

Applied Thermodynamics (Lecture#01)

Course Outline:

Basic Concepts, the system, Open and close system, properties of a system, control volume, working substance, heat and work, state and properties, thermodynamic process and cycle, forms of energy, first law of thermodynamics, first law of thermodynamics for a cycle, first law of thermodynamics for state change, Internal energy, enthalpy, specific heats, ideal gas laws, equations of state, properties of pure substances, phase diagram, use of steam tables, Phased change process of pure substances, thermodynamic processes relationship, constant volume, constant pressure, temperature, enthalpy and general law processes, steady state and steady flow process, uniform state and uniform flow processes.

Steady flow energy equation and steady flow engineering devices, second law of thermodynamics, definitions, and its applications, reversible and irreversible processes, Carnot cycle and thermodynamic temperature scale, concept of entropy and its application to flow and non-flow processes, enthalpy-entropy diagrams of working fluids, thermodynamic cycles, efficiencies, and their applications, idealized P-V and T – S diagrams, comparison with Carnot cycle, Rankine cycle and its applications, difference between direct and reversed cycles, concept of open and closed cycles.

Recommended Books:

1. Applied Thermodynamics by T. D. Eastop, A. McConkey
2. Thermodynamics, An Engineering Approach by Y.A. Cengel and M.A. Boles
3. Fundamentals of Engineering Thermodynamics by Moran, Shapiro
4. Fundamentals of Thermodynamics by Sonntag, Borgnakke, Van Wylen
5. Basic Engineering Thermodynamic by Rayner Joel

Introduction & Basic Concepts of Thermodynamics

Introduction:

The most of general sense of thermodynamics is the study of energy and its relationship to the properties of matter. All activities in nature involve some interaction between energy and matter. Thermodynamics is a science that governs the following:

- Energy and its transformation
- Feasibility of a process involving transformation of energy
- Feasibility of a process involving transfer of energy
- Equilibrium processes

More specifically, thermodynamics deals with energy conversion, energy exchange and the direction of exchange.

Areas of Application of Thermodynamics:

All natural processes are governed by the principles of thermodynamics. However, the following engineering devices are typically designed based on the principles of thermodynamics.

Automotive engines, Turbines, Compressors, Pumps, Fossil and Nuclear Power Plants, Propulsion systems for the Aircrafts, Separation and Liquefaction Plant, Refrigeration, Air-conditioning and Heating Devices.

The principles of thermodynamics are summarized in the form of a set of axioms. These axioms are known as four thermodynamic laws:

The zeroth law, the first law, the second law and the third law:

- **The Zeroth Law** deals with thermal equilibrium and provides a means for measuring temperatures.
 - **The First Law** deals with the conservation of energy and introduces the concept of internal energy.
 - **The Second Law** of thermodynamics provides with the guidelines on the conversion of internal energy of matter into work. It also introduces the concept of entropy.
 - **The Third Law** of thermodynamics defines the absolute zero of entropy. The entropy of a pure crystalline substance at absolute zero temperature is zero.

Different Approaches in the Study of Thermodynamics:

Thermodynamics can be studied through two different approaches:

(a) **Macroscopic Approach and**

(b) **Microscopic Approach**

Macroscopic Approach:

Consider a certain amount of gas in a cylindrical container. The volume (V) can be measured by measuring the diameter and the height of the cylinder. The pressure (P) of the gas can be measured by a pressure gauge. The temperature (T) of the gas can be measured using a thermometer. The state of the gas can be specified by the measured P, V and T. The values of these variables are space averaged characteristics of the properties of the gas under consideration. In classical thermodynamics, we often use this macroscopic approach.

The macroscopic approach has the following features.

- The structure of the matter is not considered.
- A few variables are used to describe the state of the matter under consideration.
- The values of these variables are measurable following the available techniques of experimental physics.

