Fluid Mechanics: Fundamentals and Applications, 2nd Edition
Yunus A. Cengel, John M. Cimbala
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Chapter 1
INTRODUCTION AND BASIC CONCEPTS

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INTRODUCTION AND BASIC CONCEPTS

Schlieren image showing the thermal plume produced by Professor Cimbala as he welcomes you to the fascinating world of fluid mechanics.

Objectives

- Understand the basic concepts of Fluid Mechanics.
- Recognize the various types of fluid flow problems encountered in practice, such as;
  - viscous versus inviscid regions of flow,
  - internal versus external flow,
  - compressible versus incompressible flow,
  - laminar versus turbulent flow,
  - natural versus forced flow,
  - steady versus unsteady flow.
- Model engineering problems and solve them in a systematic manner.
- Have a working knowledge of accuracy, precision, and significant digits, and recognize the importance of dimensional homogeneity in engineering calculations.

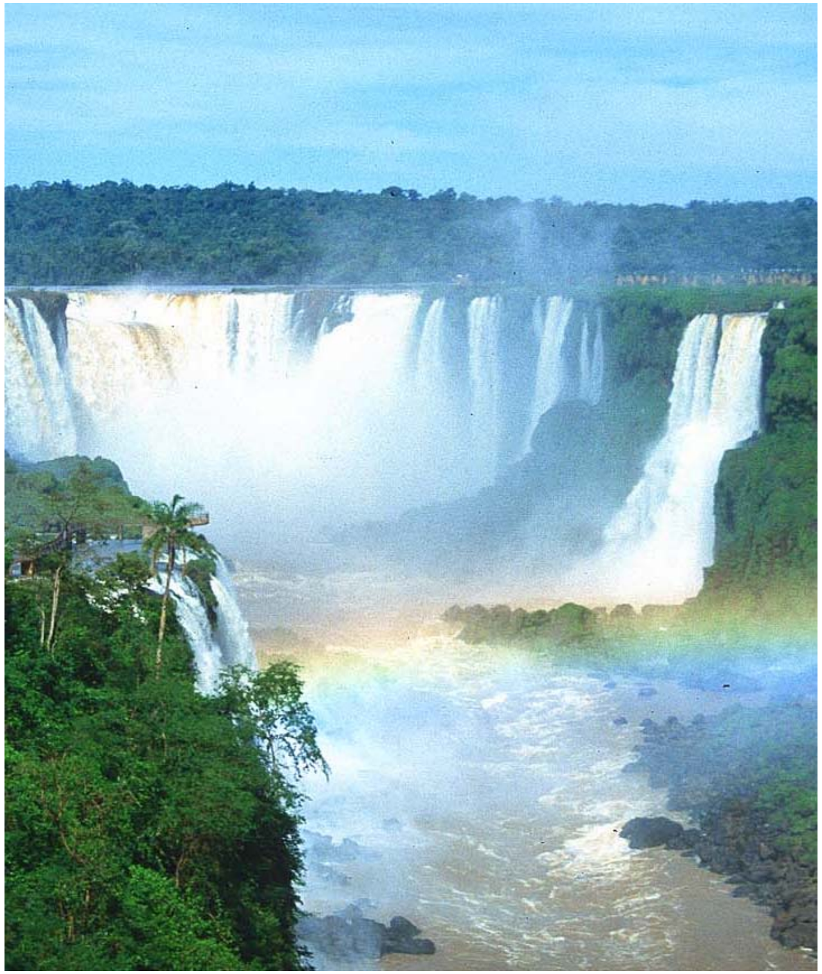
1–1 INTRODUCTION

Mechanics: The oldest physical science that deals with both stationary and moving bodies under the influence of forces.

- **Statics:** The branch of mechanics that deals with bodies at rest.
- **Dynamics:** The branch that deals with bodies in motion.

Fluid mechanics: 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 dynamics: Fluid mechanics is also referred to as fluid dynamics by considering fluids at rest as a special case of motion with zero velocity.



Fluid mechanics deals with liquids and gases in motion or at rest.

[redacted]

Hydrodynamics: The study of the motion of fluids that can be approximated as incompressible (such as liquids, especially water, and gases at low speeds).

- ✓ **Hydraulics:** A subcategory of hydrodynamics, 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.

Meteorology, oceanography, and hydrology: Deal with naturally occurring flows.

What is a Fluid?

Fluid: A substance exists in three primary phases: solid, liquid, and gas.

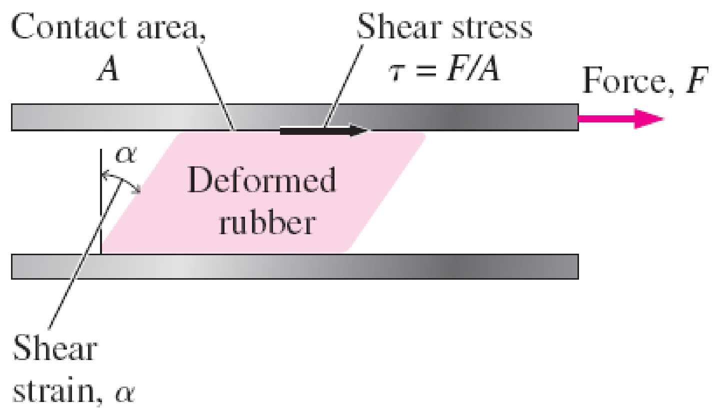
A substance in the liquid or gas phase is referred to as a **fluid.**

A solid can resist an applied shear stress by deforming.

A fluid deforms continuously under the influence of a 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 constant *rate* of strain.



Deformation of a rubber block placed between two parallel plates under the influence of a shear force. The shear stress shown is that on the rubber—an equal but opposite shear stress acts on the upper plate.

[redacted]

Stress: Force per unit area.

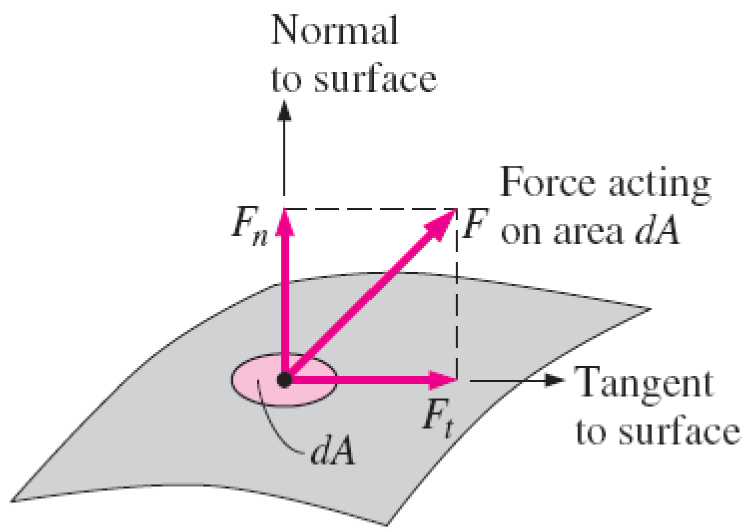
Normal stress: The normal component of a force acting on a surface per unit area.

Shear stress: The tangential component of a force acting on a surface per unit area.

Pressure: The normal stress in a fluid at rest.

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

When the walls are removed or a liquid container is tilted, a shear develops as the liquid moves to re-establish a horizontal free surface.



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

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

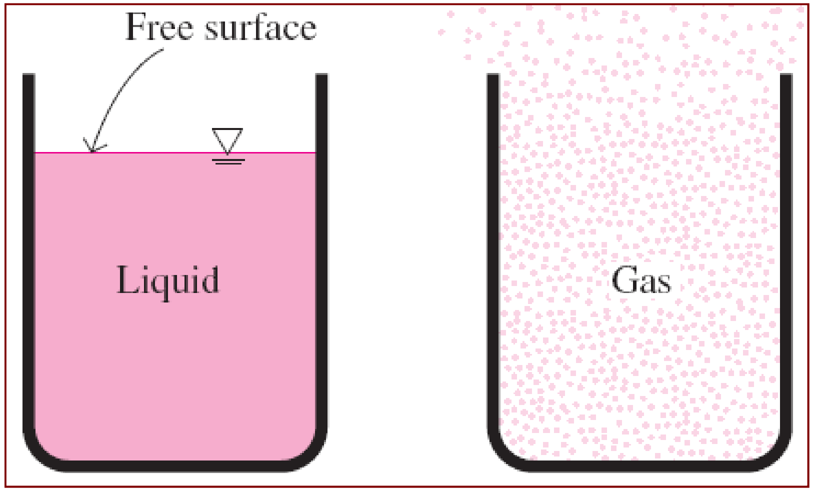
The normal stress and shear stress at the surface of a fluid element. For fluids at rest, the shear stress is zero and pressure is the only normal stress.

[redacted]

In a **liquid**, groups of molecules can move relative to each other, but the volume remains relatively constant because of the strong cohesive forces between the molecules. As a result, a liquid takes the shape of the container it is in, and it forms a free surface in a larger container in a gravitational field.

A **gas** expands until it encounters the walls of the container and fills the entire available space. This is because the gas molecules are widely spaced, and the cohesive forces between them are very small. Unlike liquids, a gas in an open container cannot form a free surface.

States of Matter

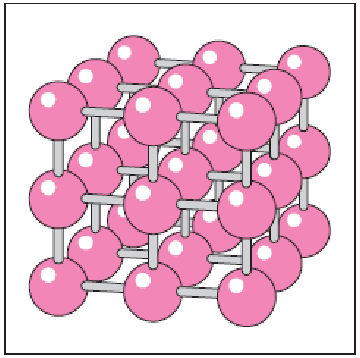


Unlike a liquid, a gas does not form a free surface, and it expands to fill the entire available space.

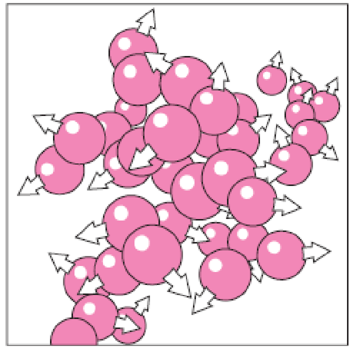
[redacted]

Intermolecular bonds are strongest in solids and weakest in gases.

Solid: The molecules in a solid are arranged in a pattern that is repeated throughout. Because of the small distances between molecules in a solid, the attractive forces of molecules on each other are large and keep the molecules at fixed positions.

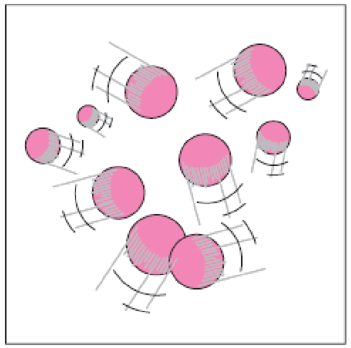


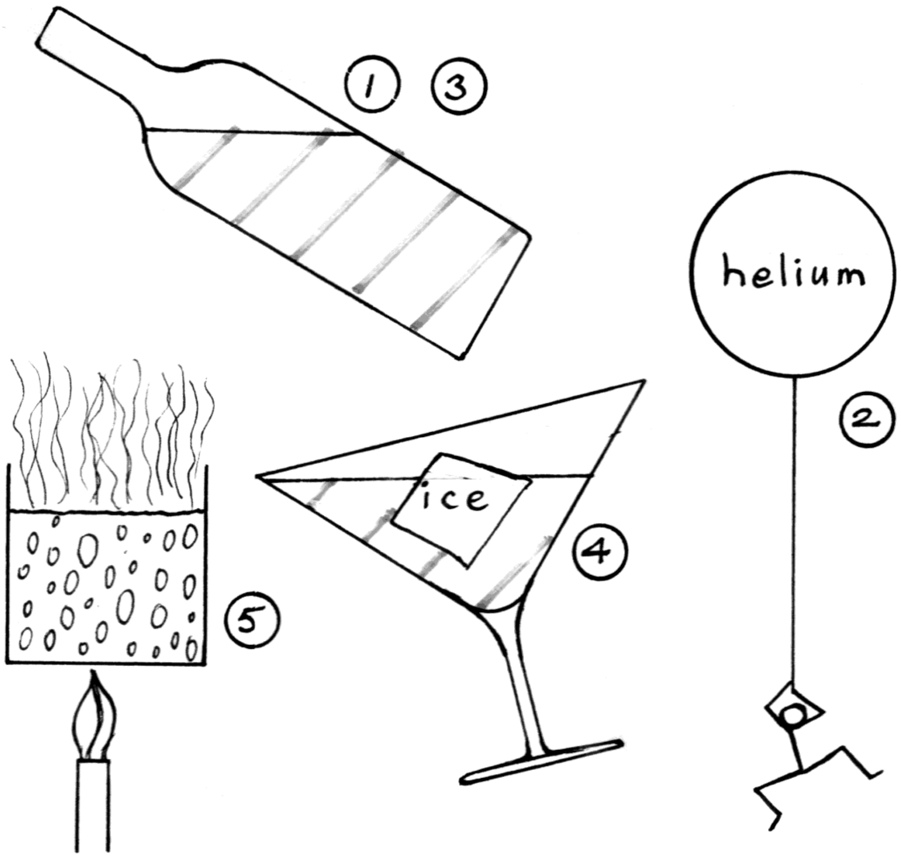
Liquid: In liquids molecules can rotate, move about each other and translate freely in the liquid phase.



Gas: In the gas phase, the molecules are far apart from each other, and molecular ordering is nonexistent. Gas molecules move about at random, continually colliding with each other and the walls of the container in which they are contained.

Particularly at low densities, the intermolecular forces are very small, and collisions are the only mode of interaction between the molecules.

