Thermodynamics: An Engineering Approach
Seventh Edition in SI Units
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Chapter 1
INTRODUCTION AND BASIC CONCEPTS

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Objectives

- Identify the unique vocabulary associated with thermodynamics through the precise definition of basic concepts to form a sound foundation for the development of the principles of thermodynamics.
- Review the metric SI and the English unit systems.
- Explain the basic concepts of thermodynamics such as system, state, state postulate, equilibrium, process, and cycle.
- Review concepts of temperature, temperature scales, pressure, and absolute and gage pressure.
- Introduce an intuitive systematic problem-solving technique.

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THERMODYNAMICS AND ENERGY

- **Thermodynamics**: The science of *energy*.
- **Energy**: The ability to cause changes.
- The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamis* (power).
- **Conservation of energy principle**: During an interaction, energy can change from one form to another but the total amount of energy remains constant.
- Energy cannot be created or destroyed.
- **The first law of thermodynamics**: An expression of the conservation of energy principle.
- The first law asserts that *energy* is a thermodynamic property.

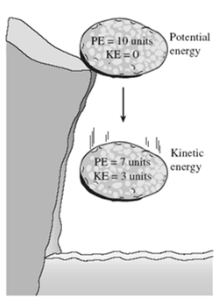

FIGURE 1–1
Energy cannot be created or destroyed; it can only change forms (the first law).

- **The second law of thermodynamics:** It asserts that energy has *quality* as well as *quantity,* and actual processes occur in the direction of decreasing quality of energy.
- **Classical thermodynamics**: A macroscopic approach to the study of thermodynamics that does not require a knowledge of the behavior of individual particles.
- It provides a direct and easy way to the solution of engineering problems and it is used in this text.
- **Statistical thermodynamics**: A microscopic approach, based on the average behavior of large groups of individual particles.
- It is used in this text only in the supporting role.

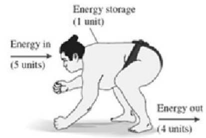

FIGURE 1–2
Conservation of energy principle for the human body.

FIGURE 1–3
Heat flows in the direction of decreasing temperature.

Application Areas of Thermodynamics

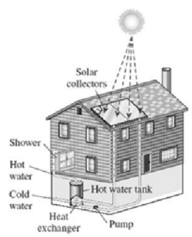

FIGURE 1–4
The design of many engineering systems, such as this solar hot water system, involves thermodynamics.

Refrigeration systems

Boats

Aircraft and spacecraft

Power plants

All activities in nature involve some interaction between energy and matter; thus, it is hard to imagine an area that does not relate to thermodynamics in some manner.

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Human body

Cars

Wind turbines

Air conditioning systems

Industrial applications

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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)

TABLE 1–2

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

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

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

$$\text{Force} = (\text{Mass})(\text{Acceleration})$$

$$F = ma$$

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

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

Work = Force × Distance
1 J = 1 N·m
1 cal = 4.1868 J
1 Btu = 1.0551 kJ

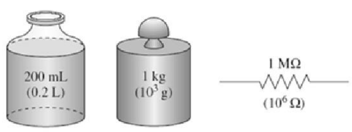

FIGURE 1–6
The SI unit prefixes are used in all branches of engineering.

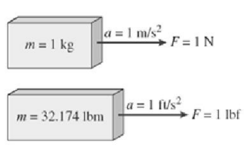

FIGURE 1–7
The definition of the force units.

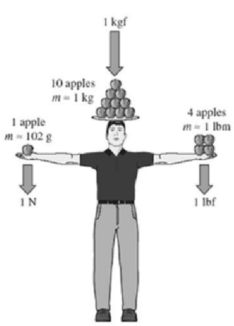

FIGURE 1–8
The relative magnitudes of the force units newton (N), kilogram-force (kgf), and pound-force (lbf).

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

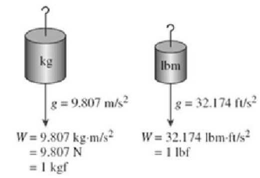

FIGURE 1–10
The weight of a unit mass at sea level.

