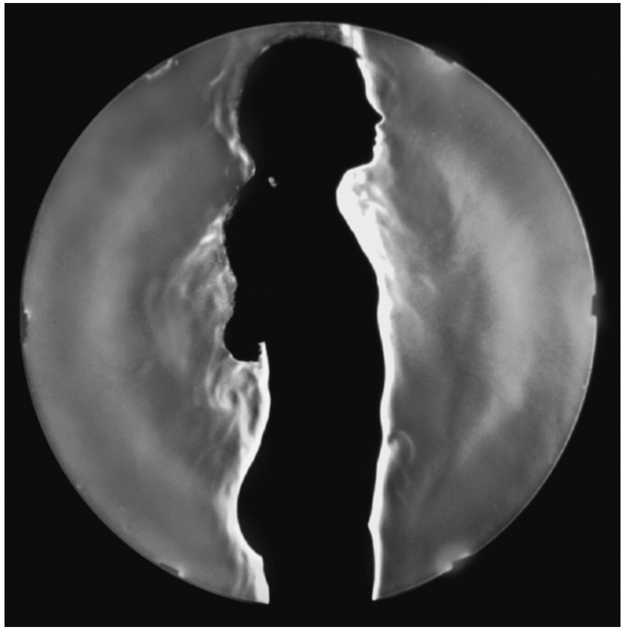
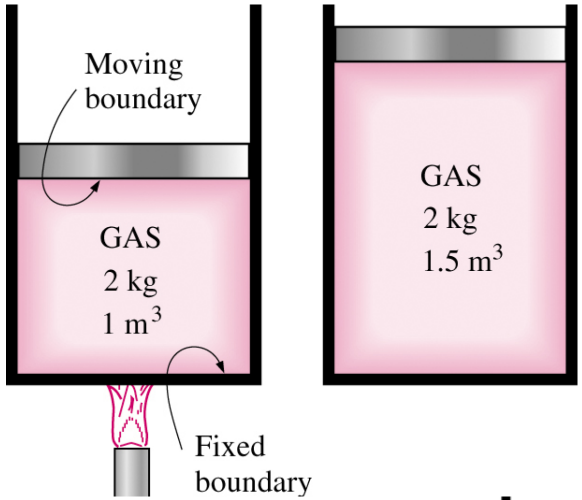
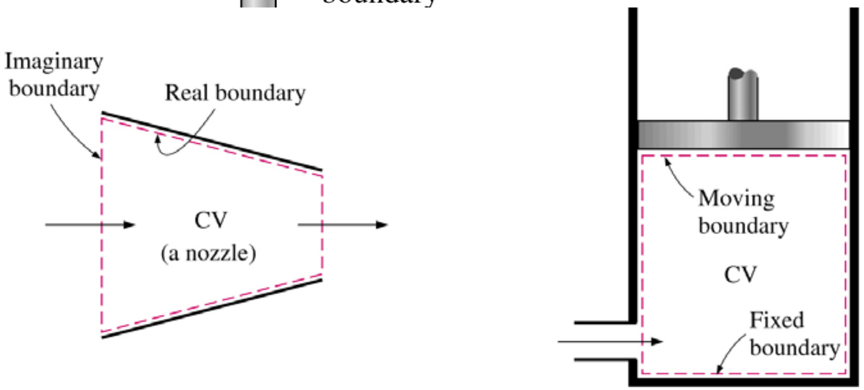


FIGURE 9-2



1-5 System and Control Volume (1)





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

(*b*) A control volume (CV) with fixed and moving boundaries

- A system is defined as a quantity of matter or a region in space chosen for study.
- A closed system consists of a fixed amount of mass.
- An open system, or control volume, is a properly selected region in space.

1-5 System and Control Volume (2)

Basic Equations:

We need forms of the following:

- Conservation of mass
- Newton's second law of motion
- The principle of angular momentum
- The first law of thermodynamics
- The second law of thermodynamics

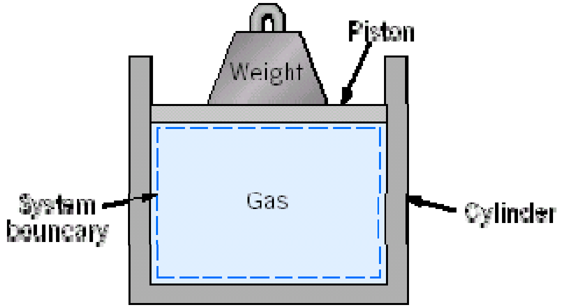


Fig. 1.2 Piston-cylinder assembly.

