Chapter 1: Basic Concepts

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Fall 2014

Note to Instructors

These slides were developed[1] during the spring semester 2005, as a teaching aid for the undergraduate Fluid Mechanics course (ME33: Fluid Flow) in the Department of Mechanical and Nuclear Engineering at Penn State University. This course had two sections, one taught by myself and one taught by Prof. John Cimbala. While we gave common homework and exams, we independently developed lecture notes. This was also the first semester that ***Fluid Mechanics: Fundamentals and Applications*** was used at PSU. My section had 93 students and was held in a classroom with a computer, projector, and blackboard. While slides have been developed for each chapter of ***Fluid Mechanics: Fundamentals and Applications,*** I used a combination of blackboard and electronic presentation. In the student evaluations of my course, there were both positive and negative comments on the use of electronic presentation. Therefore, these slides should only be integrated into your lectures with careful consideration of your teaching style and course objectives.

Eric Paterson
Penn State, University Park
August 2005

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[1] These slides were originally prepared using the LaTeX typesetting system (http://www.tug.org/) and the beamer class (http://latex-beamer.sourceforge.net/), but were translated to PowerPoint for wider dissemination by McGraw-Hill.

Introduction

- **Mechanics** is the oldest physical science that deals with both stationary and moving bodies under the influence of forces.
- The branch of mechanics that deals with bodies at rest is called **statics,** while the branch that deals with bodies in motion is called **dynamics.** The subcategory **fluid mechanics** is defined as the science that deals with the behavior of fluids at rest (*fluid statics*) or in motion (*fluid dynamics*), and the interaction of fluids with solids or other fluids at the boundaries. Fluid mechanics is also referred to as **fluid dynamics** by considering fluids at rest as a special case of motion with zero velocity (Fig. 1–1).

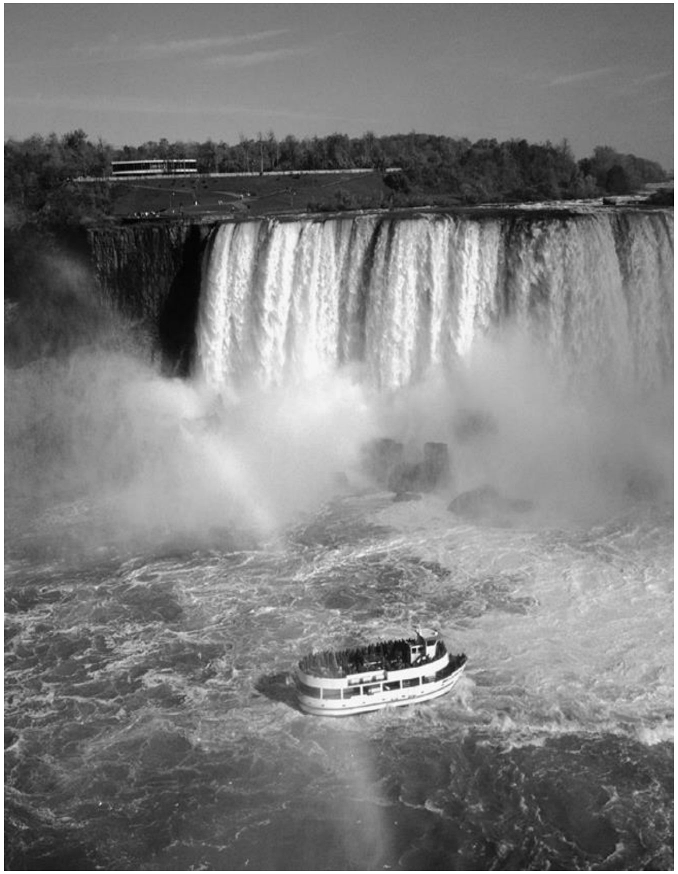


FIGURE 1–1 Fluid mechanics deals with liquids and gases in motion or at rest. © *Vol. 16/Photo Disc.*

Introduction

Fluid mechanics itself is also divided into several categories. The study of

- **Hydrodynamics:** the motion of fluids that are practically incompressible (such as liquids, especially water, and gases at low speeds) is usually referred to as**.**
- A subcategory of hydrodynamics is **hydraulics,** which deals with liquid flows in pipes and open channels.
- **Gas dynamics** deals with the flow of fluids that undergo significant density changes, such as the flow of gases through nozzles at high speeds.
- **Aerodynamics** deals with the flow of gases (especially air) over bodies such as aircraft, rockets, and automobiles at high or low speeds.
- Some other specialized categories such as **meteorology, oceanography,** and **hydrology** deal with naturally occurring flows.

What is a fluid?

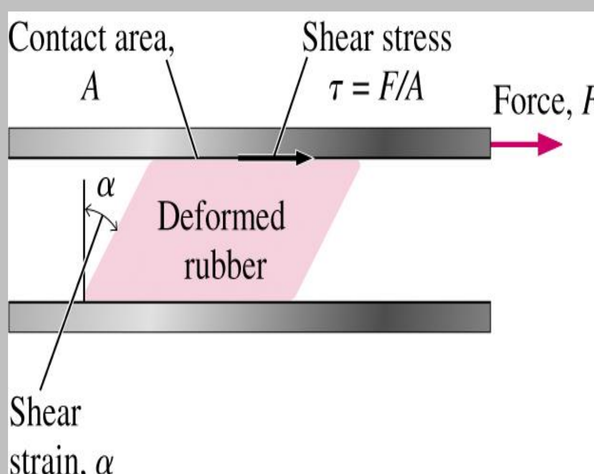
- A substance in the liquid or gas phase is referred to as a **fluid.**
- Distinction between a solid and a fluid is made on the basis of the substance's ability to resist an applied shear (or tangential) stress that tends to change its shape.
- A solid can resist an applied shear stress by deforming, whereas a fluid deforms continuously under the influence of shear stress, no matter how small.
- In solids stress is proportional to *strain*, but in fluids stress is proportional to *strain rate*. When a constant shear force is applied, a solid eventually stops deforming, at some fixed strain angle, whereas a fluid never stops deforming and approaches a certain rate of strain.

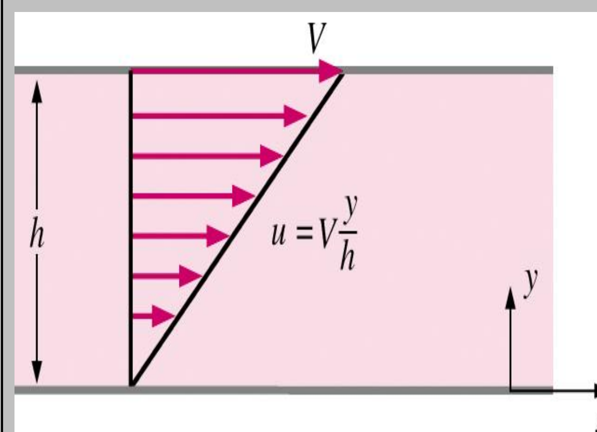
What is a fluid?