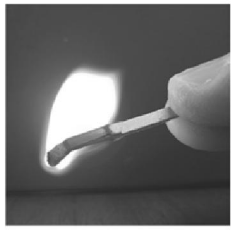

FIGURE 1–11
A typical match yields about one Btu (or one kJ) of energy if completely burned.

Specific weight γ**:** The weight of a unit volume of a substance.

$$\gamma = \rho g$$

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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

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

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

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

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.

FIGURE 1–12
To be dimensionally homogeneous, all the terms in an equation must have the same dimensions.

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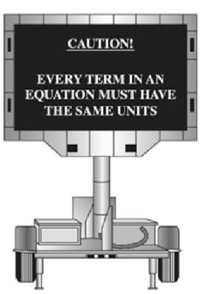

FIGURE 1–15
Always check the units in your calculations.

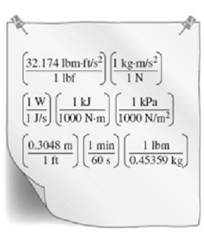

FIGURE 1–16
Every unity conversion ratio (as well as its inverse) is exactly equal to one. Shown here are a few commonly used unity conversion ratios.

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FIGURE 1–17
A mass of 1 kg weighs 9.807 N on earth.

FIGURE 1–18
A quirk in the metric system of units.

$$W = mg = (453.6\ \text{g})(9.81\ \text{m/s}^2)\left(\frac{1\ \text{N}}{1\ \text{kg}\cdot\text{m/s}^2}\right)\left(\frac{1\ \text{kg}}{1000\ \text{g}}\right) = 4.49\ \text{N}$$

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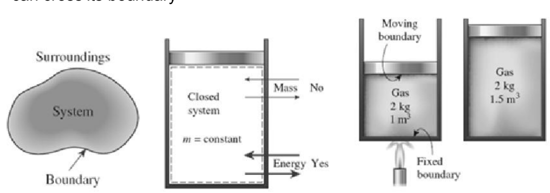
SYSTEMS AND CONTROL VOLUMES

- **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



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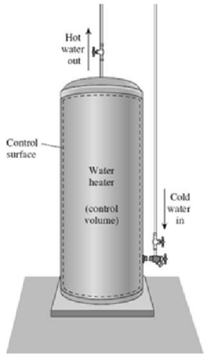
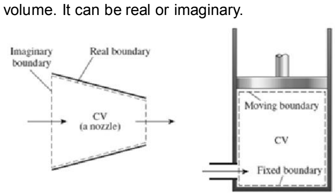


FIGURE 1–23
An open system (a control volume) with one inlet and one exit.

- **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.



(*a*) A control volume with real and imaginary boundaries (*b*) A control volume with fixed and moving boundaries

FIGURE 1–22
A control volume can involve fixed, moving, real, and imaginary boundaries.

PROPERTIES OF A SYSTEM

- **Property:** Any characteristic of a system.
- Some familiar properties are pressure *P*, temperature *T*, volume *V*, and mass *m*.
- Properties are considered to be either *intensive* or *extensive*.
- **Intensive properties:** Those that are independent of the mass of a system, such as temperature, pressure, and density.
- **Extensive properties:** Those whose values depend on the size—or extent—of the system.
- **Specific properties:** Extensive properties per unit mass.

$(v = V/m) \quad (e = E/m)$

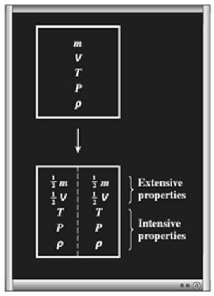


FIGURE 1–24
Criterion to differentiate intensive and extensive properties.

Continuum

- Matter is made up of atoms that are widely spaced in the gas phase. Yet it is very convenient to disregard the atomic nature of a substance and view it as a continuous, homogeneous matter with no holes, that is, a **continuum**.
- The continuum idealization allows us to treat properties as point functions and to assume the properties vary continually in space with no jump discontinuities.
- This idealization is valid as long as the size of the system we deal with is large relative to the space between the molecules.
- This is the case in practically all problems.
- In this text we will limit our consideration to substances that can be modeled as a continuum.