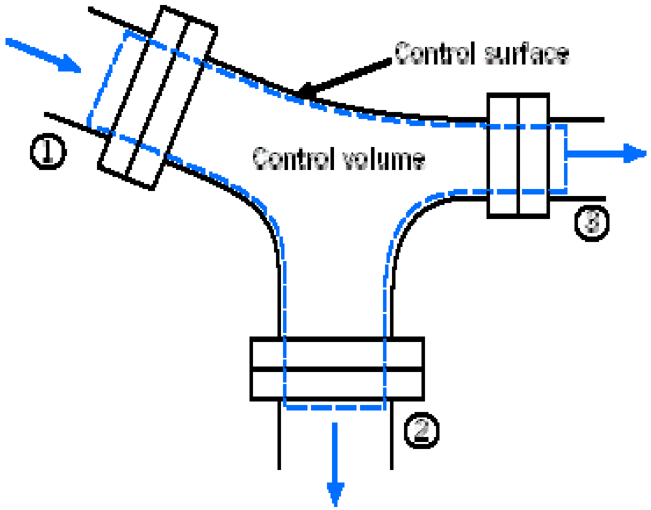
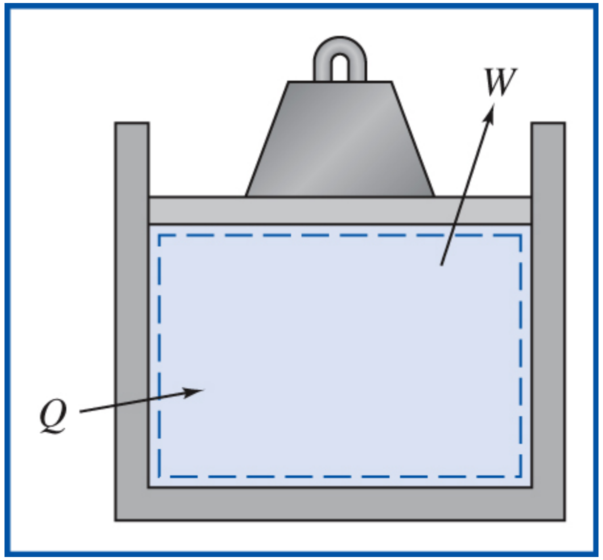


Fig. 1.3 Fluid flow through a pipe junction.

1-5 System and Control Volume (3)

- **EXAMPLE1.1** First Law Application to Closed System

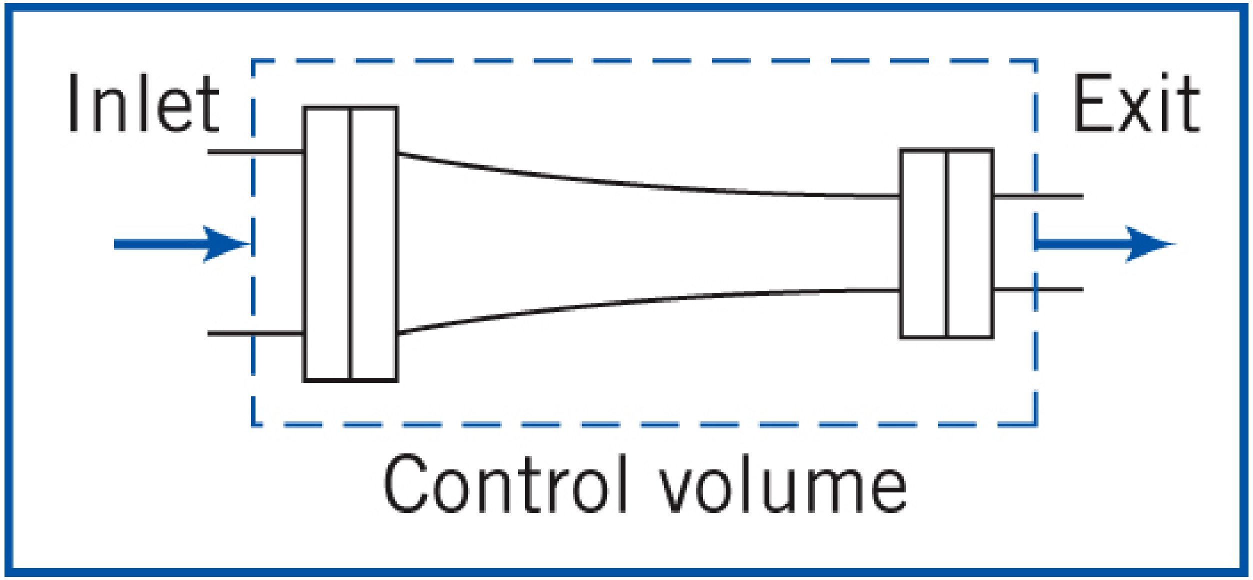
  A piston-cylinder device contains 0.95 kg of oxygen initially at a temperature of 27 ℃ and a pressure due to the weight of 150 kPa (abs). Heat is added to the gas until it reaches a temperature of 627 ℃. Determine the amount of heat added during the process.



1-5 System and Control Volume (4)

- **EXAMPLE1.2** 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.



1-6 Dimensions and Units (1)

- Any physical quantity can be characterized by **dimensions**.
- The magnitudes assigned to dimensions are called **units**.
- Primary dimensions include: mass m, length L, time t, and temperature T.
- Secondary dimensions can be expressed in terms of primary dimensions and include: velocity V, energy E, and volume V.
- Unit systems include English system and the metric SI (International System). We'll use both.
- **Dimensional homogeneity** is a valuable tool in checking for errors. Make sure every term in an equation has the same units.
- **Unity conversion ratios** are helpful in converting units. Use them.