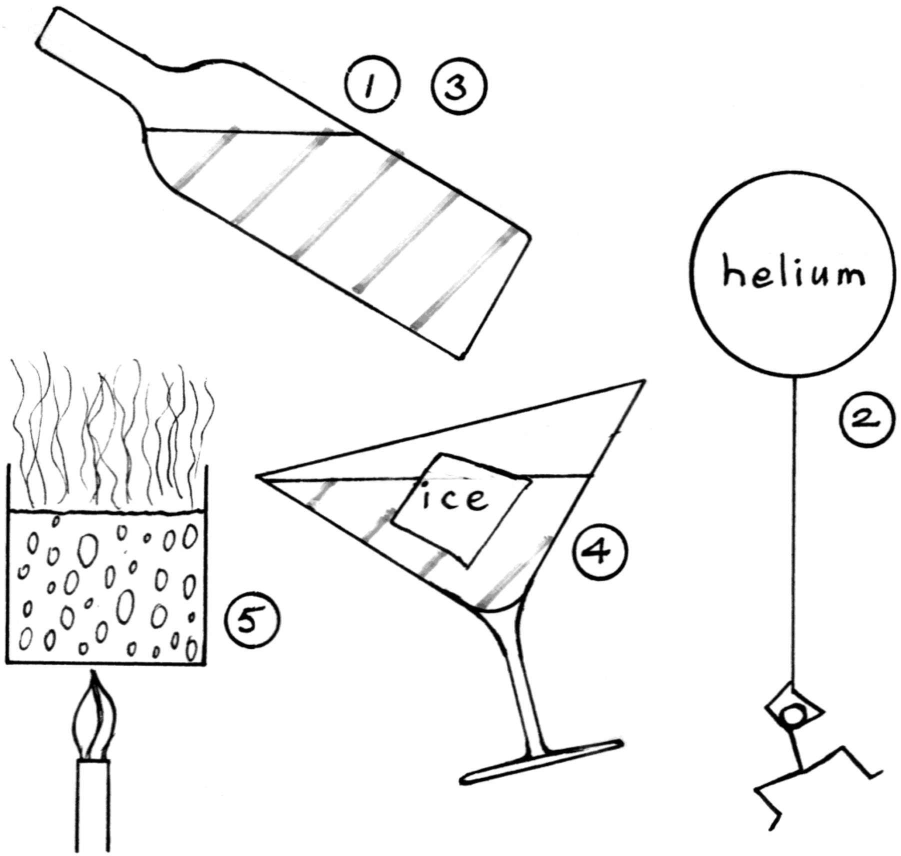




How many of the following statements are correct?

(a) all
(b) four
(c) three
(d) two
(e) one

(1) All fluids are liquids
(2) All gases are fluids
(3) All liquids are fluids
(4) If a solid melts it becomes liquid
(5) If a liquid evaporates it behaves like a gas



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[redacted]

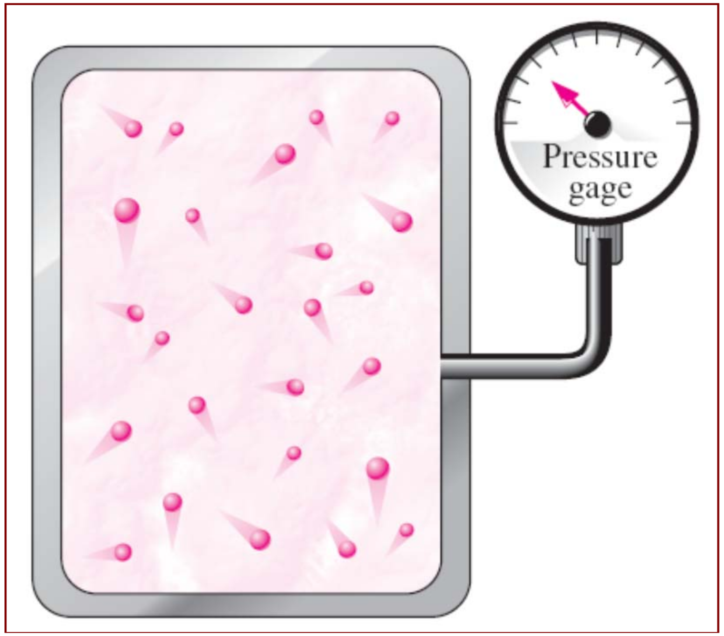
Gas and *vapor* are often used as synonymous words.

Gas: The vapor phase of a substance is customarily called a *gas* when it is above the critical temperature.

Vapor: Usually implies that the current phase is not far from a state of condensation.

Macroscopic or *classical* approach: Does not require a knowledge of the behavior of individual molecules and provides a direct and easy way to analyze engineering problems.

Microscopic or *statistical* approach: Based on the average behavior of large groups of individual molecules.



The pressure of a gas in a container is the result of momentum transfer between the molecules and the walls of the container.

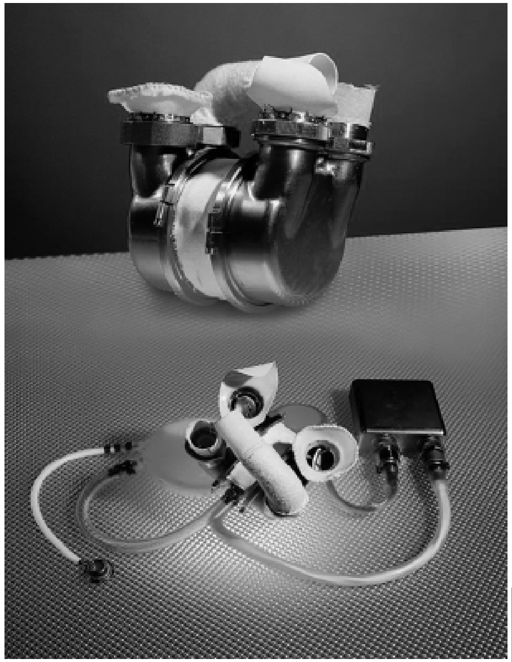
On a microscopic scale, pressure is determined by the interaction of individual gas molecules. However, we can measure the pressure on a macroscopic scale with a pressure gage.

Fluid Mechanics

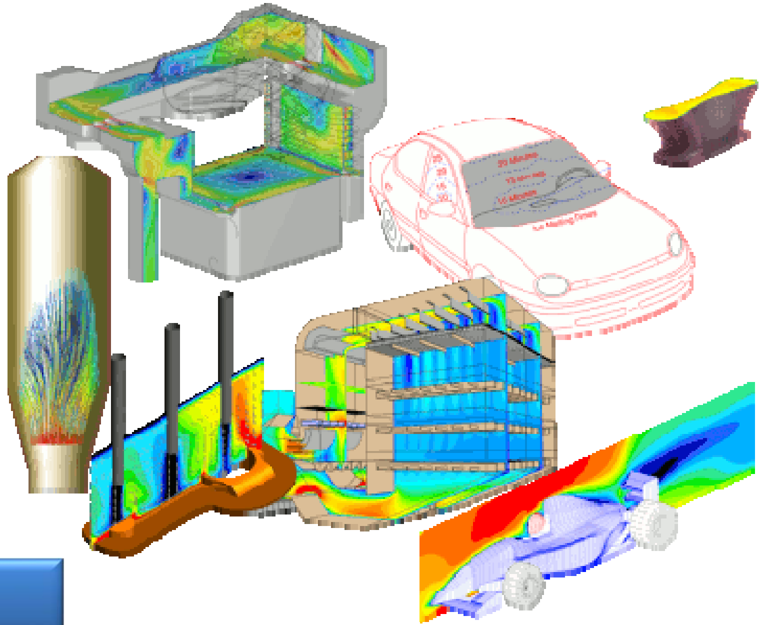
- Fluids essential to life
  - Human body 65% water
  - Earth's surface is 2/3 water
  - Atmosphere extends 17km above the earth's surface
- History shaped by fluid mechanics
  - Geomorphology
  - Human migration and civilization
  - Modern scientific and mathematical theories and methods
  - Warfare
- Affects every part of our lives

Application Areas of Fluid Mechanics

Fluid dynamics is used extensively in the design of artificial hearts.



CFD flow modeling
(Computational Fluid Dynamics)



Artifical Hearts

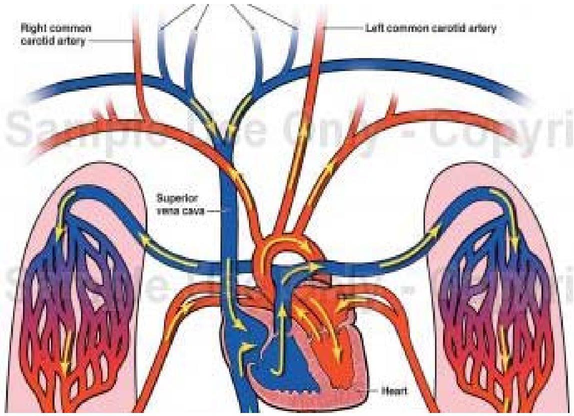
[redacted]

Natural Flows and Weather

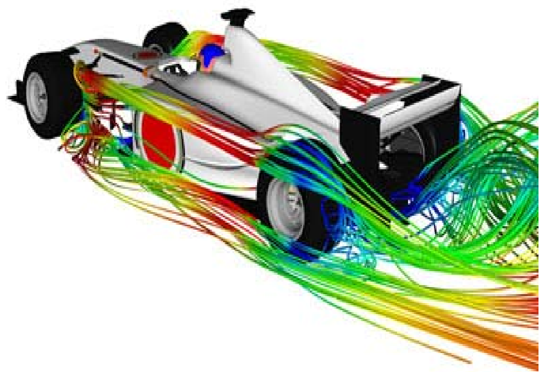
Boats

Aircraft and spacecraft

Power Plant



Human Body



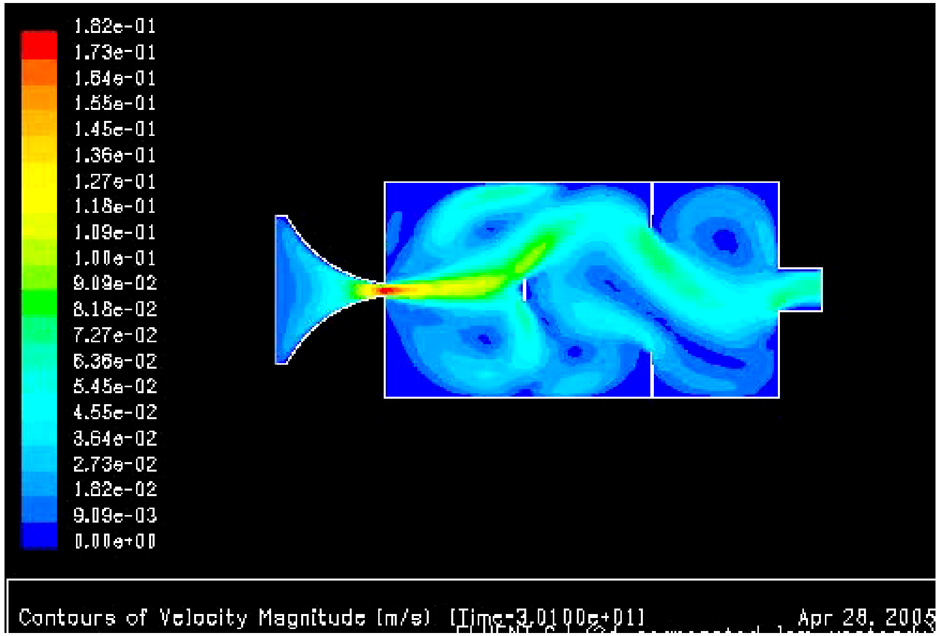
Cars

[redacted]