- 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

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

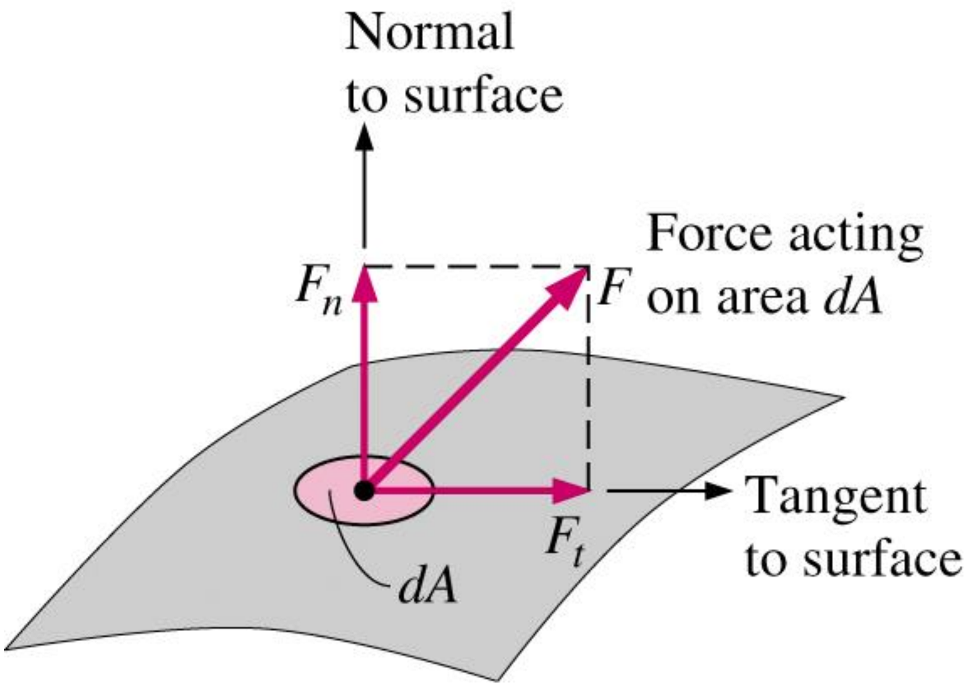




Fluid

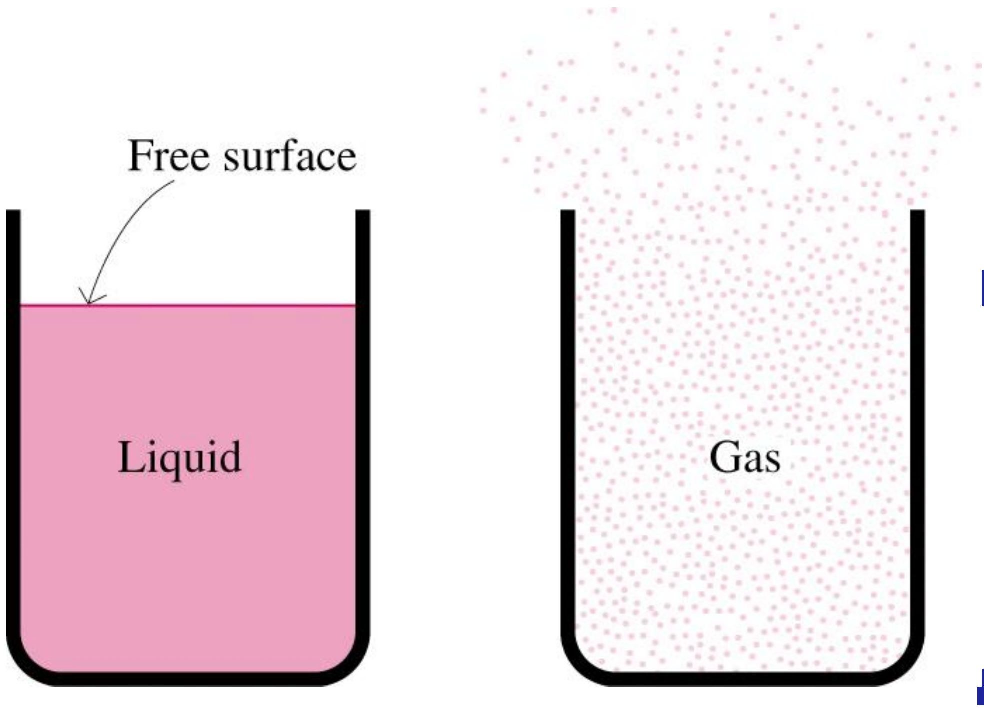
$$\tau = \frac{F}{A} \propto \mu \frac{V}{h}$$

What is a fluid?



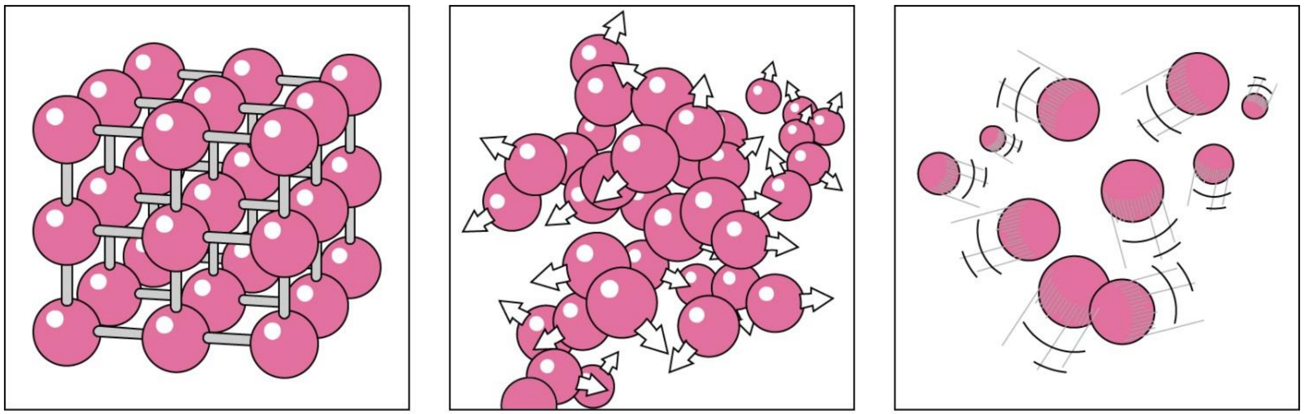
- Stress is defined as the force per unit area.
- Normal component: normal stress
  - In a fluid at rest, the normal stress is called **pressure**
- Tangential component: shear stress

What is a fluid?



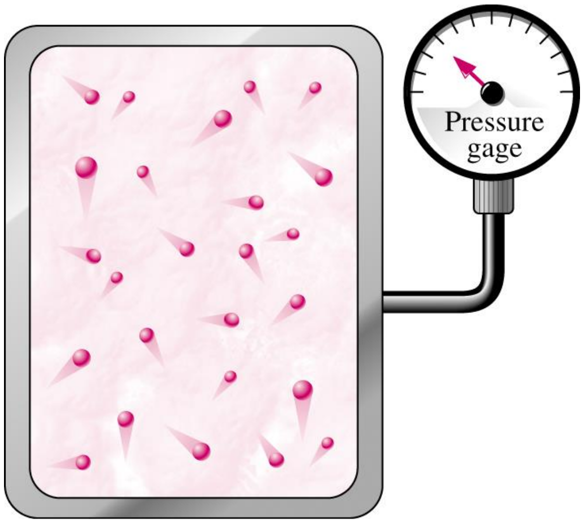
- A liquid takes the shape of the container it is in and forms a free surface in the presence of gravity
- A gas expands until it encounters the walls of the container and fills the entire available space. Gases cannot form a free surface
- Gas and vapor are often used as synonymous words

What is a fluid?



(a) solid (b) liquid (c) gas

On a microscopic scale, pressure is determined by the interaction of individual gas molecules.



Intermolecular bonds are strongest in solids and weakest in gases. One reason is that molecules in solids are closely packed together, whereas in gases they are separated by relatively large distances

Application Areas of Fluid Mechanics

Natural flows and weather
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Boats
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Aircraft and spacecraft
© Vol. 1/Photo Disc.