Microscopic Approach:

On the other hand, the gas can be considered as assemblage of a large number of particles each of which moves randomly with independent velocity. The state of each particle can be specified in terms of position coordinates (x_i, y_i, z_i) and the momentum components (p_{xi}, p_{yi}, p_{zi}) . If we consider a gas occupying a volume of 1 cm^3 at ambient temperature and pressure, the number of particles present in it is of the order of 10^{20} . The same number of position coordinates and momentum components are needed to specify the state of the gas. The microscopic approach can be summarized as:

- A knowledge of the molecular structure of matter under consideration is essential.
- A large number of variables are needed for a complete specification of the state of the matter.

SI Units

SI is the abbreviation of System International Unites. The SI units for mass, length, time and force are kilogram, meter, second and newton respectively. The unit of length is meter, m, defined as $1, 650, 763.73$ wavelengths in vacuum of the radiation corresponding to the orange-red line of the spectrum of Krypton-86. The unit of time is second, s. The second is defined as the duration of $9, 192, 631, 770$ cycles of the radiation associated with a specified transition of the Cesium 133 atom. The unit of mass is kilogram, kg. It is equal to the mass of a particular cylinder of platinum-iridium alloy kept at the International Bureau of Weights and Measures.

The amount of substance can also be expressed in terms of the mole (mol). One kilomole of a substance is the amount of that substance in kilograms numerically equal to its molecular weight. The number of kilomoles of a substance, n , is obtained by dividing the mass (m) in kilograms by the molecular weight (M), in kg/ kmol.

$$n = m/M$$

The unit for temperature is Kelvin, K. One K is the fraction $1/273.16$ of the thermodynamic temperature of the triple point of water. Quite often the Celsius, $^{\circ}\text{C}$, is used to express the temperature of a substance.

$$^{\circ}\text{C} = \text{K} - 273.16$$

The SI unit of force, called the newton, N is a secondary unit. The, N, is the force required to accelerate a mass of 1 kilogram at the rate of 1 meter per (second)².

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

The smaller or bigger quantities are expressed using the following prefixes The smaller or bigger quantities are expressed using the following prefixes

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{12}	tera	<i>T</i>	10^{-2}	centi	<i>c</i>
10^9	giga	<i>G</i>	10^{-3}	milli	<i>m</i>
10^6	mega	<i>M</i>	10^{-6}	micro	μ
10^3	kilo	<i>k</i>	10^{-9}	nano	<i>n</i>
10^2	hecto	<i>h</i>	10^{-12}	pico	<i>p</i>

Pressure:

Pressure is the normal force exerted by a system against unit area of the boundary surface.

$$\lim_{\delta A \rightarrow 0} \frac{F_n}{\delta A}$$

where δA approaches zero.

The unit for pressure in SI is Pascal, Pa; $1 \text{ Pa} = 1 \text{ N/m}^2$

Two other units are widely used; $1 \text{ bar} = 10^5 \text{ Pa} = 100 \text{ kPa} = 0.1 \text{ MPa}$

and the standard atmosphere, where

$1 \text{ atm} = 101.325 \text{ kPa} = 1.01325 \text{ bar} =$ pressure exerted by a column of 760 mm of Hg

Energy:

Energy is the capacity to exert a force through a distance. In SI, the unit of energy is Newton-meter, N m or Joule, J.

Power:

The rate of energy transfer or storage is called power. The unit of power is watt, W.

$$\underline{1 \text{ W} = 1 \text{ J/s} = 1 \text{ N m/s} \text{ and } 1 \text{ kW} = 1000 \text{ W.}}$$

Apart from these, the following units are used for various parameters of interest