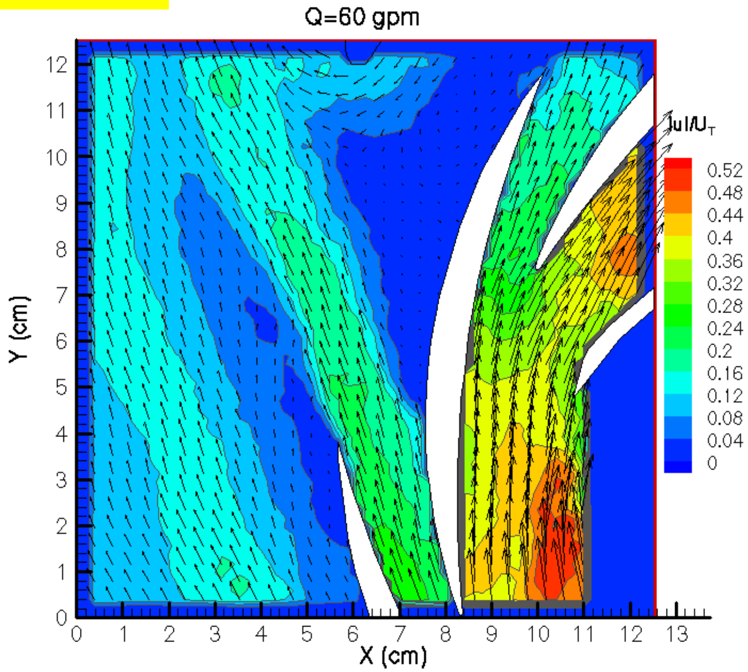
Wind Turbines

Piping and Plumbing Systems

Industrial applications

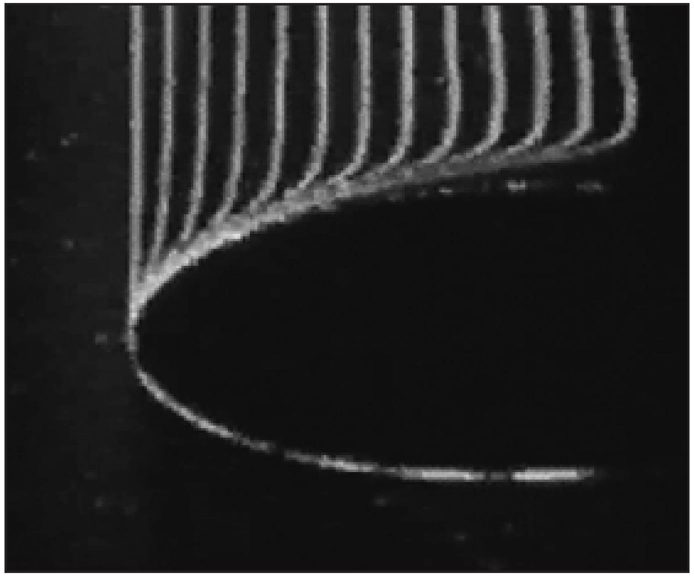


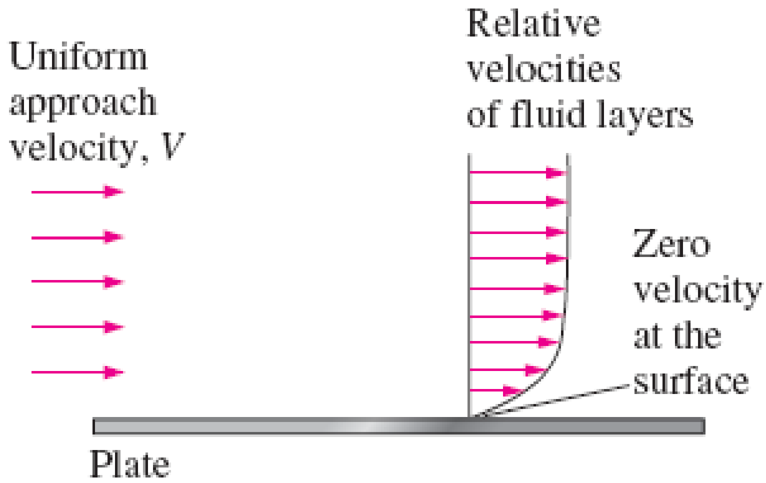
Target Flow meter



Centrifugal Pump flow in stall condition

1–2 THE NO-SLIP CONDITION



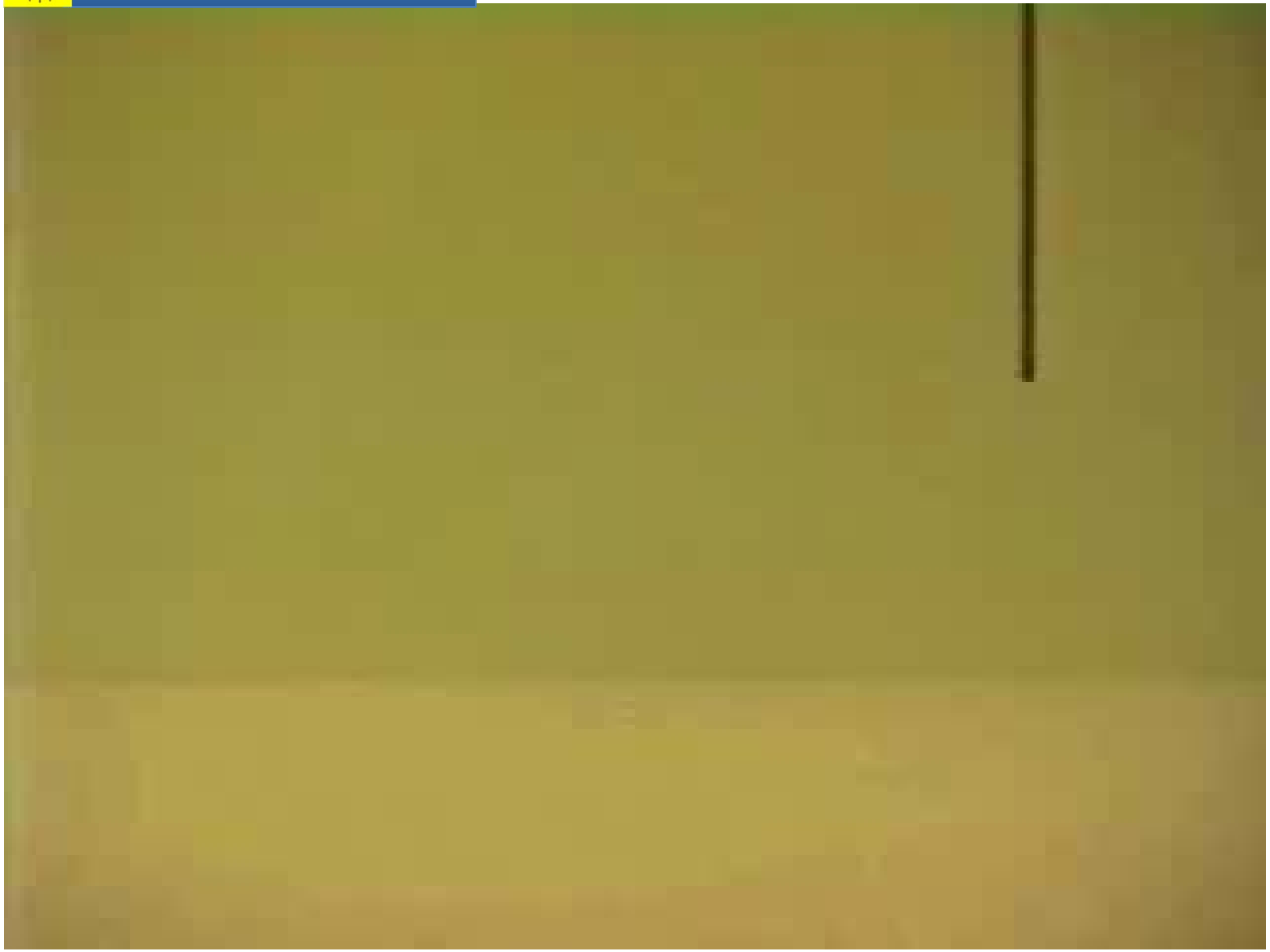


The development of a velocity profile due to the no-slip condition as a fluid flows over a blunt nose.

A fluid flowing over a stationary surface comes to a complete stop at the surface because of the no-slip condition, which is the force a fluid exerts on a surface in the flow direction.

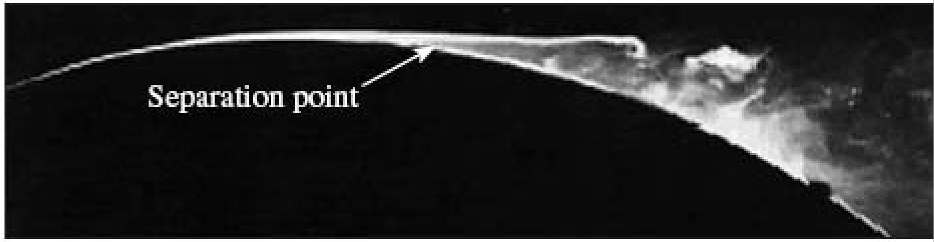
The flow of a fluid in a stationary pipe or over a solid surface that is nonporous. All experimental observations indicate that a fluid in motion comes to a complete stop at the surface and assumes a zero velocity relative to the surface. A fluid in direct contact with a solid "sticks" to the surface due to viscous effects, and there is no slip. This is known as the **no-slip condition**.

No-Slip Condition



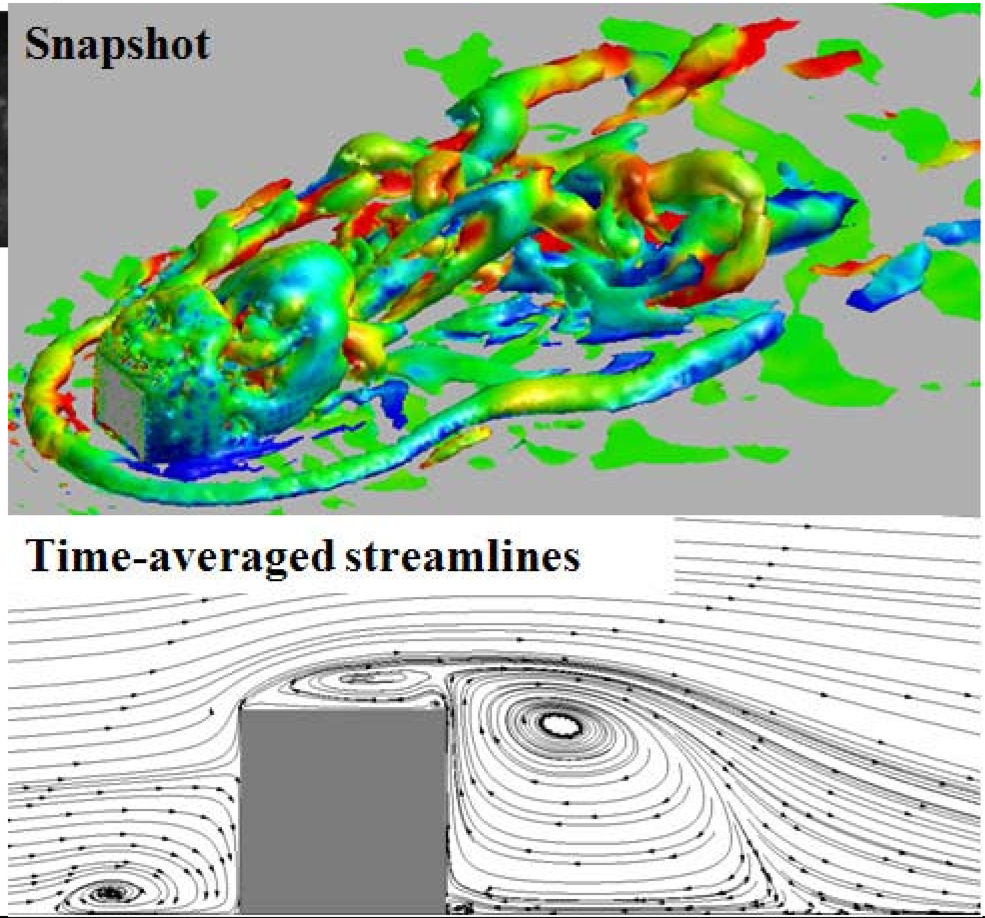
[redacted]

Boundary layer: The flow region adjacent to the wall in which the viscous effects (and thus the velocity gradients) are significant.
The fluid property responsible for the no-slip condition and the development of the boundary layer is ***viscosity.***

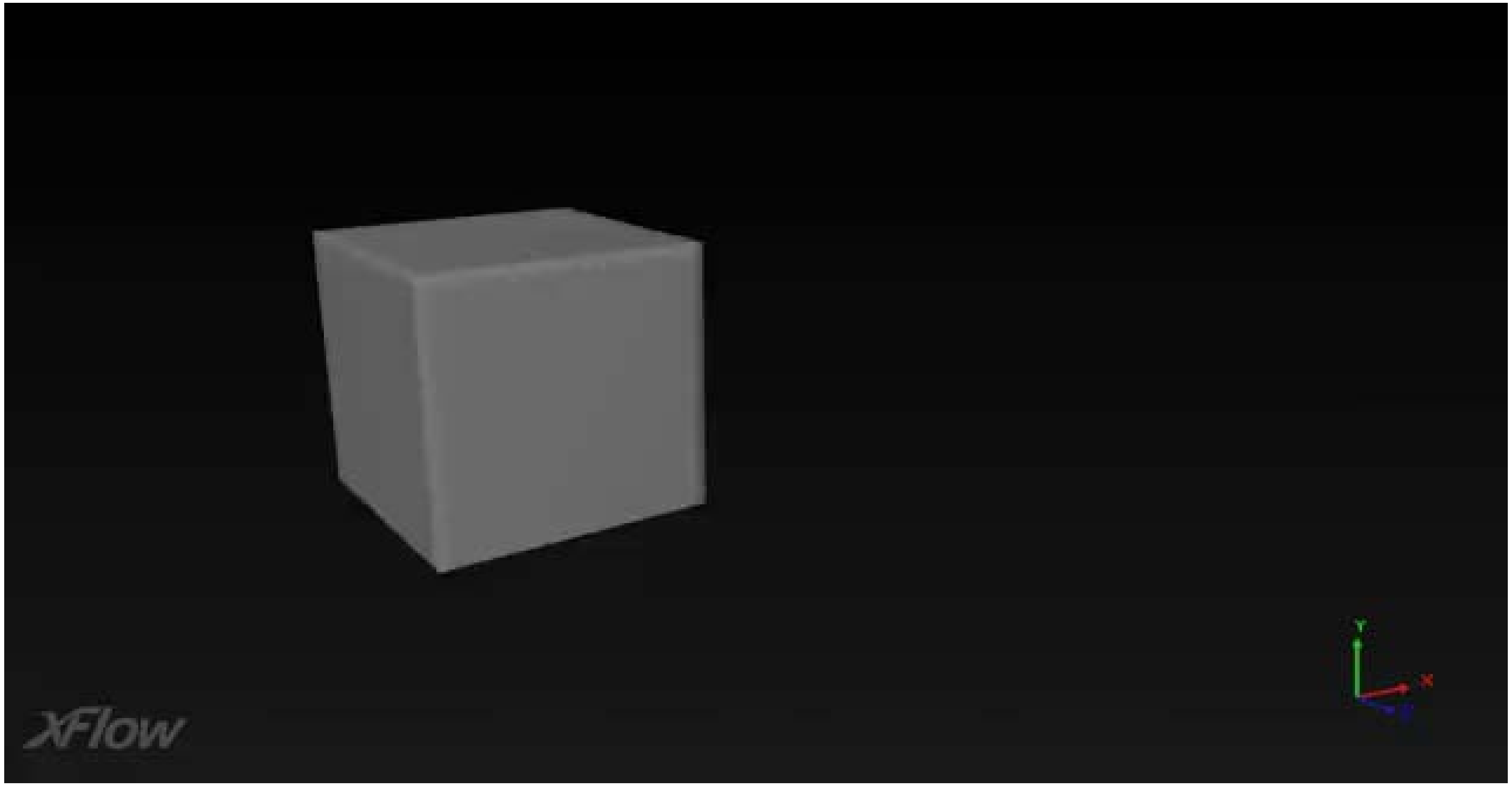


Flow separation during flow over a curved surface

When a fluid is forced to flow over a curved surface, such as the back side of a cylinder at sufficiently high velocity 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.**



Flow Separation

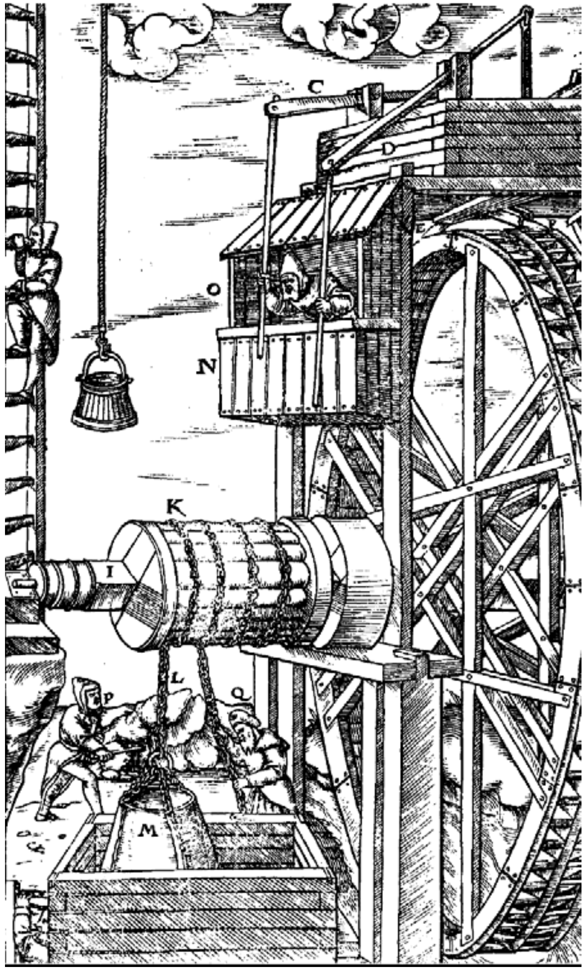


1–3 A BRIEF HISTORY OF FLUID MECHANICS

from 283 to 133 BC

Segment of Pergamon pipeline. Each clay pipe section was 13 to 18 cm in diameter.