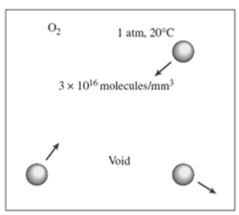


FIGURE 1–25
Despite the large gaps between molecules, a substance can be treated as a continuum because of the very large number of molecules even in an extremely small volume.

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DENSITY AND SPECIFIC GRAVITY

Density

$$\rho = \frac{m}{V} \qquad (\mathrm{kg/m^3})$$

Specific volume

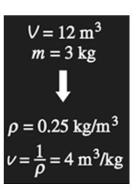
$$v = \frac{V}{m} = \frac{1}{\rho}$$

Specific gravity: The ratio of the density of a substance to the density of some standard substance at a specified temperature (usually water at 4°C).

$$\mathrm{SG} = \frac{\rho}{\rho_{\mathrm{H_2O}}}$$

Specific weight: The weight of a unit volume of a substance.

$$\gamma_s = \rho g \qquad (\mathrm{N/m^3})$$



Density is mass per unit volume; specific volume is volume per unit mass.

TABLE 1–3
Specific gravities of some substances at 0°C

Substance	SG
Water	1.0
Blood	1.05
Seawater	1.025
Gasoline	0.7
Ethyl alcohol	0.79
Mercury	13.6
Wood	0.3–0.9
Gold	19.2
Bones	1.7–2.0
Ice	0.92
Air (at 1 atm)	0.0013

STATE AND EQUILIBRIUM

- Thermodynamics deals with *equilibrium* states.
- **Equilibrium**: A state of balance.
- In an equilibrium state there are no unbalanced potentials (or driving forces) within the system.
- **Thermal equilibrium**: If the temperature is the same throughout the entire system.
- **Mechanical equilibrium:** If there is no change in pressure at any point of the system with time.
- **Phase equilibrium:** If a system involves two phases and when the mass of each phase reaches an equilibrium level and stays there.
- **Chemical equilibrium:** If the chemical composition of a system does not change with time, that is, no chemical reactions occur.

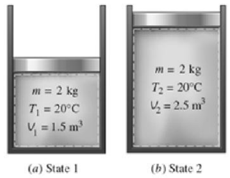


FIGURE 1–27
A system at two different states.

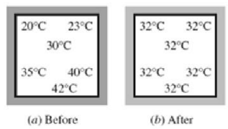


FIGURE 1–28
A closed system reaching thermal equilibrium.

The State Postulate

- The number of properties required to fix the state of a system is given by the **state postulate**:
  - ✓ *The state of a simple compressible system is completely specified by two independent, intensive properties.*
- **Simple compressible system:** If a system involves no electrical, magnetic, gravitational, motion, and surface tension effects.

The state of nitrogen is fixed by two independent, intensive properties.

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PROCESSES AND CYCLES

Process: Any change that a system undergoes from one equilibrium state to another.
Path: The series of states through which a system passes during a process.
To describe a process completely, one should specify the initial and final states, as well as the path it follows, and the interactions with the surroundings.
Quasistatic or quasi-equilibrium process: When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times.

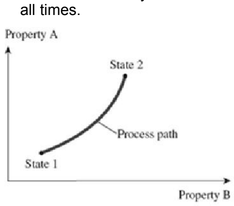

FIGURE 1–30
A process between states 1 and 2 and the process path.

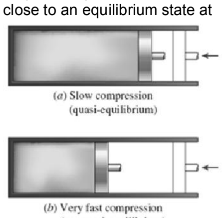

FIGURE 1–31
Quasi-equilibrium and nonquasi-equilibrium compression processes.

- Process diagrams plotted by employing thermodynamic properties as coordinates are very useful in visualizing the processes.
- Some common properties that are used as coordinates are temperature *T*, pressure *P*, and volume *V* (or specific volume *v*).
- The prefix *iso-* is often used to designate a process for which a particular property remains constant.
- **Isothermal process**: A process during which the temperature *T* remains constant.
- **Isobaric process**: A process during which the pressure *P* remains constant.
- **Isochoric (or isometric) process**: A process during which the specific volume *v* remains constant.
- **Cycle**: A process during which the initial and final states are identical.