Power plants
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Human body
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Cars
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Wind turbines
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Piping and plumbing systems
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Industrial applications
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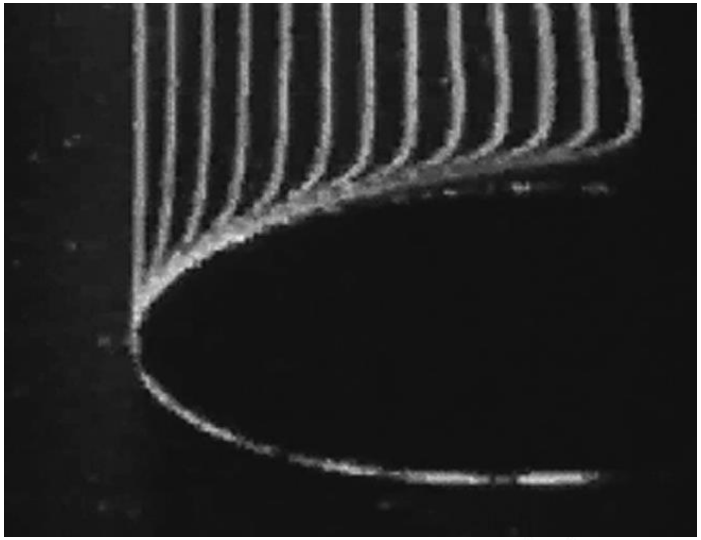
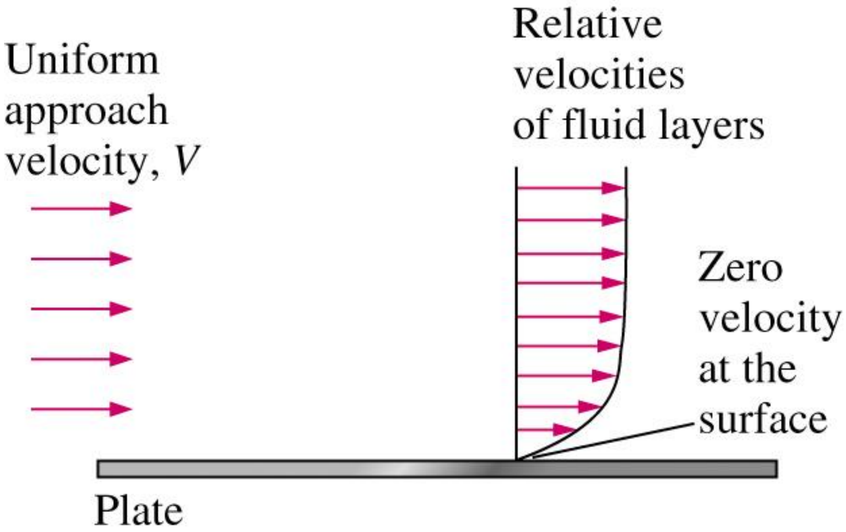
No-slip condition

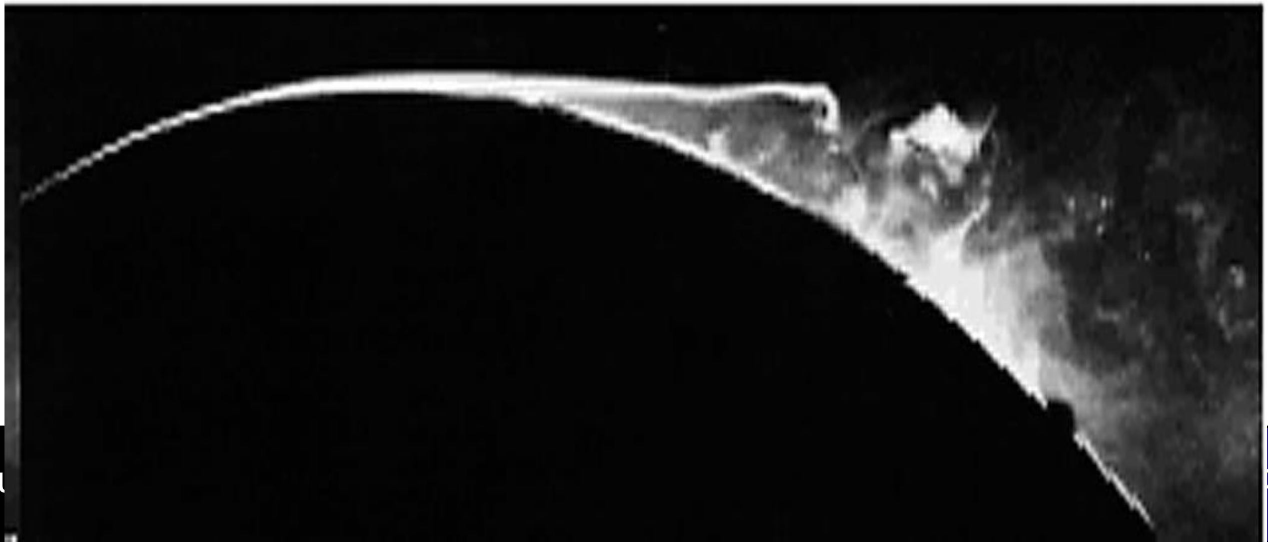




- No-slip condition: A fluid in direct contact with a solid ``sticks'' to the surface due to viscous effects
- Responsible for generation of wall shear stress τ_w, surface drag $D = \int \tau_w \, dA$, and the development of the boundary layer
- The fluid property responsible for the no-slip condition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

No-slip condition

When a fluid is forced to flow over a curved surface, the boundary layer can no longer remain attached to the surface, and at some point it separates from the surface—a process called **flow separation**. We emphasize that the no-slip condition applies *everywhere* along the surface, even downstream of the separation point. Flow separation is discussed in greater detail in Chap. 10.



A BRIEF HISTORY OF FLUID MECHANICS

Please refer to section 1-3 in the text book

From 283 to 133 BC, they built a series of pressurized lead and clay pipelines, up to 45 km long that operated at pressures exceeding 1.7 MPa (180 m of head)

Done at the Hellenistic city of Pergamon in present-day Turkey.

Classification of Flows

- 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

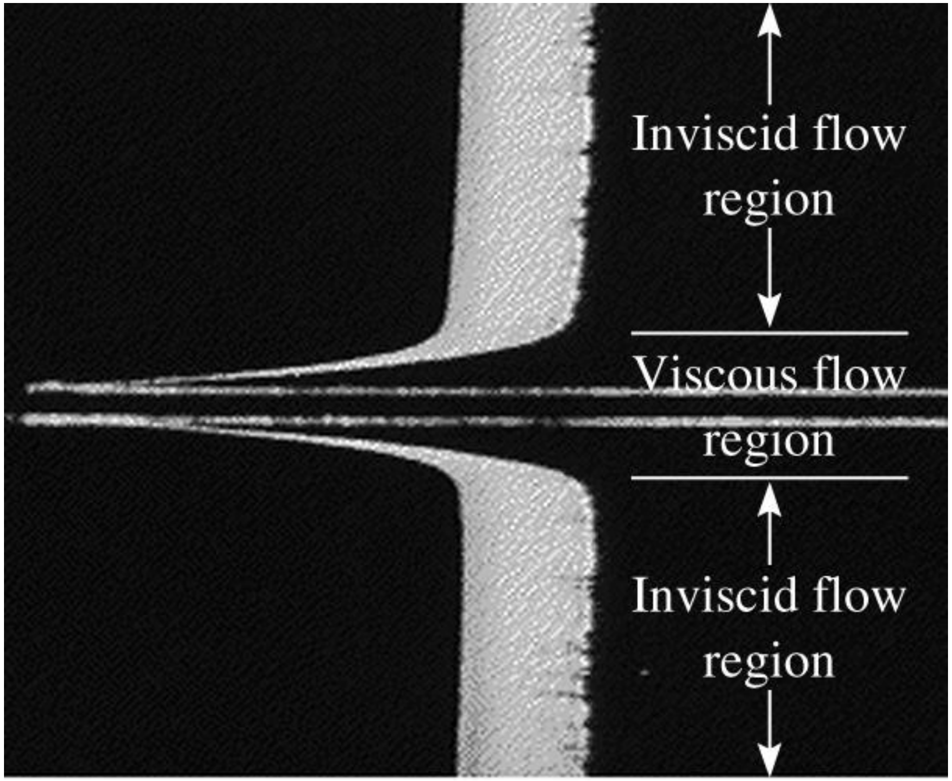
$$\rho \frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U} \cdot \nabla) \mathbf{U} = -\nabla p + \rho \mathbf{g} + \mu \nabla^2 \mathbf{U}$$