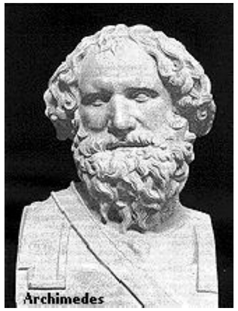
1556



A mine hoist powered by a reversible water wheel.

History

Faces of Fluid Mechanics



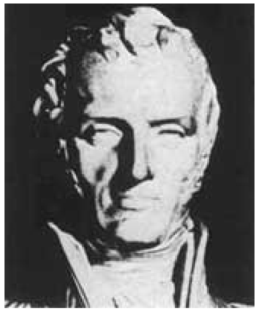
Archimedes
(C. 287-212 BC)

Newton
(1642-1727)

Leibniz
(1646-1716)

Bernoulli
(1667-1748)

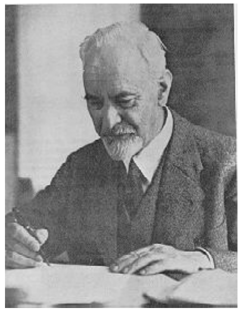
Euler
(1707-1783)



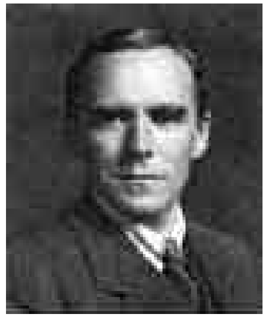
Navier
(1785-1836)

Stokes
(1819-1903)

Reynolds
(1842-1912)



Prandtl
(1875-1953)



Taylor
(1886-1975)

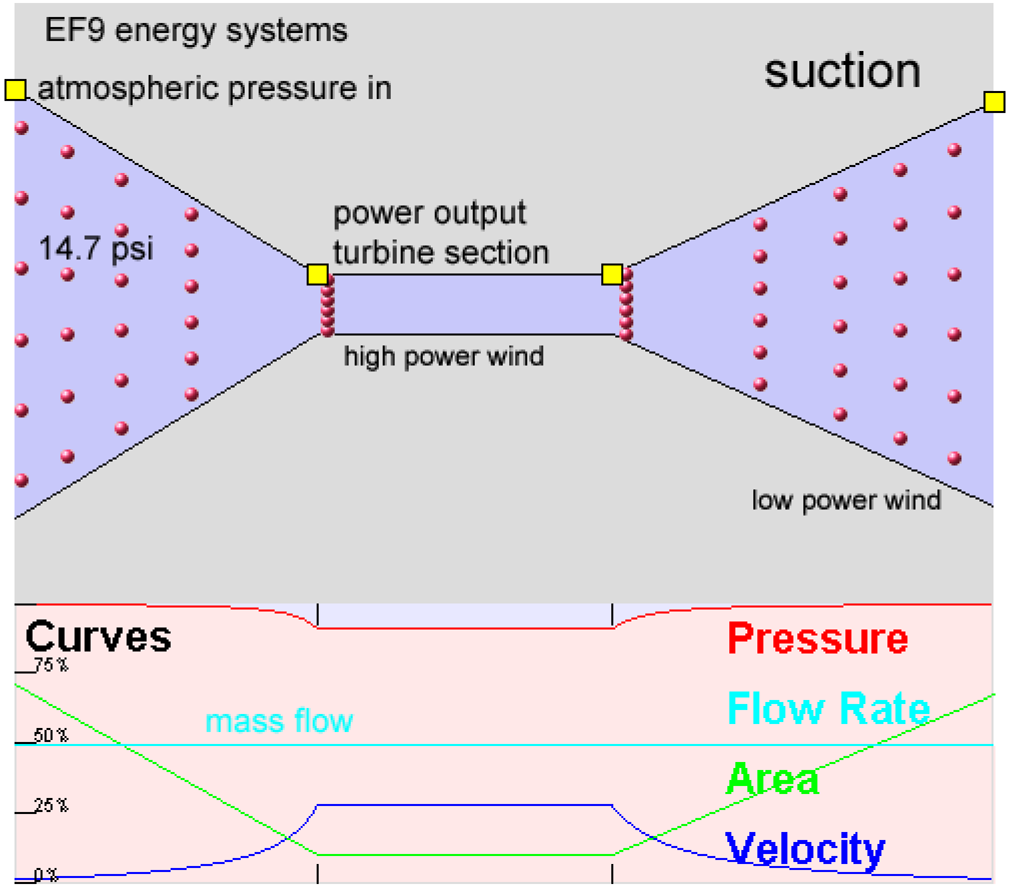
History of Fluid Mechanics

[redacted]

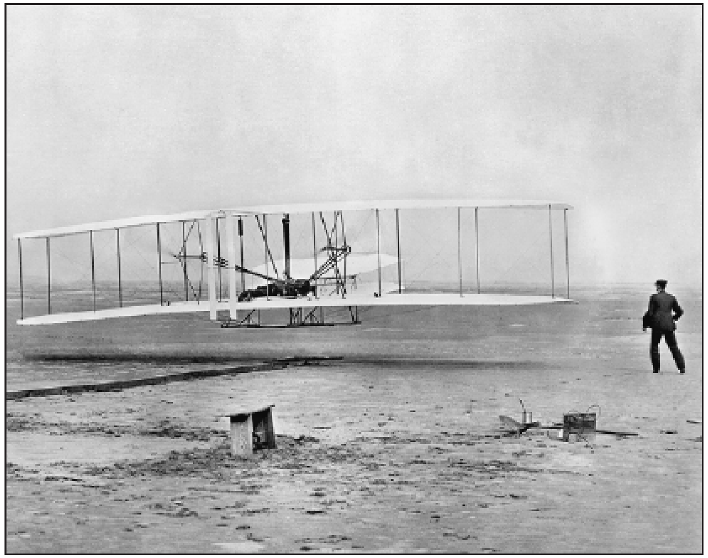
450 × 286 - A **wind turbine** in northern Germany. It was the **world's largest turbine**.

Osborne Reynolds' original apparatus for demonstrating the onset of turbulence in pipes, being operated by John Lienhard at the University of Manchester in 1975.

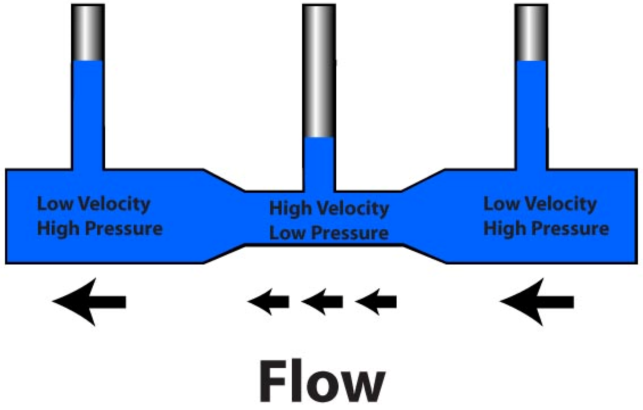
Energy Line


EF9 energy systems
atmospheric pressure in
suction
14.7 psi
power output
turbine section
high power wind
low power wind
Curves
75 %
50 %
25 %
0 %
mass flow
Pressure
Flow Rate
Area
Velocity

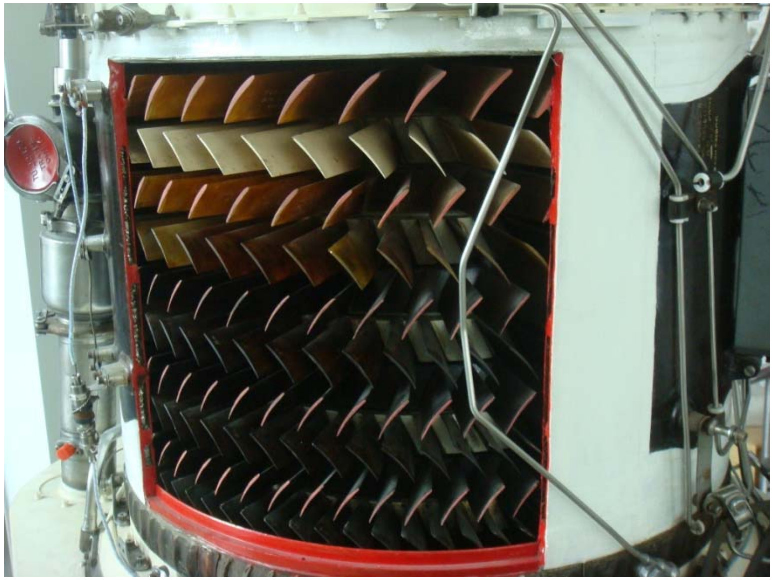
[redacted]



The Wright brothers take flight at Kitty Hawk.



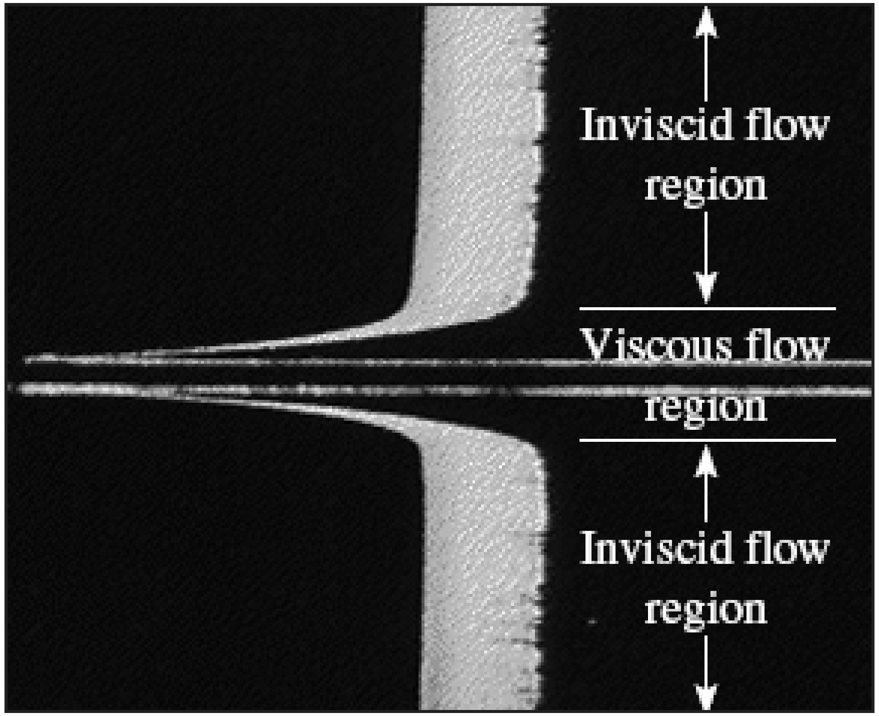
Bernoullli (1700-1782)



Viscous versus Inviscid Regions of Flow

Viscous flows: Flows in which the frictional effects are significant.

Inviscid flow regions: In many flows of practical interest, there are *regions* (typically regions not close to solid surfaces) where viscous forces are negligibly small compared to inertial or pressure forces.



The fluid sticks to the plate on both sides because of the no-slip condition, and the thin boundary layer in which the viscous effects are significant near the plate surface is the ***viscous flow region***.

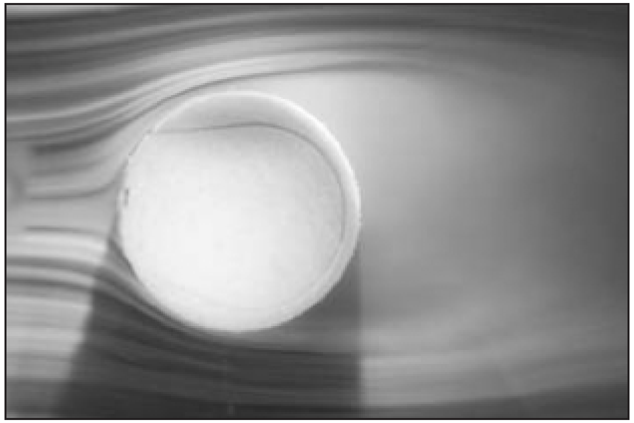
The flow of an originally uniform fluid stream over a flat plate, and the regions of viscous flow (next to the plate on both sides) and inviscid flow (away from the plate).

Internal versus External Flow

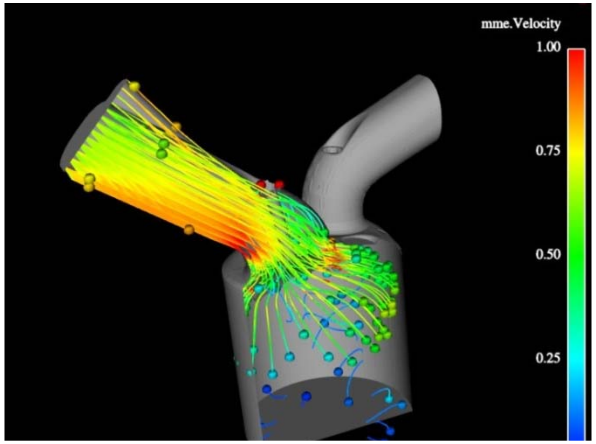
External flow: The flow of an unbounded fluid over a surface such as a plate, a wire, or a pipe. In external flows the viscous effects are limited to boundary layers near solid surfaces and to wake regions downstream of bodies.