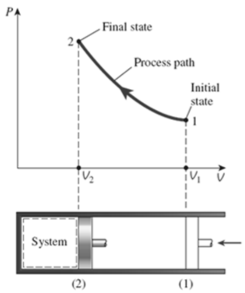

FIGURE 1–32
The *P*-*V* diagram of a compression process.

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The Steady-Flow Process

- The term *steady* implies *no change with time*. The opposite of steady is *unsteady*, or *transient*.
- A large number of engineering devices operate for long periods of time under the same conditions, and they are classified as *steady-flow devices*.
- **Steady-flow process**: A process during which a fluid flows through a control volume steadily.
- Steady-flow conditions can be closely approximated by devices that are intended for continuous operation such as turbines, pumps, boilers, condensers, and heat exchangers or power plants or refrigeration systems.

During a steady-flow process, fluid properties within the control volume may change with position but not with time.

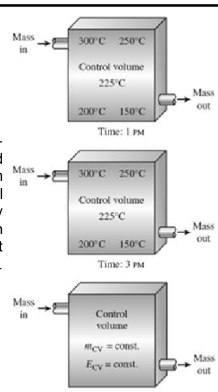

FIGURE 1–34
Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

TEMPERATURE AND THE ZEROTH LAW OF THERMODYNAMICS

- **The zeroth law of thermodynamics**: If two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.
- By replacing the third body with a thermometer, the zeroth law can be restated as *two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact*.

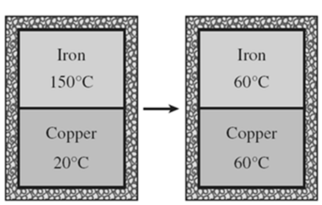

FIGURE 1–35
Two bodies reaching thermal equilibrium after being brought into contact in an isolated enclosure.

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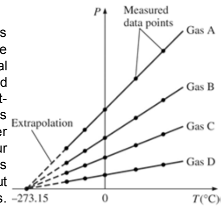
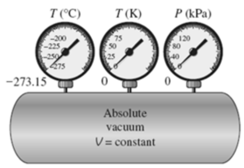
Temperature Scales

- All temperature scales are based on some easily reproducible states such as the freezing and boiling points of water: the *ice point* and the *steam point*.
- **Ice point**: A mixture of ice and water that is in equilibrium with air saturated with vapor at 1 atm pressure (0°C or 32°F).
- **Steam point**: A mixture of liquid water and water vapor (with no air) in equilibrium at 1 atm pressure (100°C or 212°F).
- **Celsius scale**: in SI unit system
- **Fahrenheit scale**: in English unit system
- **Thermodynamic temperature scale**: A temperature scale that is independent of the properties of any substance.
- **Kelvin scale** (SI) **Rankine scale** (E)
- A temperature scale nearly identical to the Kelvin scale is the **ideal-gas temperature scale**. The temperatures on this scale are measured using a constant-volume gas thermometer.

P versus *T* plots of the experimental data obtained from a constant-volume gas thermometer using four different gases at different (but low) pressures.

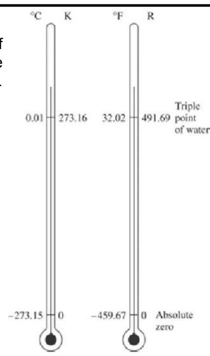


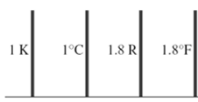


A constant-volume gas thermometer would read -273.15°C at absolute zero pressure. 25

$$T(\mathrm{K}) = T(^\circ\mathrm{C}) + 273.15$$
$$T(\mathrm{R}) = T(^\circ\mathrm{F}) + 459.67$$
$$T(\mathrm{R}) = 1.8T(\mathrm{K})$$
$$T(^\circ\mathrm{F}) = 1.8T(^\circ\mathrm{C}) + 32$$
$$\Delta T(\mathrm{K}) = \Delta T(^\circ\mathrm{C})$$
$$\Delta T(\mathrm{R}) = \Delta T(^\circ\mathrm{F})$$

Comparison of temperature scales.