Viscous vs. Inviscid Regions of Flow

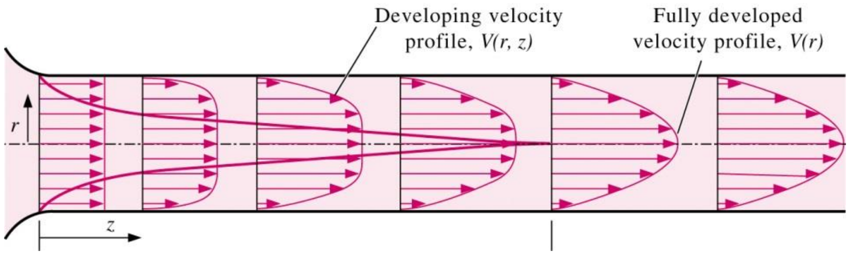
- Regions where frictional effects are significant are called viscous regions. They are usually close to solid surfaces.
- Regions where frictional forces are small compared to inertial or pressure forces are called inviscid

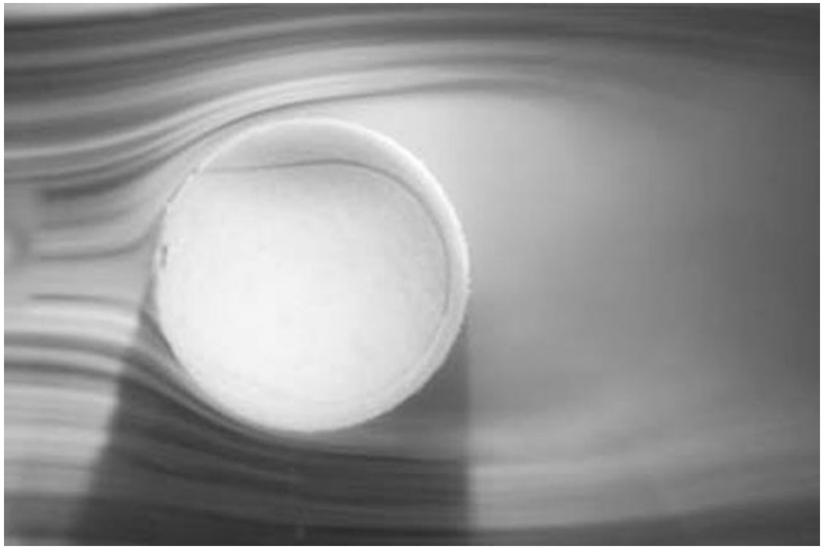
For inviscid flows:

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



Internal vs. External Flow





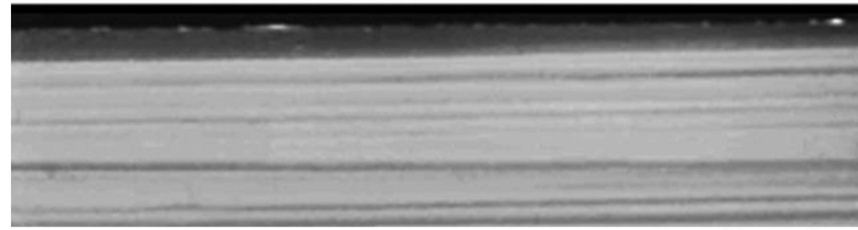
- Internal flows are dominated by the influence of viscosity throughout the flow field
- For external flows, viscous effects are limited to the boundary layer and wake.

Compressible vs. Incompressible Flow

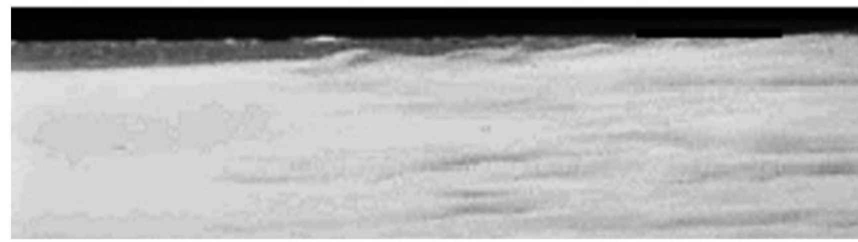
- A flow is classified as incompressible if the density remains nearly constant.
- Liquid flows are typically incompressible.
- Gas flows are often compressible, especially for high speeds.
- Mach number, Ma = V/c is a good indicator of whether or not compressibility effects are important.
  - Ma < 0.3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

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= $\rho UL/\mu$ is the key parameter in determining whether or not a flow is laminar or turbulent.



Laminar



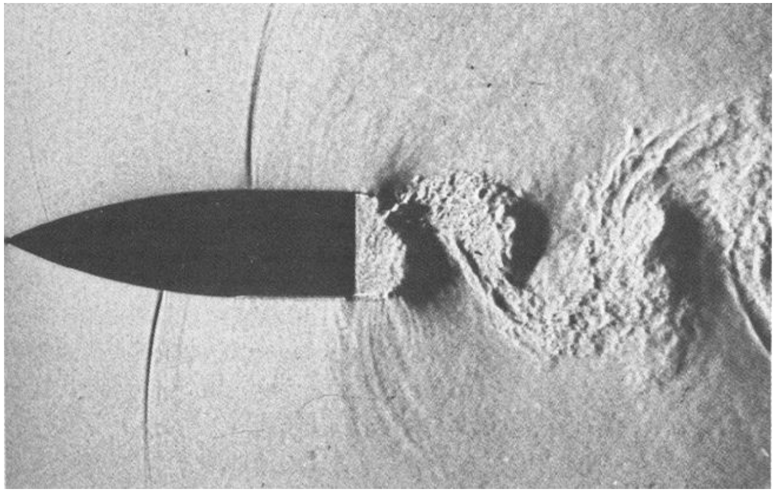
Transitional

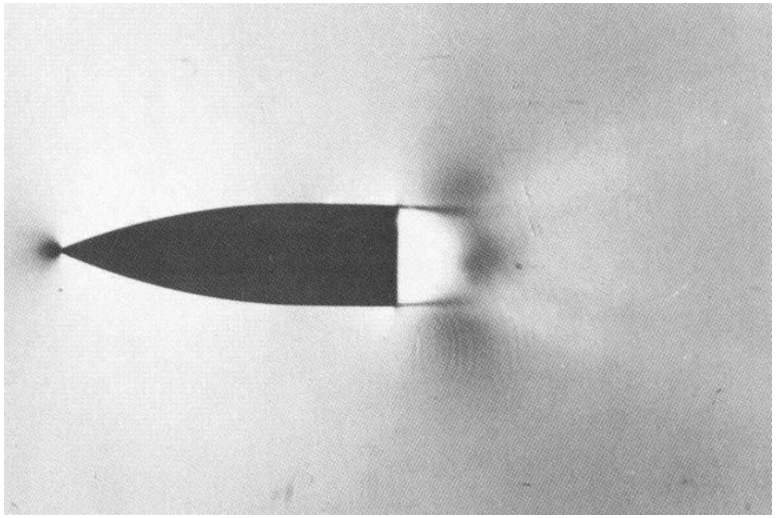
Turbulent

Natural (or Unforced) versus Forced Flow

- A fluid flow is said to be natural or forced, depending on how the fluid motion is initiated.
- In **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.
- In **natural flows,** any fluid motion is due to natural means such as the buoyancy effect, which manifests itself as the rise of the warmer (and thus lighter) fluid and the fall of cooler (and thus denser) fluid