Frequency, Hertz = Hz = s^{-1} ; Electric current, Ampere = A

Electric charge, Coulomb, C = As ; Electric potential, Volt = V = W/A

Magnetic flux, Weber, Wb = Vs ; Magnetic flux density, Tesla, T = Wb/m²

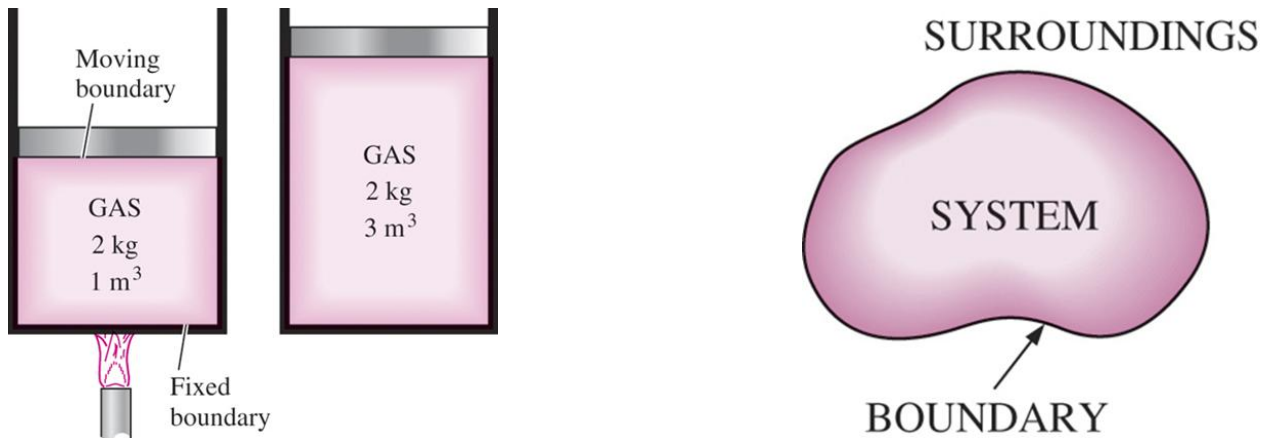
System:

A thermodynamic system is defined as a definite quantity of matter or a region in space upon which attention is focussed in the analysis of a problem. We may want to study a quantity of matter contained within a closed rigid walled chamber, or we may want to consider something such as gas pipeline through which the matter flows. The composition of the matter inside the system may be fixed or may change through chemical and nuclear reactions. A system may be arbitrarily defined. It becomes

important when exchange of energy between the system and the everything else outside the system is considered. The judgment on the energetics of this exchange is very important.

Surroundings:

Everything external to the system is surroundings. The system is distinguished from its surroundings by a specified boundary which may be at rest or in motion. The interactions between a system and its surroundings, which take place across the boundary, play an important role in thermodynamics. A system and its surroundings together comprise a universe.



Types of systems:

Two types of systems can be distinguished. These are referred to, respectively, as closed systems and open systems or control volumes. A closed system or a control mass refers to a fixed quantity of matter, whereas a control volume is a region in space through which mass may flow. A special type of closed system that does not interact with its surroundings is called an Isolated system .

Two types of exchange can occur between the system and its surroundings:

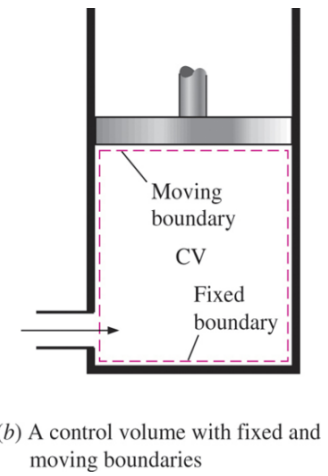
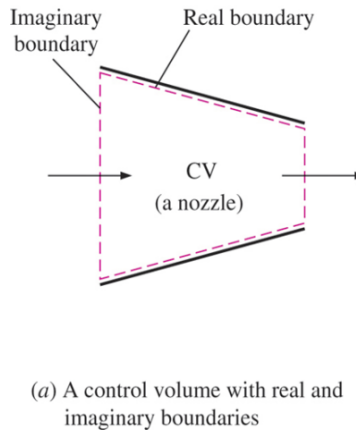
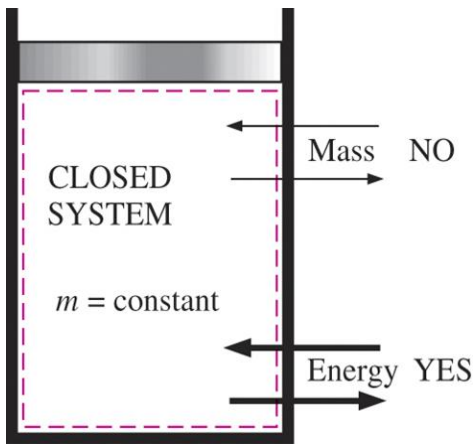
- energy exchange (heat or work) and
- exchange of matter (movement of molecules across the boundary of the system and surroundings).