Internal flow: The flow in a pipe or duct if the fluid is completely bounded by solid surfaces. Internal flows are dominated by the influence of viscosity throughout the flow field.

- Water flow in a pipe is internal flow, and airflow over a ball is external flow .
- The flow of liquids in a duct is called *open-channel flow* if the duct is only partially filled with the liquid and there is a free surface.



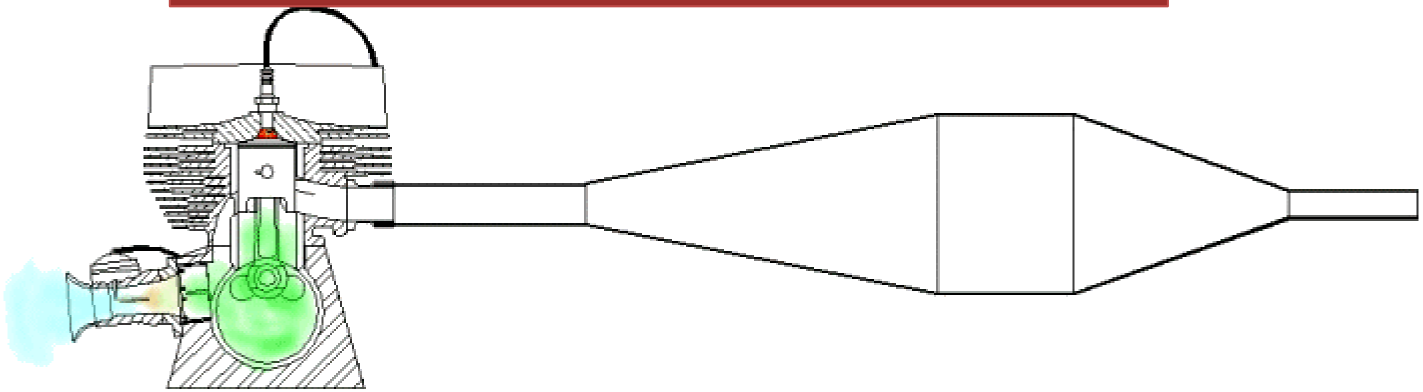
External flow over a tennis ball, and the turbulent wake region behind.



3D Visualization of Internal Flow a of an Intake Port

External flow around a car

Internal flow around in a combustion engine



Compressible versus Incompressible Flow

Incompressible flow: If the density of flowing fluid remains nearly constant throughout (e.g., liquid flow).

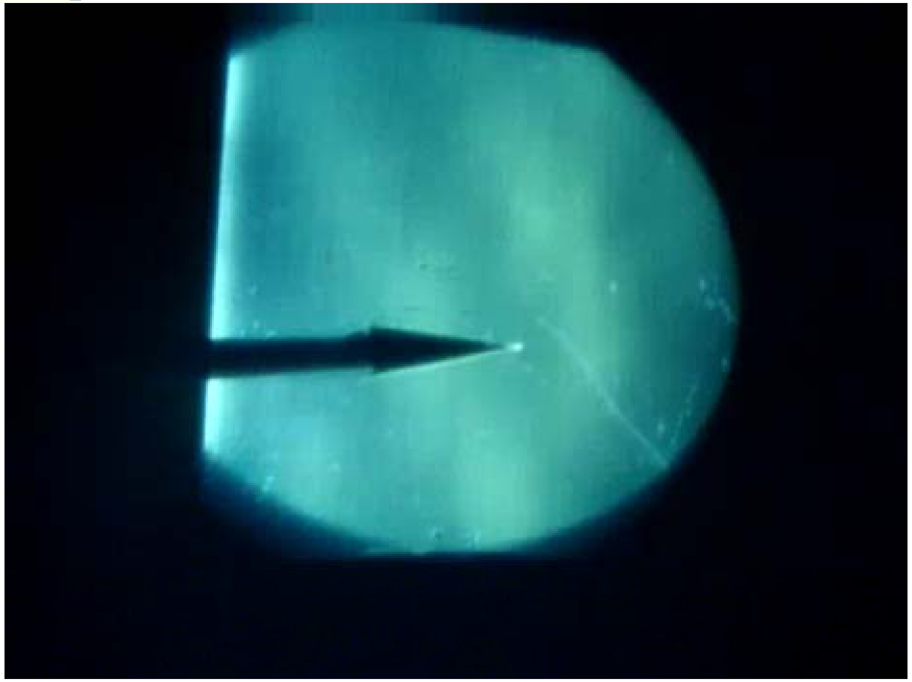
Compressible flow: If the density of fluid changes during flow (e.g., high-speed gas flow)

When analyzing rockets, spacecraft, and other systems that involve high-speed gas flows, the flow speed is often expressed by **Mach number**

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

Ma = 1	Sonic flow
Ma < 1	Subsonic flow
Ma > 1	Supersonic flow
Ma >> 1	Hypersonic flow

Supersonic Wind Tunnel



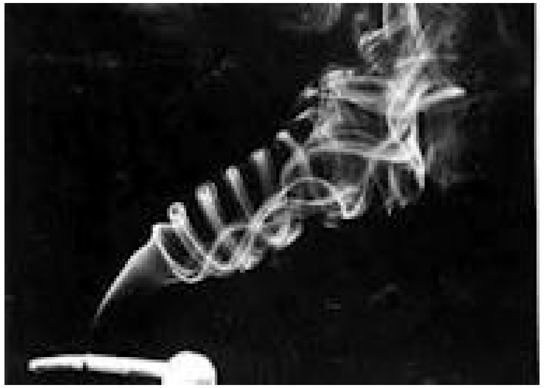
Schlieren image of a small model of the space shuttle orbiter being tested at Mach 3 in the supersonic wind tunnel of the Penn State Gas Dynamics Lab. Several *oblique shocks* are seen in the air surrounding the spacecraft.

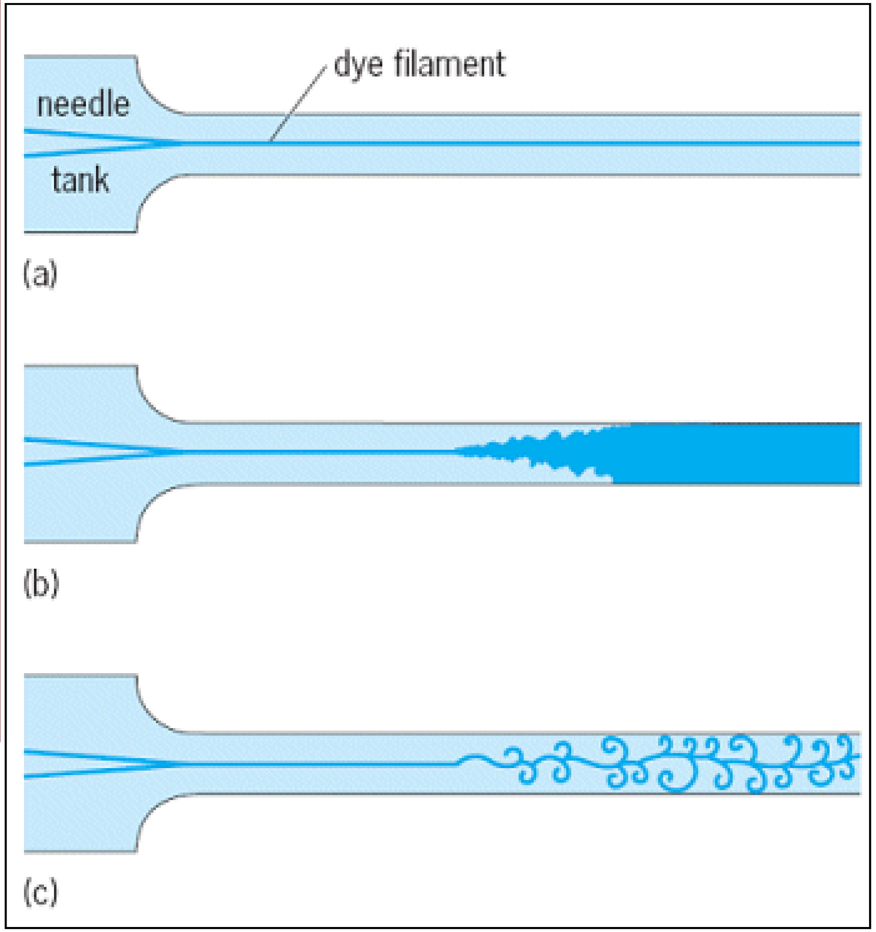
Laminar versus Turbulent Flow

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

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

Transitional flow: A flow that alternates between being laminar and turbulent.





Laminar, transitional, and turbulent flows.

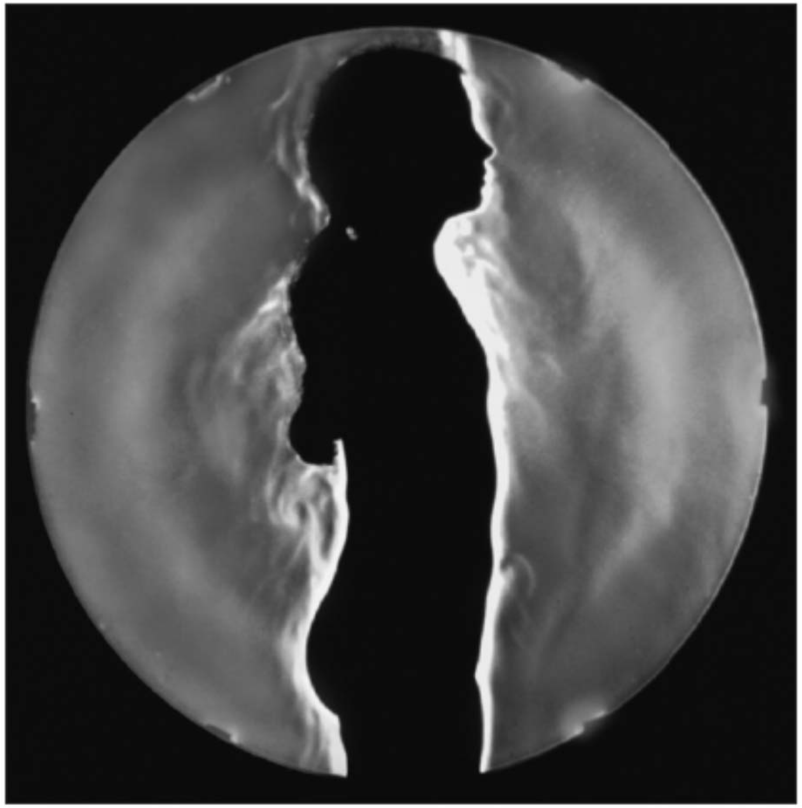
Laminar versus Turbulent Flow

Natural (or Unforced) versus Forced Flow

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.

Natural flow: Fluid motion is due to natural means such as the buoyancy effect, which manifests itself as the rise of warmer (and thus lighter) fluid and the fall of cooler (and thus denser) fluid.

Forced Flow in Axial Fan



In this schlieren image of a girl in a swimming suit, the rise of lighter, warmer air adjacent to her body indicates that humans and warm-blooded animals are surrounded by thermal plumes of rising warm air.

Steady versus Unsteady Flow

The term steady implies *no change at a point with time*.

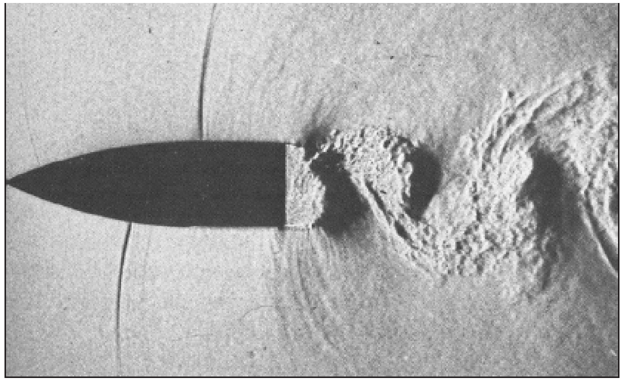
The opposite of steady is unsteady.

The term uniform implies *no change with location* over a specified region.

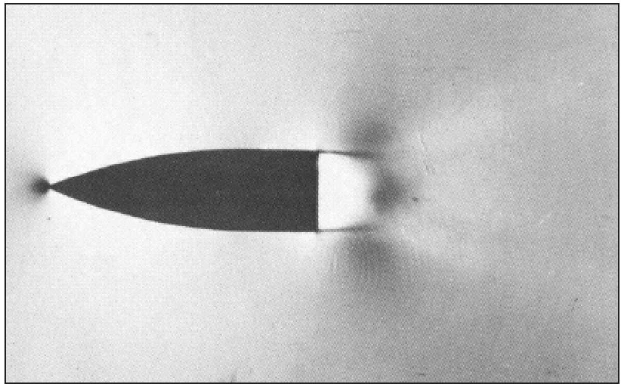
The term periodic refers to the kind of unsteady flow in which the flow oscillates about a steady mean.

Many devices such as turbines, compressors, boilers, condensers, and heat exchangers operate for long periods of time under the same conditions, and they are classified as steady devices.