Steady vs. Unsteady Flow

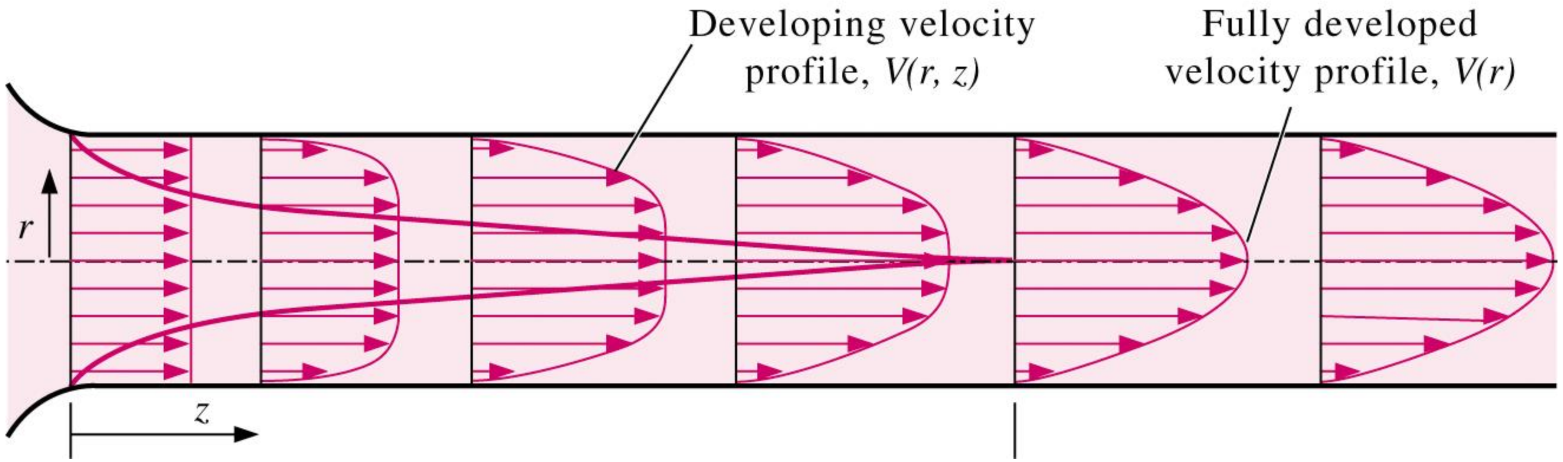




- Steady implies no change at a point with time. Transient terms in N-S equations are zero $\frac{\partial \mathbf{U}}{\partial t} = \frac{\partial \rho}{\partial t} = 0$
- Unsteady is the opposite of steady.
  - Transient usually describes a starting, or developing flow.
  - Periodic refers to a flow which oscillates about a mean.
- Unsteady flows may appear steady if “time-averaged”

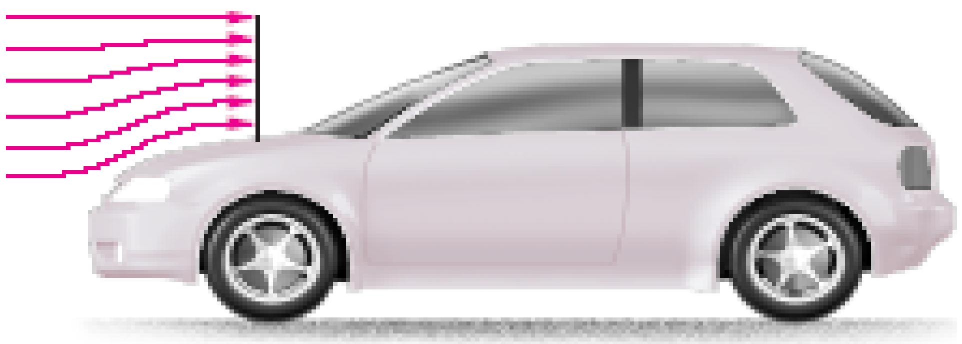
One-, Two-, and Three-Dimensional Flows

- N-S equations are 3D vector equations.
- Velocity vector, $\boldsymbol{U}(x,y,z,t) = [U_x(x,y,z,t), U_y(x,y,z,t), U_z(x,y,z,t)]$
- 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.



One-, Two-, and Three-Dimensional Flows

A flow may be approximated as *two-dimensional* when the aspect ratio is large and the flow does not change appreciably along the longer dimension. For example, the flow of air over a car antenna can be considered two-dimensional except near its ends since the antenna's length is much greater than its diameter, and the airflow hitting the antenna is fairly uniform



One-, Two-, and Three-Dimensional Flows

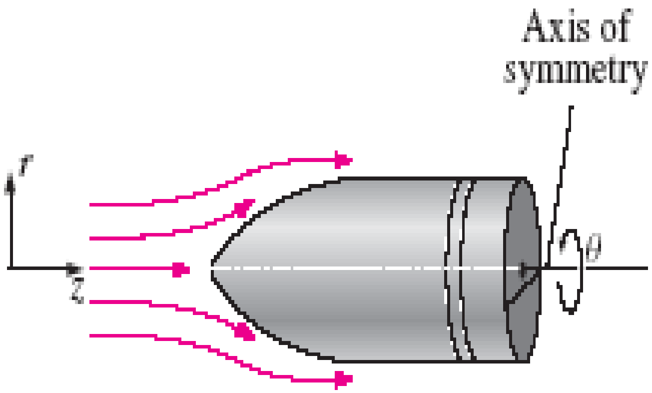


FIGURE 1–22
Axisymmetric flow over a bullet.

EXAMPLE 1–1 Axisymmetric Flow over a Bullet

Consider a bullet piercing through calm air. Determine if the time-averaged airflow over the bullet during its flight is one-, two-, or three-dimensional (Fig. 1–22).

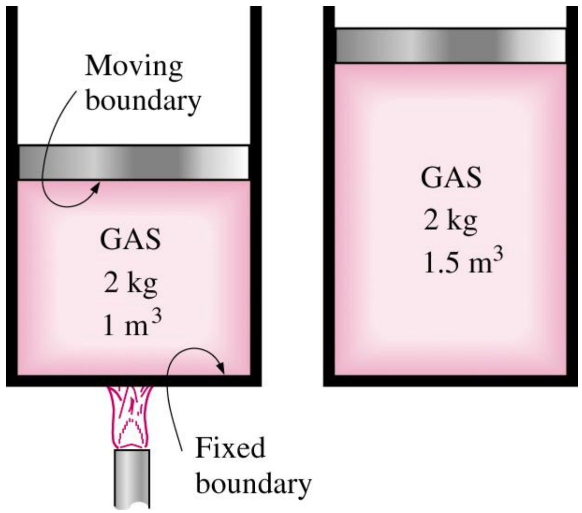
SOLUTION It is to be determined whether airflow over a bullet is one-, two-, or three-dimensional.

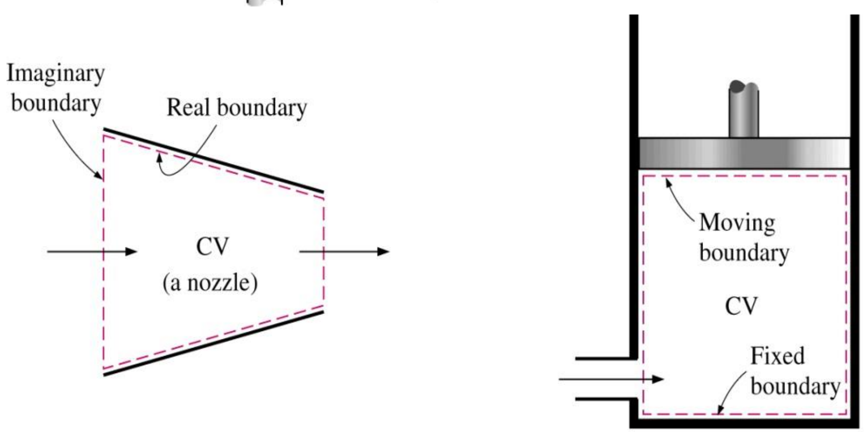
Assumptions There are no significant winds and the bullet is not spinning.