Types of systems:

Based on the types of exchange, one can define

- **isolated systems:** no exchange of matter and energy
- **closed systems:** no exchange of matter but some exchange of energy
- **open systems:** exchange of both matter and energy

If the boundary does not allow heat (energy) exchange to take place it is called adiabatic boundary otherwise it is diathermal boundary.

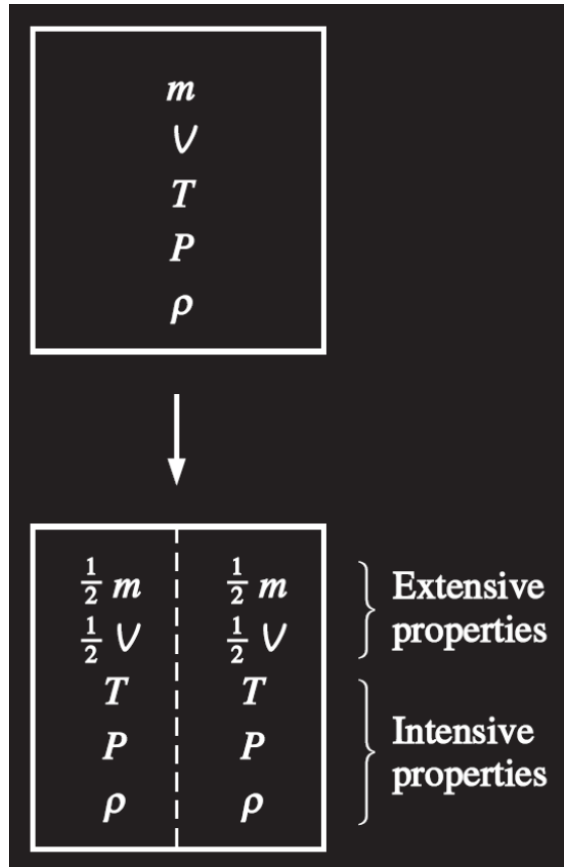


Property: Any characteristic of a system. Some familiar properties are pressure P , temperature T , volume V , and mass m . Properties are considered to be either intensive or extensive.

Intensive properties: Those that is 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.



Criterion to differentiate intensive and extensive properties.

The ratio of the extensive property to the mass is called the specific value of that property .

specific volume, $v = V/m = 1/\rho$ (ρ is the density)

specific internal energy, $u = U/m$

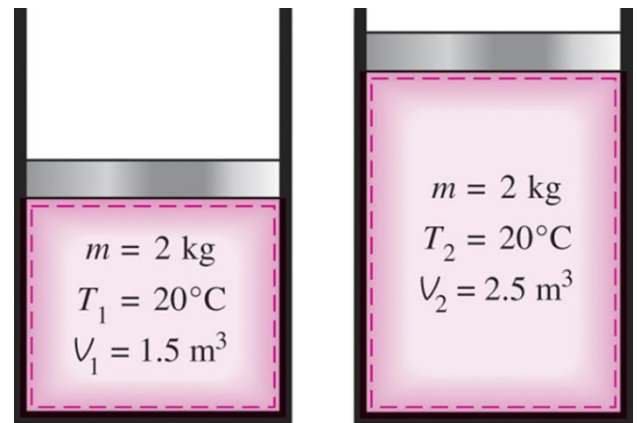
Similarly, the molar properties are defined as the ratios of the properties to the mole number (N) of the substance

$$\text{Molar volume} = v = V/N$$

$$\text{Molar internal energy} = u = U/N$$

State:

It is the condition of a system as defined by the values of all its properties. It gives a complete description of the system. Any operation in which one or more properties of a system change is called a change of state.