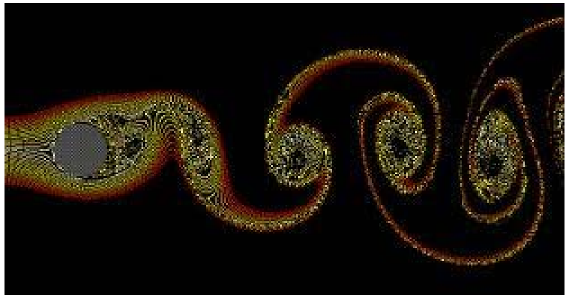
Oscillating wake of a blunt-based airfoil at Mach number 0.6



İnstantaneous image



A long-exposure (time-averaged) image



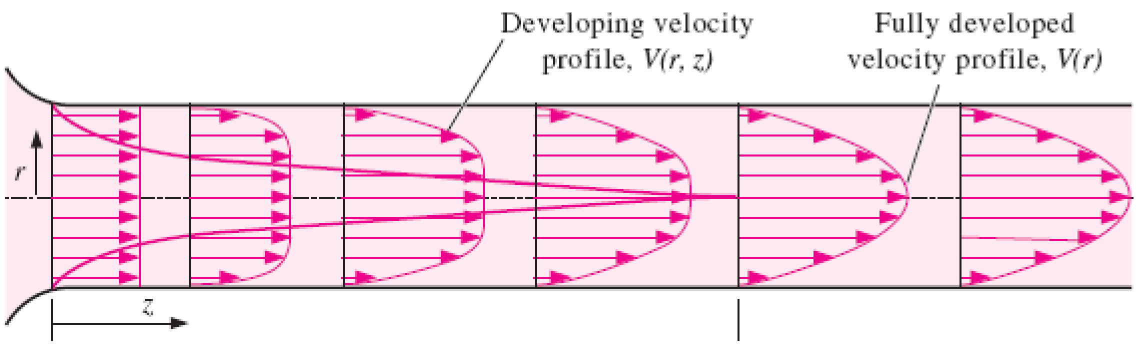
Unsteady flow past a cylinder

Steady flow past in a shower

One – Two - and Three-Dimensional Flows

- A flow field is best characterized by its velocity distribution.
- A flow is said to be one-, two-, or three-dimensional if the flow velocity varies in one, two, or three dimensions, respectively.
- However, the variation of velocity in certain directions can be small relative to the variation in other directions and can be ignored.

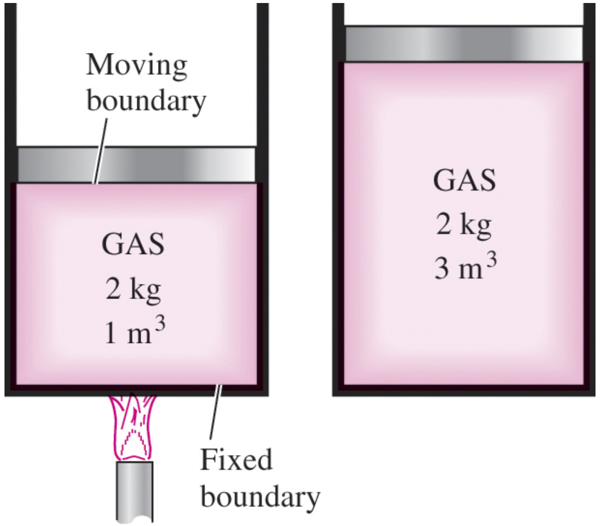
Flow over a car antenna is approximately 2-D except near the top and bottom of the antenna.

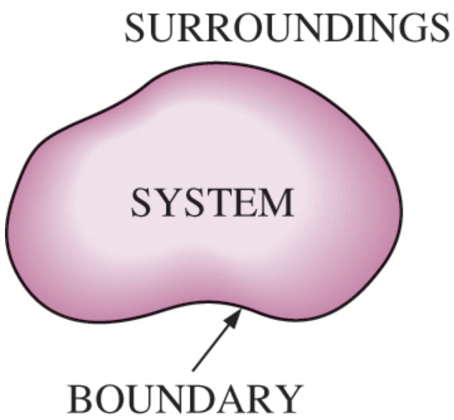


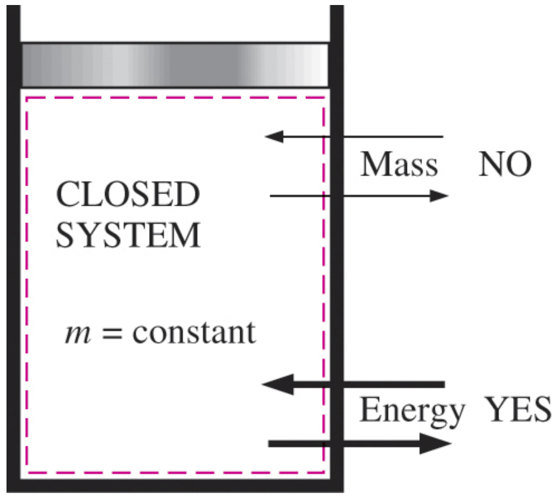
The development of the velocity profile in a circular pipe. $V = V(r, z)$ and thus the flow is two-dimensional in the entrance region, and becomes one-dimensional downstream when the velocity profile fully develops and remains unchanged in the flow direction, $V = V(r)$.

1–5 SYSTEM AND CONTROL VOLUME

- **System**: A quantity of matter or a region in space chosen for study.
- **Surroundings**: The mass or region outside the system
- **Boundary**: The real or imaginary surface that separates the system from its surroundings.
- The boundary of a system can be *fixed* or *movable.*
- Systems may be considered to be *closed* or *open*.



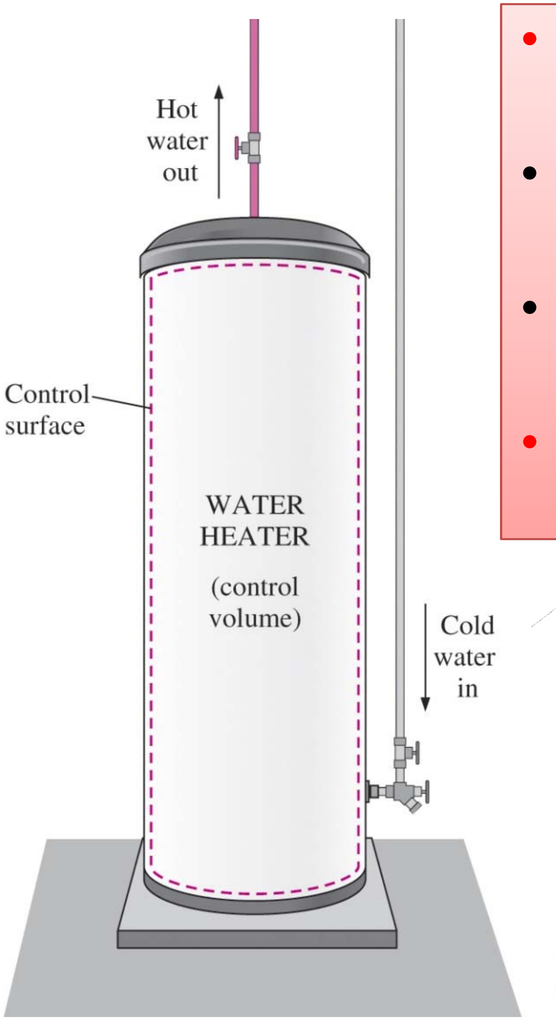




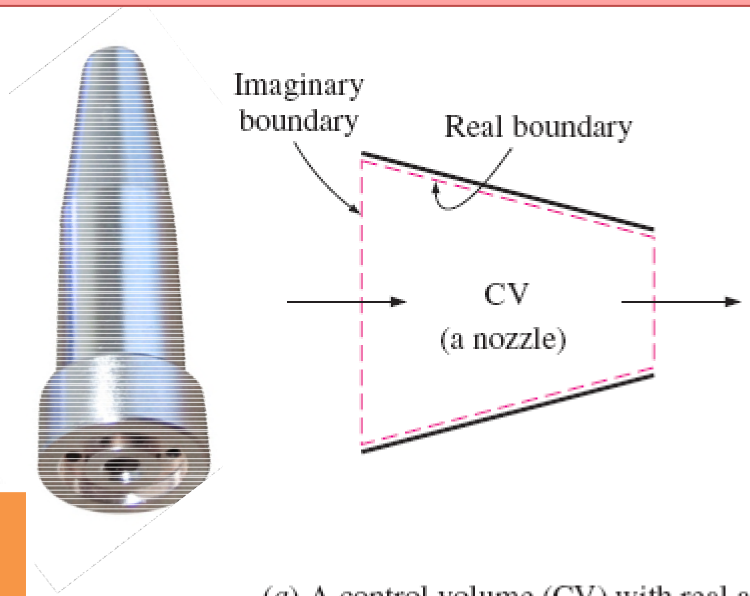
Closed system (Control mass): A fixed amount of mass, and no mass can cross its boundary.

[redacted]

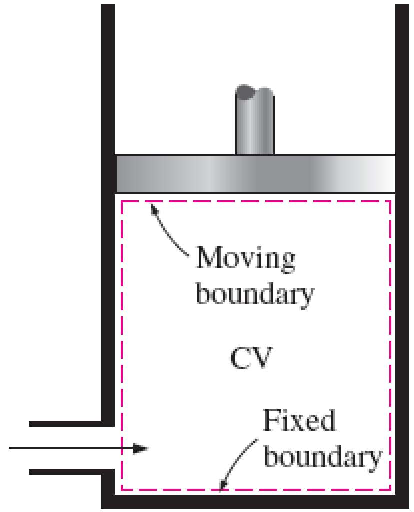
- **Open system (control volume):** A properly selected region in space.
- It usually encloses a device that involves mass flow such as a compressor, turbine, or nozzle.
- Both mass and energy can cross the boundary of a control volume.
- **Control surface:** The boundaries of a control volume. It can be real or imaginary.



An open system (a control volume) with one inlet and one exit.



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



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

1–6 IMPORTANCE OF DIMENSIONS AND UNITS

- Any physical quantity can be characterized by **dimensions**.
- The magnitudes assigned to the dimensions are called **units**.
- Some basic dimensions such as mass *m*, length *L*, time *t*, and temperature *T* are selected as **primary** or **fundamental dimensions**, while others such as velocity *V*, energy *E*, and volume *V* are expressed in terms of the primary dimensions and are called **secondary dimensions**, or **derived dimensions**.
- **Metric SI system**: A simple and logical system based on a decimal relationship between the various units.
- **English system**: It has no apparent systematic numerical base, and various units in this system are related to each other rather arbitrarily.

TABLE 1–1

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

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

Standard prefixes in SI units

Multiple	Prefix
10^{12}	tera, T
10^{9}	giga, G
10^{6}	mega, M
10^{3}	kilo, k
10^{2}	hecto, h
10^{1}	deka, da
10^{-1}	deci, d
10^{-2}	centi, c
10^{-3}	milli, m
10^{-6}	micro, μ
10^{-9}	nano, n
10^{-12}	pico, p

Some SI and English Units

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

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

Work = Force × Distance

1 J = 1 N·m

1 cal = 4.1868 J

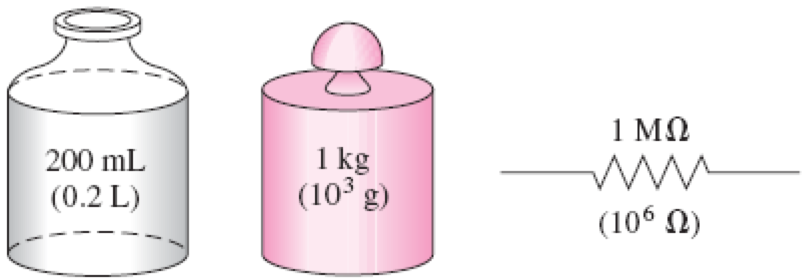
1 Btu = 1.0551 kJ

Force = (Mass) (Acceleration)

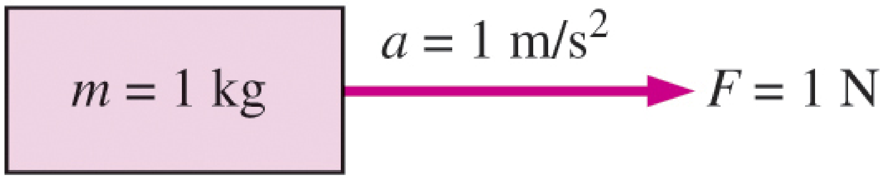
$$F = ma$$

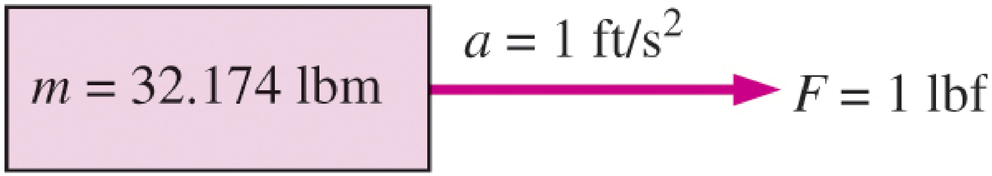
$$1 \text{ N} = 1 \text{ kg} \cdot \text{m/s}^2$$

$$1 \text{ lbf} = 32.174 \text{ lbm} \cdot \text{ft/s}^2$$



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



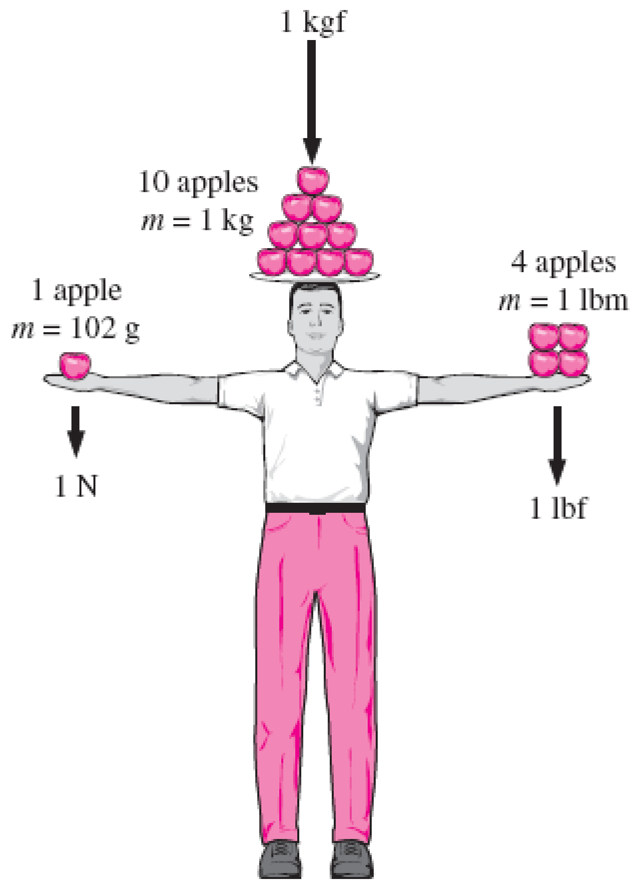


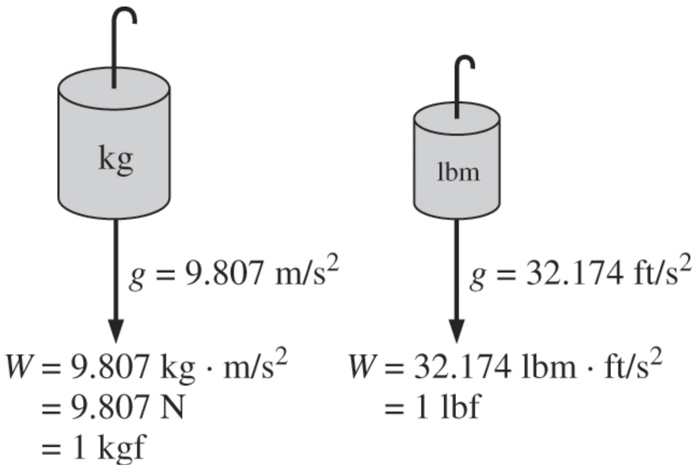
The definition of the force units.