Analysis The bullet possesses an axis of symmetry and is therefore an axisymmetric body. The airflow upstream of the bullet is parallel to this axis, and we expect the time-averaged airflow to be rotationally symmetric about the axis—such flows are said to be axisymmetric. The velocity in this case varies with axial distance z and radial distance r, but not with angle θ. Therefore, the time-averaged airflow over the bullet is two-dimensional.

Discussion While the time-averaged airflow is axisymmetric, the *instantaneous* airflow is not, as illustrated in Fig. 1–19.

System and Control Volume





(*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 (known as a control mass) consists of a fixed amount of mass.
- An open system, or control volume, is a properly selected region in space. It usually encloses a device that involves mass flow such as a compressor, turbine, or nozzle.

System and Control Volume

- In general, *any arbitrary region in space* can be selected as a control volume. There are no concrete rules for the selection of control volumes, but the proper choice certainly makes the analysis much easier.
- We'll discuss control volumes in more detail in Chapter 6.

Dimensions and Units

- Any physical quantity can be characterized by **dimensions**.
- The magnitudes assigned to dimensions are called **units**.
- Primary dimensions (or fundamental dimensions) include: mass *m*, length *L*, time *t*, and temperature *T, etc*.

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)

By *General Conference of Weights and Measures*

Dimensions and Units

- Secondary dimensions (derived 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.

Dimensions and Units

Based on the notational scheme introduced in 1967,

- The degree symbol was officially dropped from the absolute temperature unit,
- All unit names were to be written without capitalization even if they were derived from proper names (Table 1–1).
- However, the abbreviation of a unit was to be capitalized if the unit was derived from a proper name. For example, the SI unit of force, which is named after Sir Isaac Newton (1647–1723), is *newton* (not Newton), and it is abbreviated as N.
- Also, the full name of a unit may be pluralized, but its abbreviation cannot. For example, the length of an object can be 5 m or 5 meters, *not* 5 ms or 5 meter.
- Finally, no period is to be used in unit abbreviations unless they appear at the end of a sentence. For example, the proper abbreviation of meter is m (not m.).

Dimensions and Units

Some SI and English Units

- In SI, the units of mass, length, and time are the kilogram (kg), meter (m), and second (s), respectively. The respective units in the English system are the pound-mass (lbm), foot (ft), and second (s).

$$1 \text{ lbm} = 0.45359 \text{ kg}$$

$$1 \text{ ft} = 0.3048 \text{ m}$$

Dimensions and Units

Force Units

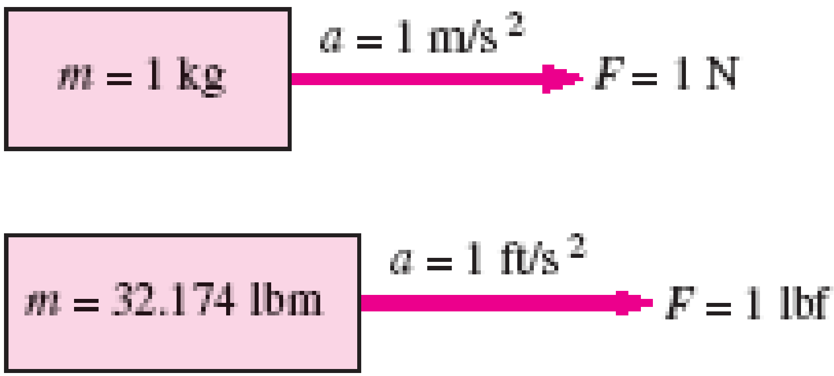


FIGURE 1–27
The definition of the force units.

We call a mass of *32.174 lbm 1 slug*

Dimensions and Units

- **Weight** *W* is a *force.* It is the gravitational force applied to a body, and its magnitude is determined from Newton's second law,

$$W = mg \quad (\mathrm{N})$$

where *m* is the mass of the body, and *g* is the local gravitational acceleration (*g* is 9.807 m/s^2 or 32.174 ft/s^2 at sea level and 45° latitude).

- The weight of a unit volume of a substance is called the **specific weight** γ and is determined from $\gamma = \rho g$, where ρ is density.

Dimensions and Units

- *Work*, which is a form of energy, can simply be defined as force times distance; therefore, it has the unit “newton-meter (N . m),” which is called a joule (J). That is,

$$1 \text{ J} = 1 \text{ N} \cdot \text{m}$$

- A more common unit for energy in SI is the kilojoule (1 kJ = 10^3 J). In the English system, the energy unit is the **Btu** (British thermal unit), which is defined as the energy required to raise the temperature of 1 lbm of water at 68°F by 1°F.

- In the metric system, the amount of energy needed to raise the temperature of 1 g of water at 14.5°C by 1°C is defined as 1 **calorie** (cal), and 1 cal = 4.1868 J. The magnitudes of the kilojoule and Btu are almost identical (1 Btu = 1.0551 kJ).

Dimensions and Units

- **Dimensional homogeneity** is a valuable tool in checking for errors. Make sure every term in an equation has the same units.

EXAMPLE 1–2 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 how to correct the error and discuss what may have caused it.

SOLUTION During an analysis, a relation with inconsistent units is obtained. A correction is to be found, and the probable cause of the error is to be determined.

Analysis The two terms on the right-hand side do not have the same units, and therefore they cannot be added to obtain the total energy. Multiplying the last term by mass will eliminate the kilograms in the denominator, and the whole equation will become dimensionally homogeneous; that is, every term in the equation will have the same unit.

Discussion Obviously this error was caused by forgetting to multiply the last term by mass at an earlier stage.

Dimensions and Units

- **Unity conversion ratios** are helpful in converting units. Use them.
- *All nonprimary units (**secondary units)** can be formed by combinations of primary units*. Force units, for example, can be expressed as

$$N = kg \frac{m}{s^2} \quad \text{and} \quad lbf = 32.174 \, lbm \frac{ft}{s^2}$$

They can also be expressed more conveniently as **unity conversion ratios** as

$$\frac{N}{kg \cdot m/s^2} = 1 \quad \text{and} \quad \frac{lbf}{32.174 \, lbm \cdot ft/s^2} = 1$$

Dimensions and Units

EXAMPLE 1–4 **The Weight of One Pound-Mass**

Using unity conversion ratios, show that 1.00 lbm weighs 1.00 lbf on earth (Fig. 1–33).

Solution A mass of 1.00 lbm is subjected to standard earth gravity. Its weight in lbf is to be determined.
Assumptions Standard sea-level conditions are assumed.
Properties The gravitational constant is $g = 32.174\ \mathrm{ft/s^2}$.
Analysis We apply Newton's second law to calculate the weight (force) that corresponds to the known mass and acceleration. The weight of any object is equal to its mass times the local value of gravitational acceleration. Thus,

$$W = mg = (1.00\ \mathrm{lbm})(32.174\ \mathrm{ft/s^2})\left(\frac{1\ \mathrm{lbf}}{32.174\ \mathrm{lbm \cdot ft/s^2}}\right) = 1.00\ \mathrm{lbf}$$

Discussion Mass is the same regardless of its location. However, on some other planet with a different value of gravitational acceleration, the weight of 1 lbm would differ from that calculated here.