1-6 Dimensions and Units (2)

- Systems of Dimensions
  - ✓ $[M]$, $[L]$, $[t]$, and $[T]$
  - ✓ $[F]$, $[L]$, $[t]$, and $[T]$
  - ✓ $[F]$,$[M]$, $[L]$, $[t]$, and $[T]$

1-6 Dimensions and Units (3)

- Systems of Units
  - ✓ MLtT
    - SI (kg, m, s, K)
  - ✓ FLtT
    - British Gravitational (lbf, ft, s, ^{o}R)
  - ✓ FMLtT
    - English Engineering (lbf, lbm, ft, s, ^{o}R)

1-6 Dimensions and Units (4)

Systems of Units

TABLE 1.1 Common Unit Systems

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

1-6 Dimensions and Units (5)

- Preferred Systems of Units

✓ **SI (kg, m, s, K)**

$$1\ \text{N} \equiv 1\ \text{kg} \cdot \text{m/s}^2$$

✓ **British Gravitational (lbf, ft, s, ºR)**

$$1\ \text{slug} \equiv 1\ \text{lbf} \cdot \text{s}^2/\text{ft}$$

$$1\ \text{slug} \equiv 32.2\ \text{lbm}$$

1-6 Dimensions and Units (6)

❑ Dimensional Homogeneity:

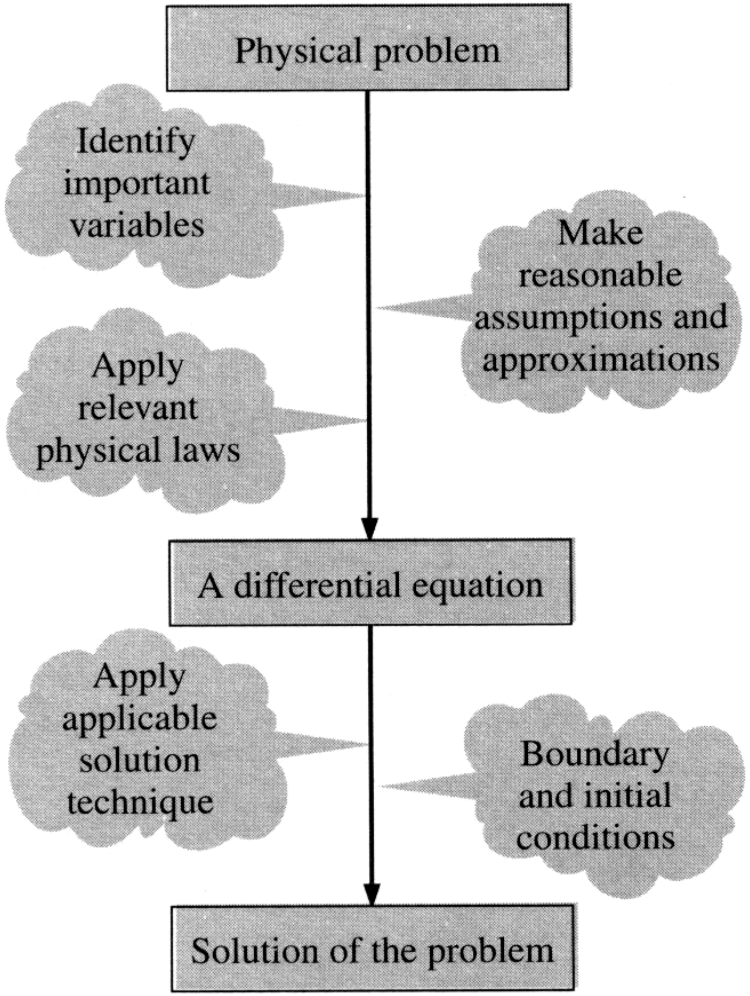
EXAMPLE 1-1 Spotting Errors from Unit Inconsistencies

While solving a problem, a person ended up with the following equation at some stage:

$$E = 25 \text{ kJ} + 7 \text{ kJ/kg}$$

where E is the total energy and has the unit of kilojoules. Determine the error that may have caused it.

1-7 Solving Engineering Problems (1)



1-8 Solving Engineering Problems (2)

- Step1: *Problem Statement*

  Step2: *Schematic*

  Step3: *Assumptions*

  Step4: *Physical Laws*

  Step5: *Properties*

  Step6: *Calculations*

  Step7: *Reasoning,Verification,and Discussion*

1-8 Solving Engineering Problems (3)

- **EXAMPLE1.3** Free-Fall of Ball in Air

The air resistance (drag force) on a 200 g ball in free flight is given by , where is in newtons and V is meters per second. If the ball is dropped from rest 500 m above the ground, determine the speed at which it hits the ground. What percentage of the terminal speed is the result? (The *terminal speed* is the steady speed a falling body eventually attains.)