(a) State 1

(b) State 2

A system at two different states.

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

Equilibrium State:

- A system is said to be in an equilibrium state if its properties will not change without some perceivable effect in the surroundings.
- Equilibrium generally requires all properties to be uniform throughout the system.
- There are mechanical, thermal, phase, and chemical equilibrium.

Nature has a preferred way of directing changes.eg:

- water flows from a higher to a lower level
- Electricity flows from a higher potential to a lower one
- Heat flows from a body at higher temperature to the one at a lower temperature
- Momentum transfer occurs from a point of higher pressure to a lower one.

- Mass transfer occurs from higher concentration to a lower one

Types of Equilibrium

Between the system and surroundings, if there is no difference in

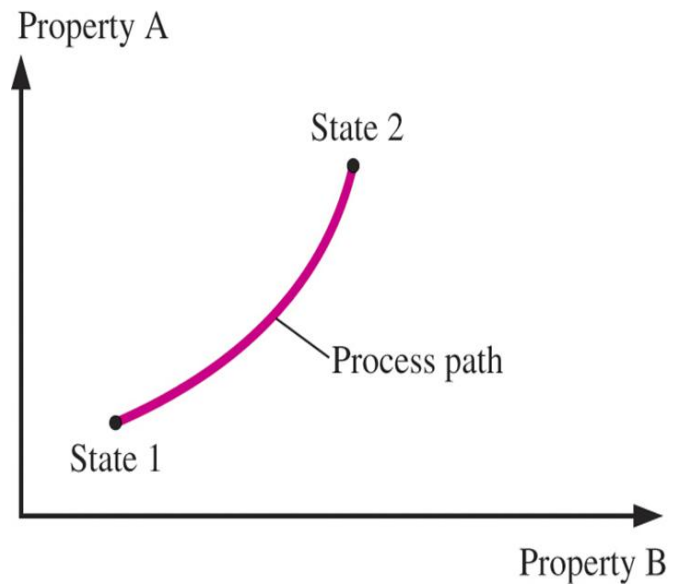
- Pressure (Mechanical equilibrium)
- Potential (Electrical equilibrium)
- Concentration of species (Species equilibrium)
- Temperature (Thermal equilibrium)

No interactions between them occur. They are said to be in equilibrium. Thermodynamic equilibrium implies all those together. A system in thermodynamic equilibrium does not deliver anything.

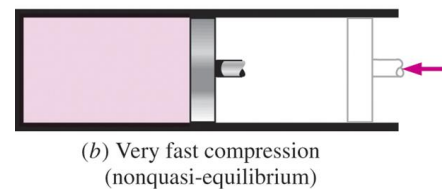
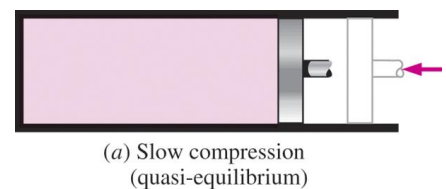
Process: Any change that a system undergoes from one equilibrium state to another.

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.