A body weighing 60 kgf on earth will weigh only 10 kgf on the moon.

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

W weight
m mass
g gravitational acceleration

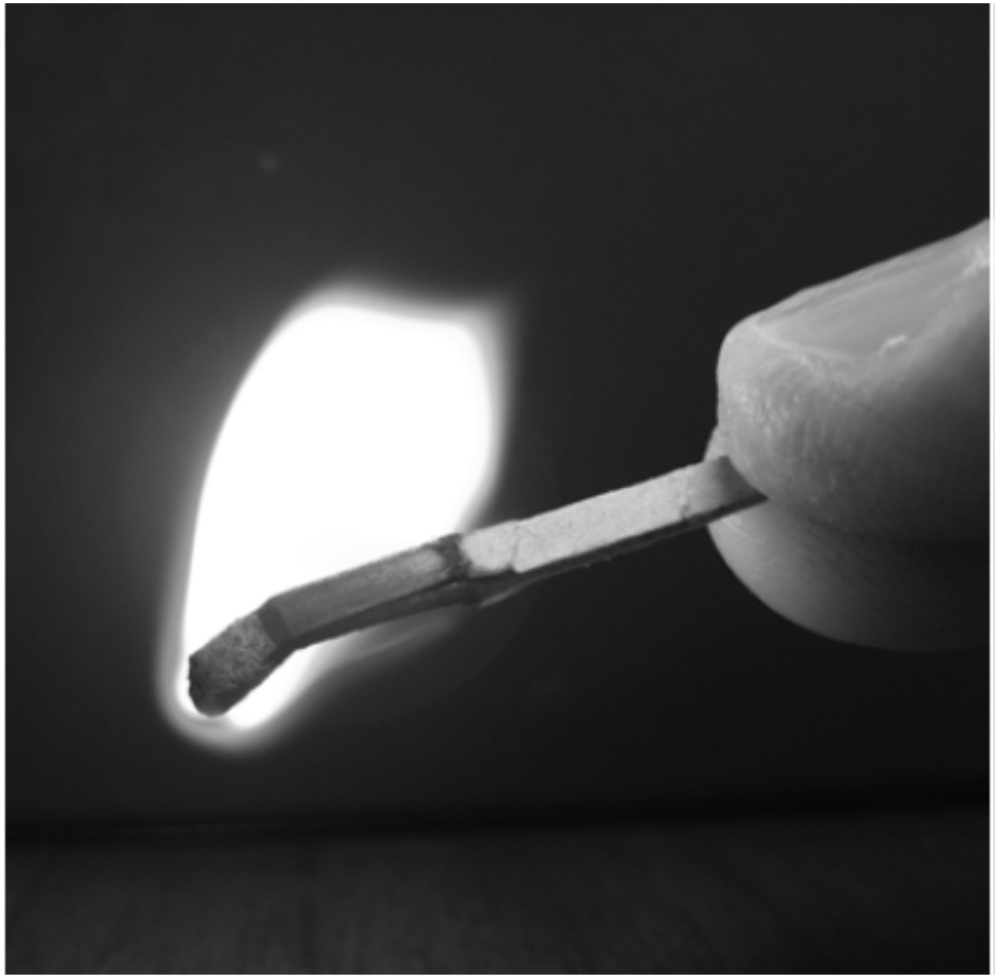




The weight of a unit mass at sea level.

The relative magnitudes of the force units newton (N), kilogram-force (kgf), and pound-force (lbf).

[redacted]



A typical match yields about one Btu (or one kJ) of energy if completely burned.

Dimensional homogeneity

All equations must be dimensionally homogeneous.

Unity Conversion Ratios

All nonprimary units (secondary units) can be formed by combinations of primary units.
Force units, for example, can be expressed as

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

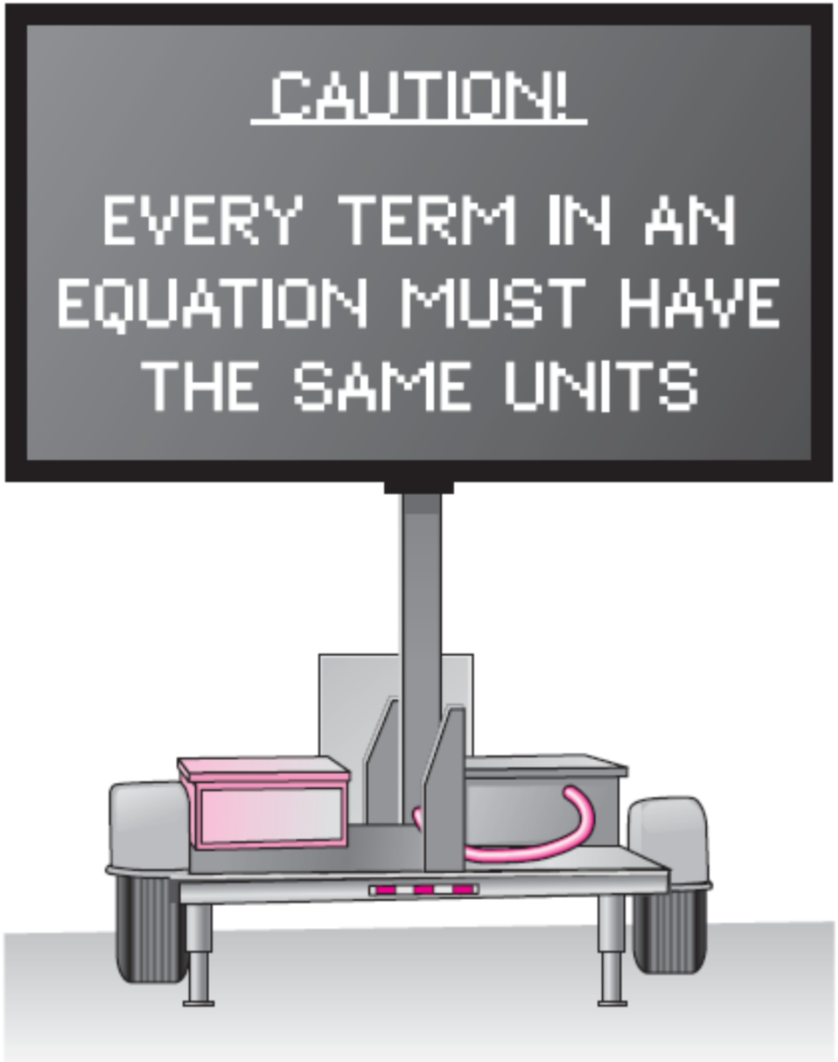
They can also be expressed more conveniently as unity conversion ratios as

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

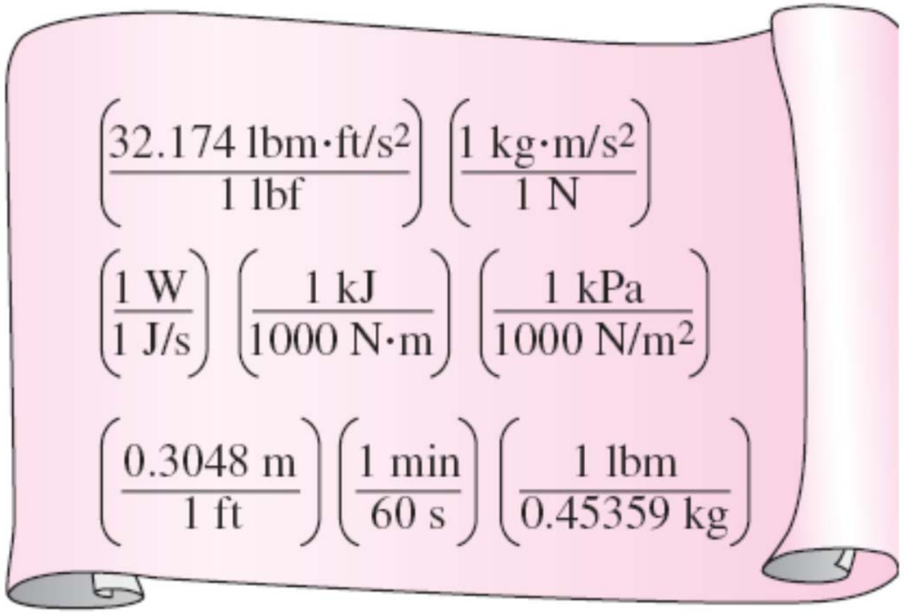
Unity conversion ratios are identically equal to 1 and are unitless, and thus such ratios (or their inverses) can be inserted conveniently into any calculation to properly convert units.

To be dimensionally homogeneous, all the terms in an equation must have the same unit.

[redacted]



Always check the units in your calculations.



Every unity conversion ratio (as well as its inverse) is exactly equal to one. Shown here are a few commonly used unity conversion ratios.

[redacted]

A quirk in the metric system of units.

EXAMPLE 1-4

A tank is filled with oil whose density is 850 kg/m^3. If the volume of the tank is V= 2 m^3, determine the amount of mass m in the tank.

OIL

$V = 2\ \text{m}^3$

$\rho = 850\ \text{kg/m}^3$

$m = ?$

Solution The volume of an oil tank is given. The mass of oil is to be determined.
Assumptions Oil is an incompressible substance and thus its density is constant.
Analysis Suppose we forgot the formula that relates mass to density and volume. However, we know that mass has the unit of kilograms. That is, whatever calculations we do, we should end up with the unit of kilograms. Putting the given information into perspective, we have

$$\rho = 850\ \text{kg/m}^3 \quad \text{and} \quad V = 2\ \text{m}^3$$

$$m = \rho V$$

$$m = (850\ \text{kg/m}^3)(2\ \text{m}^3) = \mathbf{1700\ kg}$$

Discussion Note that this approach may not work for more complicated formulas.

Experimental vs. Analytical Analysis

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

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

The analytical approach (including the numerical approach) has the advantage that it is fast and inexpensive, but the results obtained are subject to the accuracy of the assumptions, approximations, and idealizations made in the analysis.

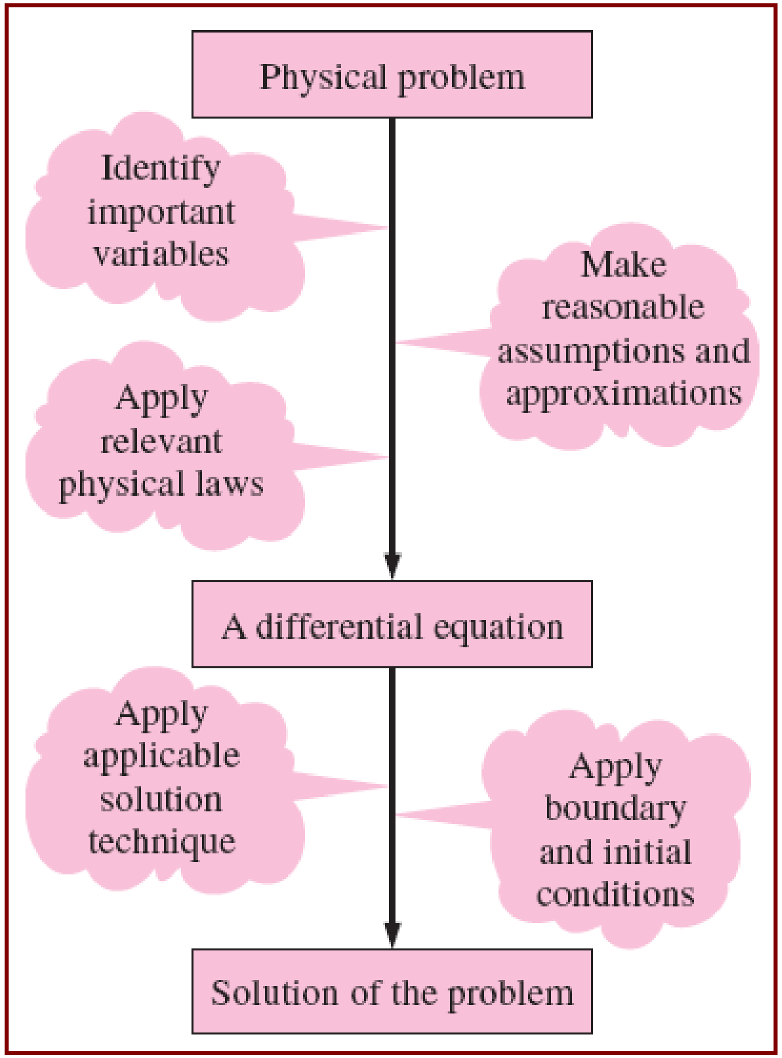
Modeling in Engineering

Why do we need differential equations? The descriptions of most scientific problems involve equations that relate the changes in some key variables to each other.