Comparison of magnitudes of various temperature units.

- The reference temperature in the original Kelvin scale was the ***ice point***, 273.15 K, which is the temperature at which water freezes (or ice melts).
- The reference point was changed to a much more precisely reproducible point, the ***triple point*** of water (the state at which all three phases of water coexist in equilibrium), which is assigned the value 273.16 K.

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The International Temperature Scale of 1990 (ITS-90)

The *International Temperature Scale of 1990* supersedes the International Practical Temperature Scale of 1968 (**IPTS-68**), 1948 (**ITPS-48**), and 1927 (**ITS-27**).

The ITS-90 is similar to its predecessors except that it is more refined with updated values of fixed temperatures, has an extended range, and conforms more closely to the thermodynamic temperature scale.

On this scale, the unit of thermodynamic temperature *T* is again the kelvin (K), defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water, which is sole defining fixed point of both the ITS-90 and the Kelvin scale and is the most important thermometric fixed point used in the calibration of thermometers to ITS-90. The unit of Celsius temperature is the degree Celsius (°C).

The ice point remains the same at 0°C (273.15 K) in both ITS-90 and ITPS-68, but the steam point is 99.975°C in ITS-90 whereas it was 100.000°C in IPTS-68.

The change is due to precise measurements made by gas thermometry by paying particular attention to the effect of sorption (the impurities in a gas absorbed by the walls of the bulb at the reference temperature being desorbed at higher temperatures, causing the measured gas pressure to increase).

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PRESSURE

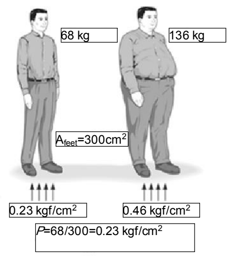
Pressure: A normal force exerted by a fluid per unit area

$$1\ \text{Pa} = 1\ \text{N/m}^2$$

$$1\ \text{bar} = 10^5\ \text{Pa} = 0.1\ \text{MPa} = 100\ \text{kPa}$$

$$1\ \text{atm} = 101{,}325\ \text{Pa} = 101.325\ \text{kPa} = 1.01325\ \text{bars}$$

$$1\ \text{kgf/cm}^2 = 9.807\ \text{N/cm}^2 = 9.807 \times 10^4\ \text{N/m}^2 = 9.807 \times 10^4\ \text{Pa} = 0.9807\ \text{bar} = 0.9679\ \text{atm}$$



The normal stress (or "pressure") on the feet of a chubby person is much greater than on the feet of a slim person.

Some basic pressure gages.

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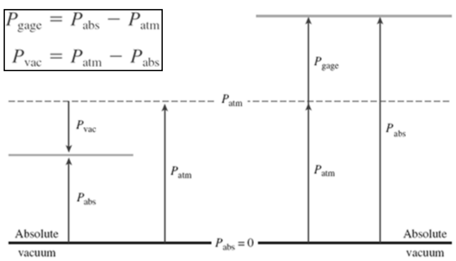
- **Absolute pressure**: The actual pressure at a given position. It is measured relative to absolute vacuum (i.e., absolute zero pressure).
- **Gage pressure**: The difference between the absolute pressure and the local atmospheric pressure. Most pressure-measuring devices are calibrated to read zero in the atmosphere, and so they indicate gage pressure.
- **Vacuum pressures**: Pressures below atmospheric pressure.