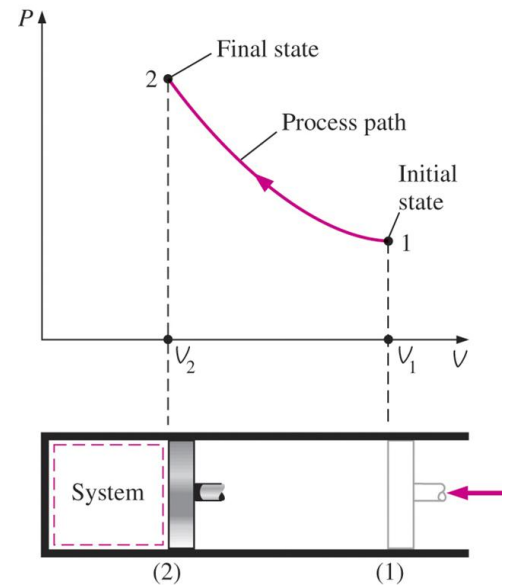


Quasi-equilibrium process: When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times.



- 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.

The P - V diagram of a



Types of Processes

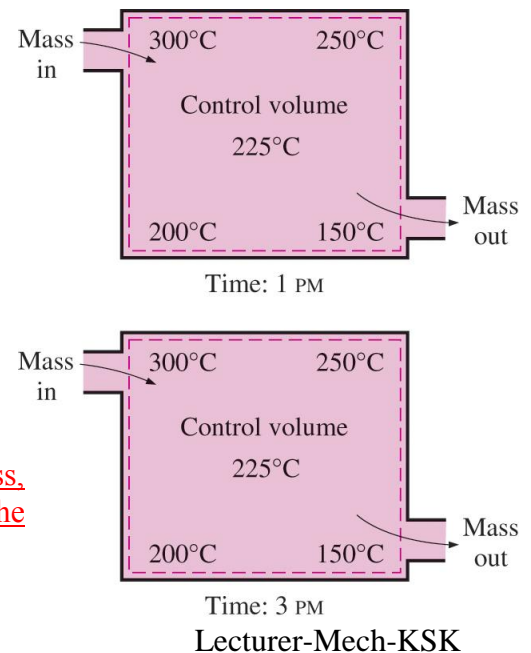
- As a matter of rule we allow one of the properties to remain a constant during a process.
 - Construe as many processes as we can (with a different property kept constant during each of them)
 - Complete the cycle by regaining the initial state
- | | |
|---|-------------------------------|
| (1) Isothermal (T) | (2) Isobaric (p) |
| (3) Isochoric (v) | (4) Isentropic (s) |
| (5) Isenthalpic (h) | (6) Isosteric (concentration) |
| (7) Adiabatic (no heat addition or removal) | |

Cycle: A process during which the initial and final states are identical.

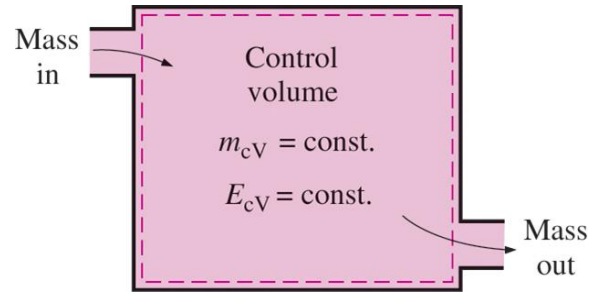
The Steady-Flow Process:

- 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**.