MATHEMATICAL MODELING OF ENGINEERING PROBLEMS

- An engineering device or process can be studied either
  - *experimentally* (testing and taking measurements)

  Advantage : deal with the actual physical system, and the desired quantity is determined by measurement, within the limits of experimental error.

  Drawback: approach is expensive, time-consuming, and often impractical. Besides, the system we are studying may not even exist.

  - *analytically* (by analysis or calculations).

  Advantage : fast and inexpensive

  Drawback: the results obtained are subject to the accuracy of the assumptions, approximations, and idealizations made in the analysis.

- In engineering studies, often a good compromise is reached by reducing the choices to just a few by analysis, and then verifying the findings experimentally.

MATHEMATICAL MODELING OF ENGINEERING PROBLEMS

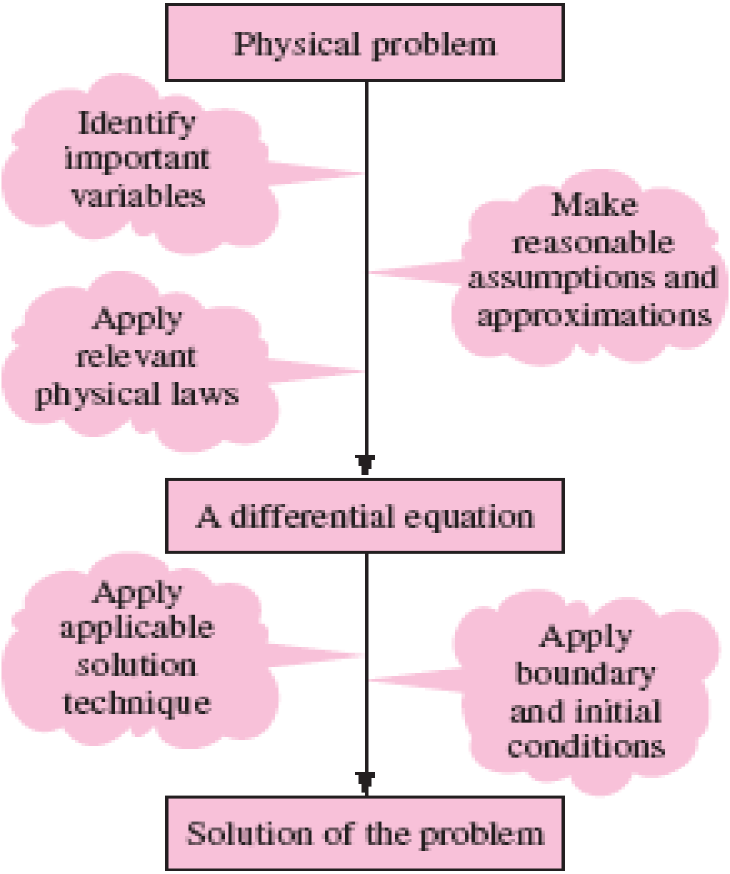


FIGURE 1–35
Mathematical modeling of physical problems.

MATHEMATICAL MODELING OF ENGINEERING PROBLEMS

- The study of physical phenomena involves two important steps.
  - In the first step, all the variables that affect the phenomena are identified, reasonable assumptions and approximations are made, and the interdependence of these variables is studied. The relevant physical laws and principles are invoked, and the problem is formulated mathematically. The equation itselfis very instructive as it shows the degree of dependence of some variables on others, and the relative importance of various terms.
  - In the second step the problem is solved using an appropriate approach, and the results are interpreted.

PROBLEM-SOLVING TECHNIQUE

- using a step-by-step approach, an engineer can reduce the solution of a complicated problem into the solution of a series of simple problems.

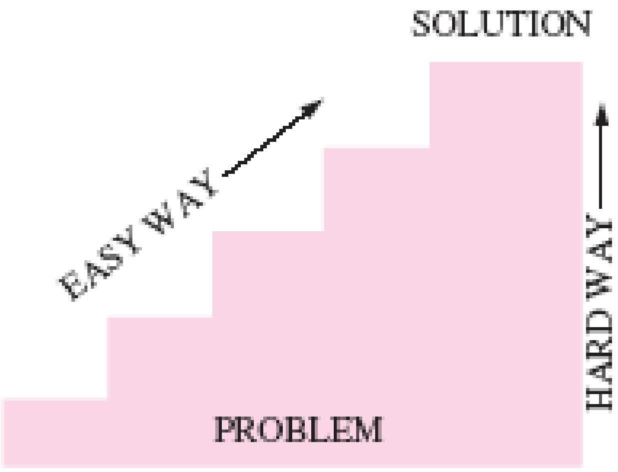


FIGURE 1–36
A step-by-step approach can greatly simplify problem solving.

PROBLEM-SOLVING TECHNIQUE

- **Step 1: Problem Statement**
- **Step 2: Schematic**
- **Step 3: Assumptions and Approximations**
- **Step 4: Physical Laws**
- **Step 5: Properties**
- **Step 6: Calculations**
- **Step 7: Reasoning, Verification, and Discussion**

Reasoning, Verification, and Discussion

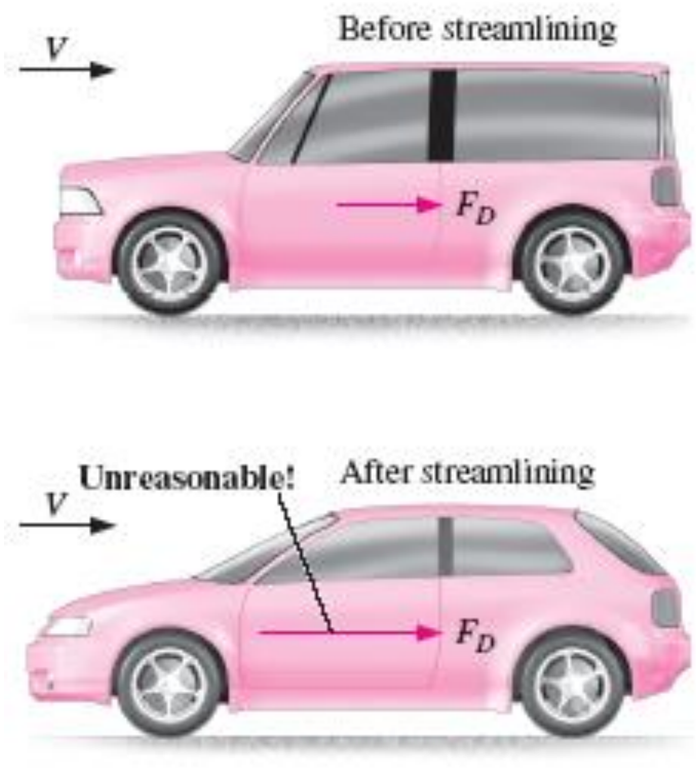


FIGURE 1–38
The results obtained from an engineering analysis must be checked for reasonableness.

ENGINEERING SOFTWARE PACKAGES

- **Engineering Equation Solver (EES)** is a program that solves systems of linear or nonlinear algebraic or differential equations numerically.
- **FLUENT** is a computational fluid dynamics (CFD) code widely used for flow-modeling applications.

Please refer to section 1-9 in the text book.

Accuracy, Precision, and Significant Digits

Engineers must be aware of three principals that govern the proper use of numbers.

1. ***Accuracy error :*** Value of one reading minus the true value. Closeness of the average reading to the true value. Generally associated with repeatable, fixed errors.
2. ***Precision error :*** Value of one reading minus the average of readings. Is a measure of the fineness of resolution and repeatability of the instrument. Generally associated with random errors.
3. ***Significant digits :*** Digits that are relevant and meaningful. When performing calculations, the final result is only as precise as the least precise parameter in the problem. When the number of significant digits is unknown, the accepted standard is 3. Use 3 in all homework and exams.