Throughout this text, the pressure ***P*** will denote ***absolute pressure*** unless specified otherwise.

$$P_{\text{gage}} = P_{\text{abs}} - P_{\text{atm}}$$

$$P_{\text{vac}} = P_{\text{atm}} - P_{\text{abs}}$$



Variation of Pressure with Depth

$$\Delta P = P_2 - P_1 = \rho g\, \Delta z = \gamma_s\, \Delta z$$

$$P = P_{\text{atm}} + \rho g h \quad \text{or} \quad P_{\text{gage}} = \rho g h$$

When the variation of density with elevation is known

$$\Delta P = P_2 - P_1 = -\int_1^2 \rho g\, dz$$

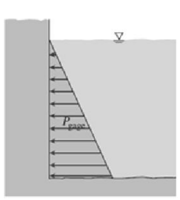


FIGURE 1–43 The pressure of a fluid at rest increases with depth (as a result of added weight).

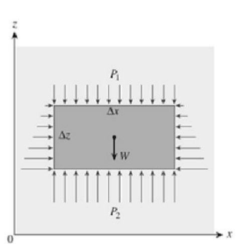


FIGURE 1–44 Free-body diagram of a rectangular fluid element in equilibrium.

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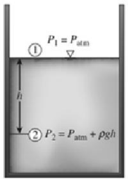
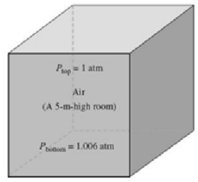


Pressure in a liquid at rest increases linearly with distance from the free surface.

In a room filled with a gas, the variation of pressure with height is negligible.



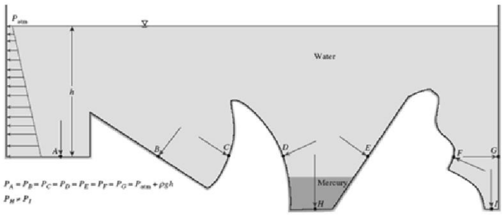


FIGURE 1–47
The pressure is the same at all points on a horizontal plane in a given fluid regardless of geometry, provided that the points are interconnected by the same fluid.

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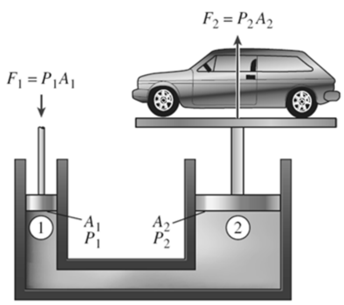
Pascal's law: The pressure applied to a confined fluid increases the pressure throughout by the same amount.

$$P_1 = P_2 \quad \rightarrow \quad \frac{F_1}{A_1} = \frac{F_2}{A_2} \quad \rightarrow \quad \frac{F_2}{F_1} = \frac{A_2}{A_1}$$

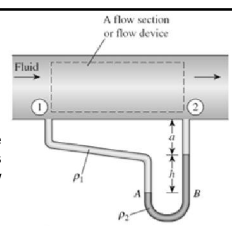
The area ratio A_2/A_1 is called the *ideal mechanical advantage* of the hydraulic lift.



Lifting of a large weight by a small force by the application of Pascal's law.

The Manometer

It is commonly used to measure small and moderate pressure differences. A manometer contains one or more fluids such as mercury, water, alcohol, or oil.



Measuring the pressure drop across a flow section or a flow device by a differential manometer.

$$P_1 + \rho_1 g(a + h) - \rho_2 gh - \rho_1 ga = P_2$$

$$P_1 - P_2 = (\rho_2 - \rho_1)gh$$

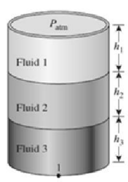
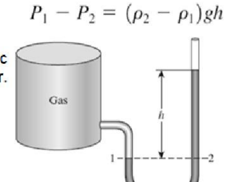


FIGURE 1–51
In stacked-up fluid layers, the pressure change across a fluid layer of density ρ and height h is ρgh.

$$P_{atm} + \rho_1 gh_1 + \rho_2 gh_2 + \rho_3 gh_3 = P_1$$

The basic manometer.



$$\boxed{P_2 = P_{atm} + \rho gh}$$

Other Pressure Measurement Devices

- **Bourdon tube**: Consists of a hollow metal tube bent like a hook whose end is closed and connected to a dial indicator needle.
- **Pressure transducers**: Use various techniques to convert the pressure effect to an electrical effect such as a change in voltage, resistance, or capacitance.
- Pressure transducers are smaller and faster, and they can be more sensitive, reliable, and precise than their mechanical counterparts.
- **Strain-gage pressure transducers:** Work by having a diaphragm deflect between two chambers open to the pressure inputs.
- **Piezoelectric transducers**: Also called solid-state pressure transducers, work on the principle that an electric potential is generated in a crystalline substance when it is subjected to mechanical pressure.