During a steady-flow process, fluid properties within the



- **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.**

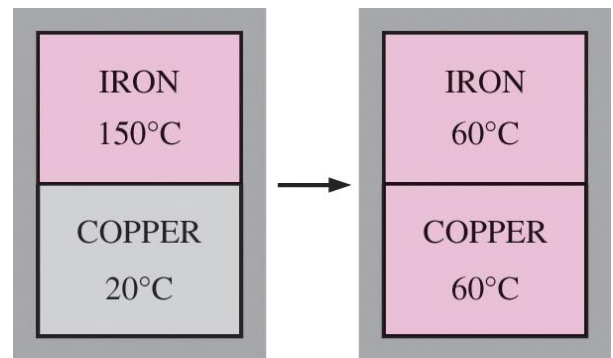


Under steady-flow conditions, the mass and energy contents of a control volume

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.**

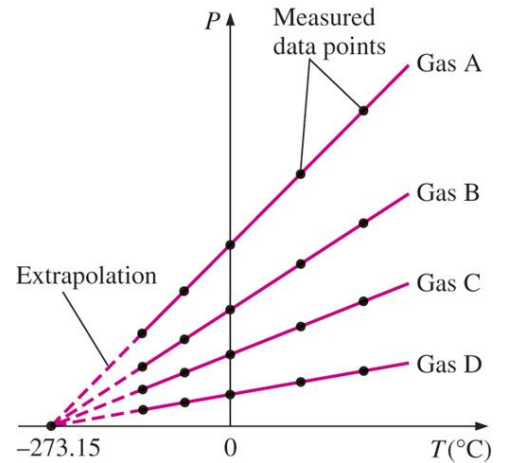
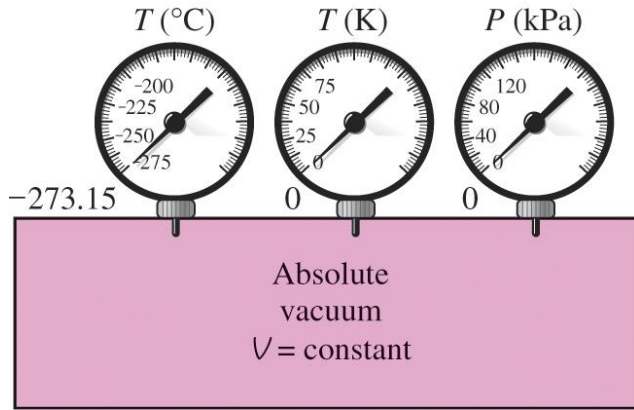
Two bodies reaching thermal equilibrium after being brought into contact in an isolated enclosure.



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.



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

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

$$T(\text{K}) = T(^{\circ}\text{C}) + 273.15$$

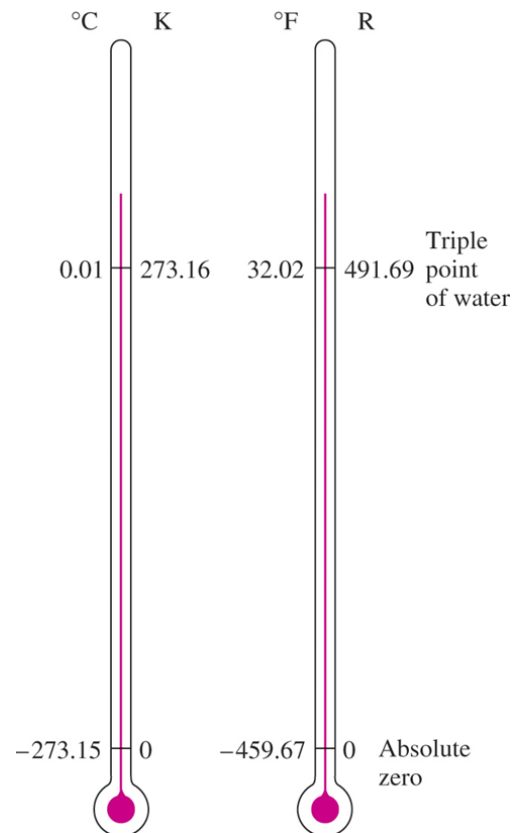
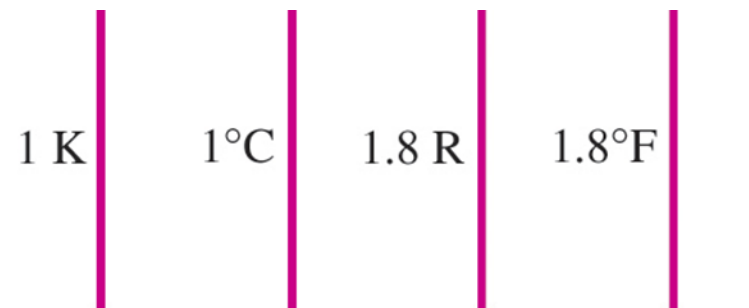
$$T(\text{R}) = T(^{\circ}\text{F}) + 459.67$$

$$T(\text{R}) = 1.8T(\text{K})$$

$$T(^{\circ}\text{F}) = 1.8T(^{\circ}\text{C}) + 32$$

$$\Delta T(\text{K}) = \Delta T(^{\circ}\text{C})$$

$$\Delta T(\text{R}) = \Delta T(^{\circ}\text{F})$$



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.