In the limiting case of infinitesimal or differential changes in variables, we obtain *differential equations* that provide precise mathematical formulations for the physical principles and laws by representing the rates of change as *derivatives.*

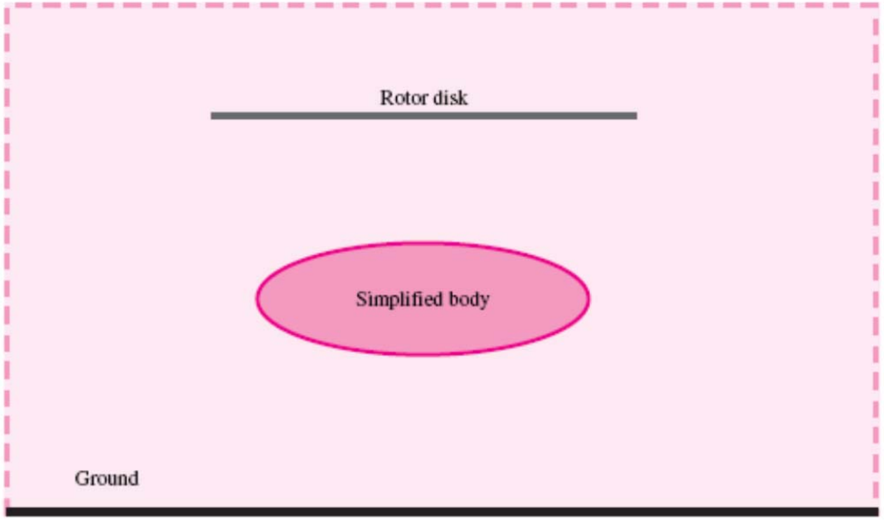
Therefore, differential equations are used to investigate a wide variety of problems in sciences and engineering.

Do we always need differential equations? Many problems encountered in practice can be solved without resorting to differential equations and the complications associated with them.



Mathematical modeling of physical problems.

(*a*) Actual engineering problem



(*b*) Minimum essential model of the engineering problem

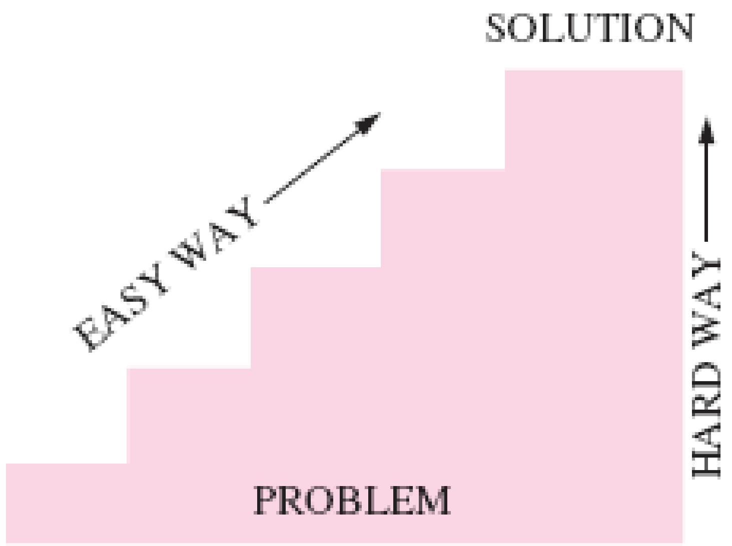
Complex model
(very accurate)
vs.
Simple model
(not-so-accurate)

Simplified models are often used in fluid mechanics to obtain approximate solutions to difficult engineering problems.
Here, the helicopter's rotor is modeled by a disk, across which is imposed a sudden change in pressure. The helicopter's body is modeled by a simple ellipsoid. This simplified model yields the essential features of the overall air flow field in the vicinity of the ground.

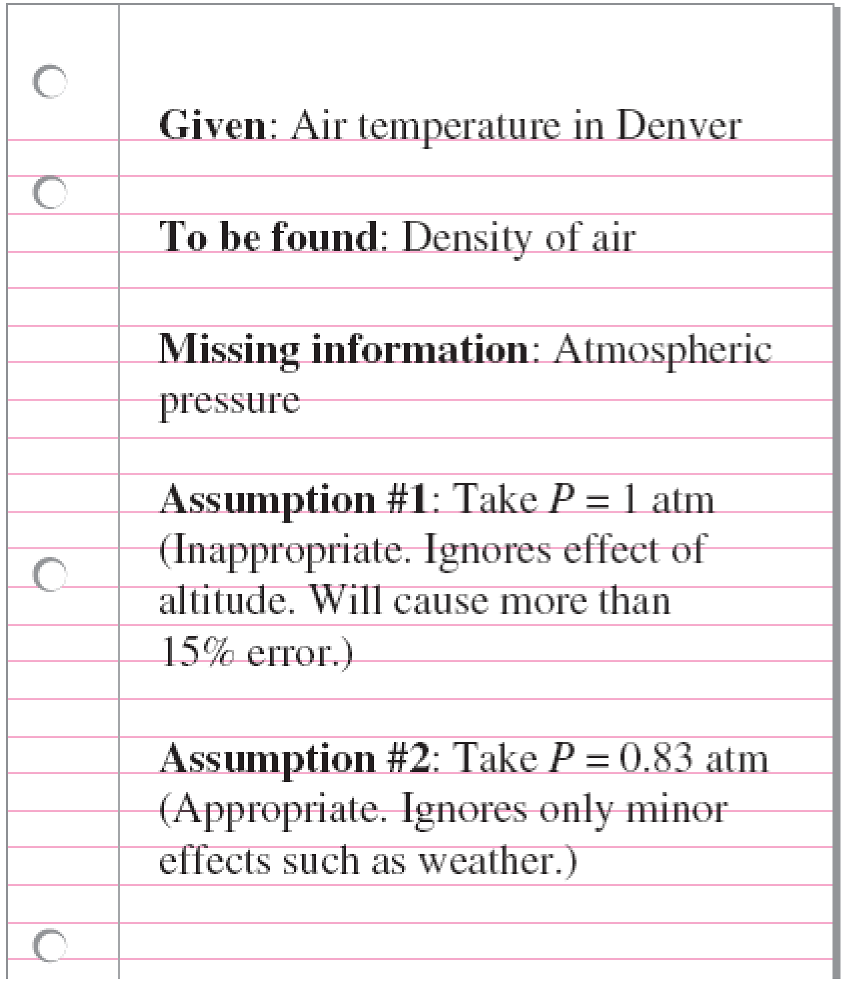
The right choice is usually the simplest model that yields satisfactory results.

- 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

[redacted]

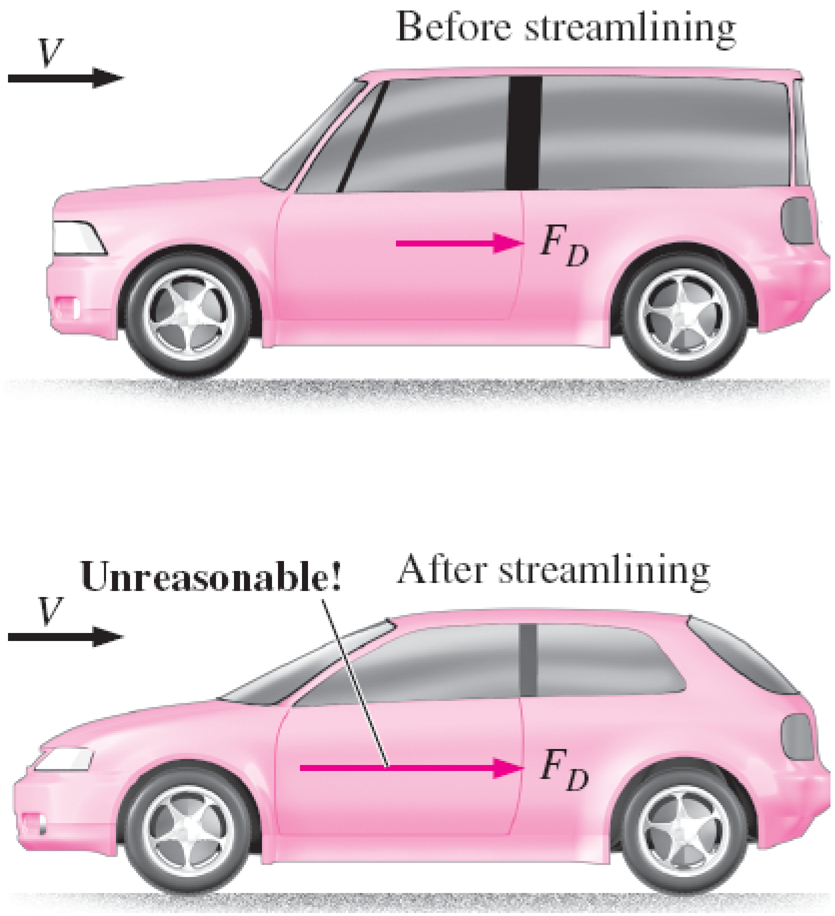


A step-by-step approach can greatly simplify problem solving.



The assumptions made while solving an engineering problem must be reasonable and justifiable.

[redacted]



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

1–9 ENGINEERING SOFTWARE PACKAGES

We should always remember that all the computing power and the engineering software packages available today are just *tools*, and tools have meaning only in the hands of masters.

Hand calculators did not eliminate the need to teach our children how to add or subtract, and sophisticated medical software packages did not take the place of medical school training.

Neither will engineering software packages replace the traditional engineering education. They will simply cause a shift in emphasis in the courses from mathematics to physics. That is, more time will be spent in the classroom discussing the physical aspects of the problems in greater detail, and less time on the mechanics of solution procedures.

An excellent word-processing program does not make a person a good writer; it simply makes a good writer a more efficient writer.

[redacted]

EES (Engineering Equation Solver)

(Pronounced as ease):

EES is a program that solves systems of linear or nonlinear algebraic or differential equations numerically.

It has a large library of built-in thermodynamic property functions as well as mathematical functions.

Unlike some software packages, EES does not solve engineering problems; it only solves the equations supplied by the user.

FlowLab

It is important for beginning students of fluid mechanics to become familiar with **Computational Fluid Dynamics (CFD).**

FlowLab is a student-oriented CFD software package that utilizes predesigned templates that enable virtually anyone to run a CFD code and generate results.

FlowLab is based on the commercial CFD program from ANSYS called FLUENT; you will see FlowLab end-of-chapter problems throughout this textbook.

Each problem is designed with two objectives:

(1) Learn or emphasize a fluid mechanics concept

(2) Become familiar with running a user-friendly CFD code

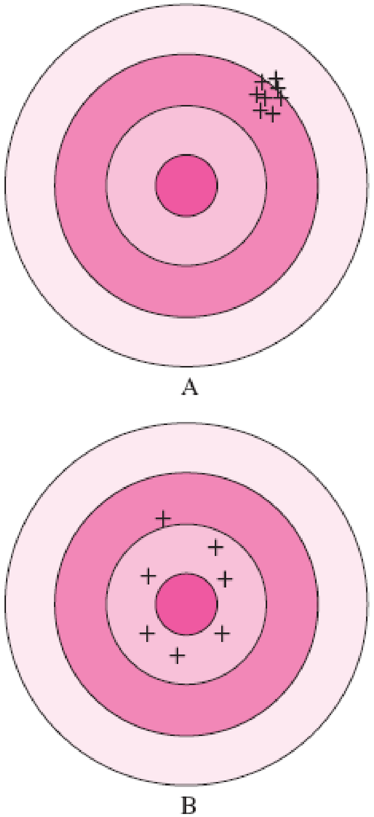
1–10 ACCURACY, PRECISION, AND SIGNIFICANT DIGITS

Accuracy error (*inaccuracy*): The value of one reading minus the true value. In general, accuracy of a set of measurements refers to the closeness of the average reading to the true value. Accuracy is generally associated with repeatable, fixed errors.

Precision error: The value of one reading minus the average of readings. In general, precision of a set of measurements refers to the fineness of the resolution and the repeatability of the instrument. Precision is generally associated with unrepeatable, random errors.

Significant digits: Digits that are relevant and meaningful.

Shooter A is more precise, but less accurate, while shooter B is more accurate, but less precise.



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.

[redacted]

Significant digits

Number	Exponential Notation	Number of Significant Digits
12.3	1.23×10^{1}	3
123,000	1.23×10^{5}	3
0.00123	1.23×10^{-3}	3
40,300	4.03×10^{4}	3
40,300.	4.0300×10^{4}	5
0.005600	5.600×10^{-3}	4
0.0056	5.6×10^{-3}	2
0.006	$6. \times 10^{-3}$	1

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

(3 significant digits)

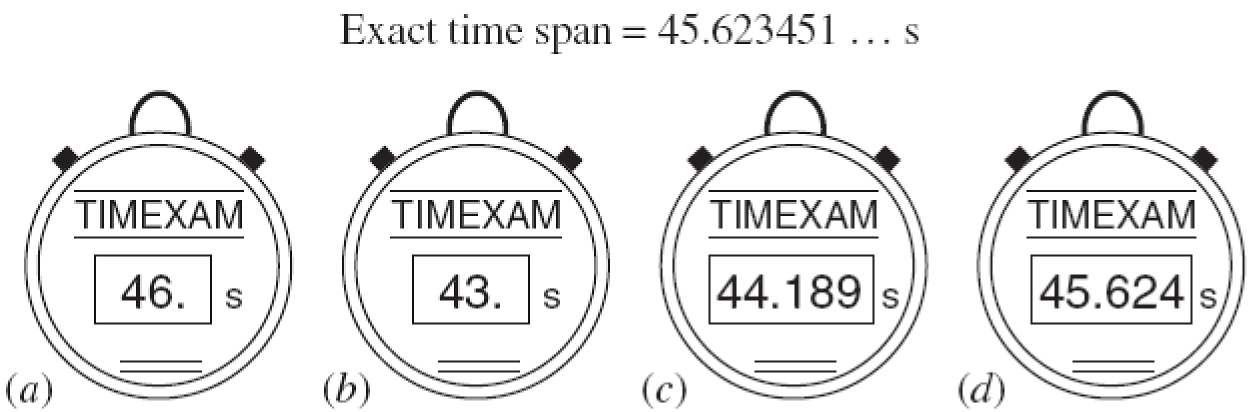
Also, $3.75 \times 0.845 = 3.16875$

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

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

A result with more significant digits than that of given data falsely implies more precision.

[redacted]



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*?

Summary

- The No-Slip Condition
- A Brief History of Fluid Mechanics
- Classification of Fluid Flows
  - Viscous versus Inviscid Regions of Flow
  - Internal versus External Flow
  - Compressible versus Incompressible Flow
  - Laminar versus Turbulent Flow
  - Natural (or Unforced) versus Forced Flow
  - Steady versus Unsteady Flow
  - One-, Two-, and Three-Dimensional Flows
- System and Control Volume
- Importance of Dimensions and Units
- Mathematical Modeling of Engineering Problems
- Problem Solving Technique
- Engineering Software Packages
- Accuracy, Precision and Significant Digits