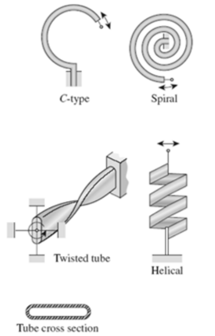


FIGURE 1–54
Various types of Bourdon tubes used to measure pressure.

THE BAROMETER AND ATMOSPHERIC PRESSURE

- Atmospheric pressure is measured by a device called a **barometer**; thus, the atmospheric pressure is often referred to as the ***barometric pressure***.
- A frequently used pressure unit is the *standard atmosphere*, which is defined as the pressure produced by a column of mercury 760 mm in height at 0°C (ρ_{Hg} = 13,595 kg/m^3) under standard gravitational acceleration (g = 9.807 m/s^2).

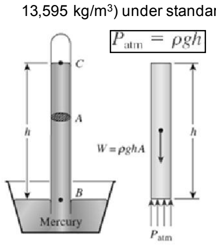
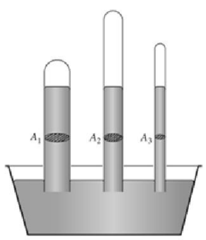


FIGURE 1–55
The basic barometer.

The length or the cross-sectional area of the tube has no effect on the height of the fluid column of a barometer, provided that the tube diameter is large enough to avoid surface tension (capillary) effects.



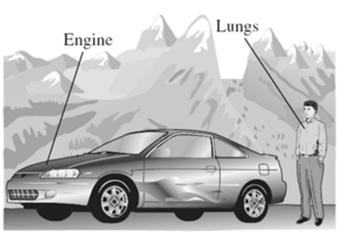


FIGURE 1–57
At high altitudes, a car engine generates less power and a person gets less oxygen because of the lower density of air.

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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

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.

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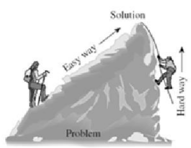

FIGURE 1–61
A step-by-step approach can greatly simplify problem solving.

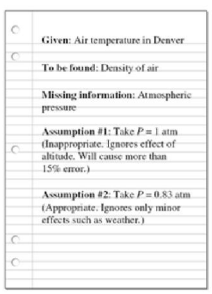

FIGURE 1–62
The assumptions made while solving an engineering problem must be reasonable and justifiable.

FIGURE 1–65
An excellent word-processing program does not make a person a good writer; it simply makes a good writer a more efficient writer.

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FIGURE 1–63
The results obtained from an engineering analysis must be checked for reasonableness.

FIGURE 1–64
Neatness and organization are highly valued by employers.

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A Remark on Significant Digits

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

Consequently, the results obtained cannot possibly be accurate to more significant digits.

Reporting results in more significant digits implies greater accuracy than exists, and it should be avoided.

FIGURE 1–67
A result with more significant digits than that of given data falsely implies more accuracy.

Summary

- Thermodynamics and energy
  - ✓ Application areas of thermodynamics
- Importance of dimensions and units
  - ✓ Some SI and English units, Dimensional homogeneity, Unity conversion ratios
- Systems and control volumes
- Properties of a system
  - ✓ Continuum
- Density and specific gravity
- State and equilibrium
  - ✓ The state postulate
- Processes and cycles
  - ✓ The steady-flow process
- Temperature and the zeroth law of thermodynamics
  - ✓ Temperature scales
  - ✓ ITS-90
- Pressure
  - ✓ Variation of pressure with depth
- The manometer
  - ✓ Other pressure measurement devices
- The barometer and atmospheric pressure
- Problem solving technique

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