Accuracy, Precision, and Significant Digits

- A measurement or calculation can be very precise without being very accurate, and vice versa. For example, suppose the true value of wind speed is 25.00 m/s. Two anemometers A and B take five wind speed readings each: *Anemometer A:* 25.50, 25.69, 25.52, 25.58, and 25.61 m/s. Average of all readings = 25.58 m/s. *Anemometer B:* 26.3, 24.5, 23.9, 26.8, and 23.6 m/s. Average of all readings = 25.02 m/s.

Accuracy, Precision, and Significant Digits

In engineering calculations, the supplied information is not known to more than a certain number of significant digits, usually three digits.

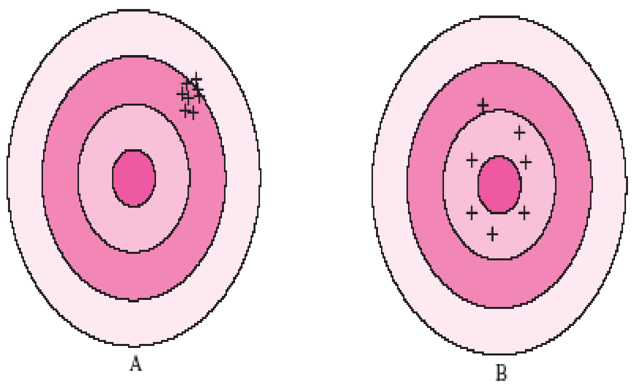


FIGURE 1–40

Illustration of accuracy versus precision. Shooter A is more precise, but less accurate, while shooter B is more accurate, but less precise.

Given: Volume: $V = 3.75$ L
Density: $\rho = 0.845$ kg/L

(3 significant digits)

Also, $3.75 \times 0.845 = 3.16875$

Find: Mass: $m = \rho V = 3.16875$ kg

Rounding to 3 significant digits:
$m = 3.17$ kg

Accuracy, Precision, and Significant Digits

EXAMPLE 1–6 Significant Digits and Volume Flow Rate

Jennifer is conducting an experiment that uses cooling water from a garden hose. In order to calculate the volume flow rate of water through the hose, she times how long it takes to fill a container (Fig. 1–42). The volume of water collected is $V = 1.1$ gal in time period $\Delta t = 45.62$ s, as measured with a stopwatch. Calculate the volume flow rate of water through the hose in units of cubic meters per minute.

SOLUTION Volume flow rate is to be determined from measurements of volume and time period.

Assumptions 1 Jennifer recorded her measurements properly, such that the volume measurement is precise to two significant digits while the time period is precise to four significant digits. 2 No water is lost due to splashing out of the container.

Analysis Volume flow rate $\dot{V}$ is volume displaced per unit time and is expressed as

Volume flow rate:

$$\dot{V} = \frac{\Delta V}{\Delta t}$$

Substituting the measured values, the volume flow rate is determined to be

$$\dot{V} = \frac{1.1 \text{ gal}}{45.62 \text{ s}}\left(\frac{3.785 \times 10^{-3} \text{ m}^3}{1 \text{ gal}}\right)\left(\frac{60 \text{ s}}{1 \text{ min}}\right) = \mathbf{5.5 \times 10^{-3} \text{ m}^3/\text{min}}$$

Accuracy, Precision, and Significant Digits

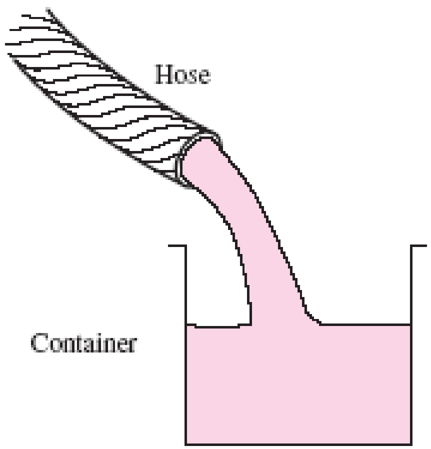


FIGURE 1–42
Schematic for Example 1–6 for the measurement of volume flow rate.

Discussion The final result is listed to two significant digits since we cannot be confident of any more precision than that. If this were an intermediate step in subsequent calculations, a few extra digits would be carried along to avoid accumulated round-off error. In such a case, the volume flow rate would be written as $\dot{V} = 5.4759 \times 10^{-3}\ \text{m}^3/\text{min}$. Based on the given information, we cannot say anything about the *accuracy* of our result, since we have no information about systematic errors in either the volume measurement or the time measurement.

Also keep in mind that good precision does not guarantee good accuracy. For example, if the batteries in the stopwatch were weak, its accuracy could be quite poor, yet the readout would still be displayed to four significant digits of precision.

In common practice, precision is often associated with *resolution*, which is a measure of how finely the instrument can report the measurement. For example, a digital voltmeter with five digits on its display is said to be more

Accuracy, Precision, and Significant Digits

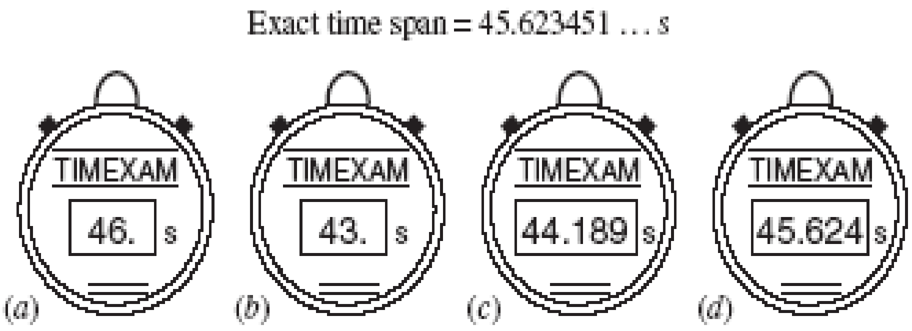


FIGURE 1–43

An instrument with many digits of resolution (stopwatch *c*) may be less accurate than an instrument with few digits of resolution (stopwatch *a*). What can you say about stopwatches *b* and *d*?

precise than a digital voltmeter with only three digits. However, the number of displayed digits has nothing to do with the overall *accuracy* of the measurement. An instrument can be very precise without being very accurate when there are significant bias errors. Likewise, an instrument with very few displayed digits can be more accurate than one with many digits (Fig. 1–43).

Summary

In this chapter some basic concepts of fluid mechanics are introduced and discussed.

- A substance in the liquid or gas phase is referred to as a *fluid*. *Fluid mechanics* is the 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.
- The flow of an unbounded fluid over a surface is *external flow*, and the flow in a pipe or duct is *internal flow* if the fluid is completely bounded by solid surfaces.
- A fluid flow is classified as being *compressible* or *incompressible*, depending on the density variation of the fluid during flow. The densities of liquids are essentially constant, and thus the flow of liquids is typically incompressible.
- The term *steady* implies *no change with time.* The opposite of steady is *unsteady,* or *transient.*
- The term *uniform* implies *no change with location* over a specified region.
- A flow is said to be *one-dimensional* when the velocity changes in one dimension only.

Summary

- A fluid in direct contact with a solid surface sticks to the surface and there is no slip. This is known as the *no-slip condition*, which leads to the formation of *boundary layers* along solid surfaces.
- A system of fixed mass is called a *closed system*, and a system that involves mass transfer across its boundaries is called an *open system* or *control volume.* A large number of engineering problems involve mass flow in and out of a system and are therefore modeled as *control volumes*.
- In engineering calculations, it is important to pay particular attention to the units of the quantities to avoid errors caused by inconsistent units, and to follow a systematic approach.
- It is also important to recognize that the information given is not known to more than a certain number of significant digits,and the results obtained cannot possibly be accurate to more significant digits.

  The information given on dimensions and units; problem-solving technique; and accuracy, precision, and significant digits will be used throughout the entire text.