PRESSURE:

Pressure is defined as a normal force exerted by a fluid per unit area. We speak of pressure only when we deal with a gas or a liquid. The counterpart of pressure in solids is normal stress. Since pressure is defined as force per unit area, it has the unit of newton per square meter (N/m^2), which is called a Pascal (Pa). That is,

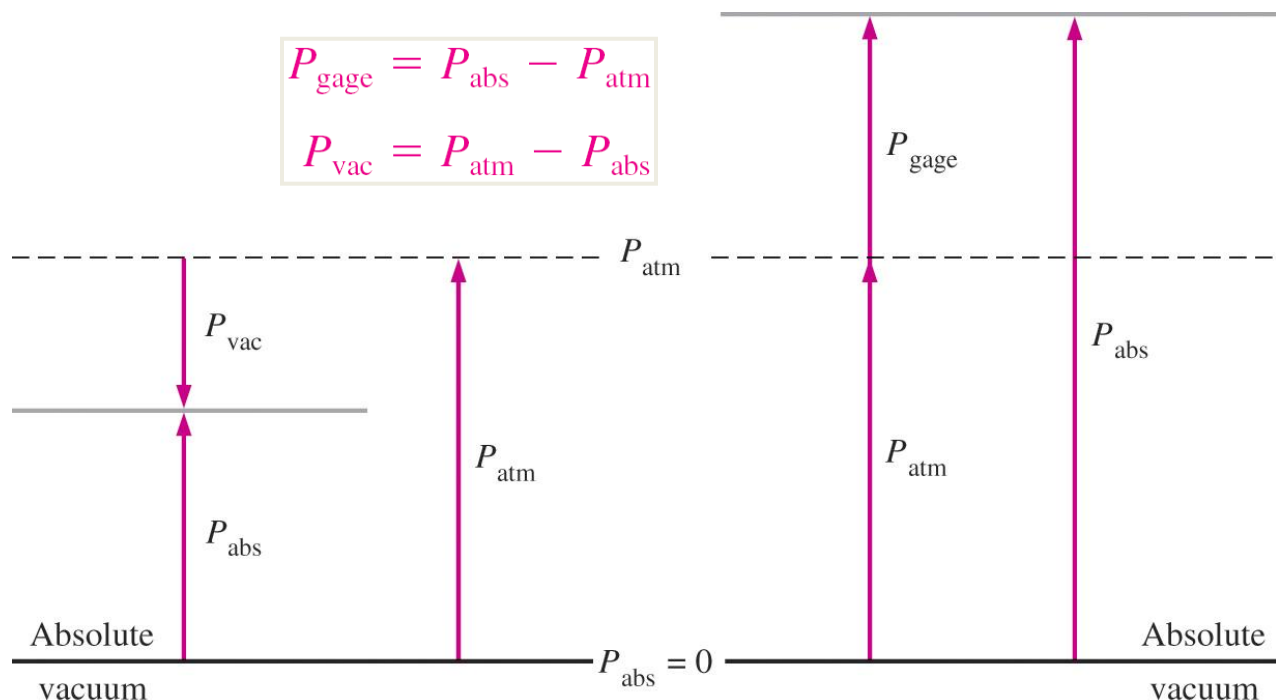
$$1 \text{ Pa} = 1 \text{ N/m}^2$$

The pressure unit Pascal is too small for pressures encountered in practice. Therefore, its multiples kilopascal ($1 \text{ kPa} = 10^3 \text{ Pa}$) and mega Pascal ($1 \text{ MPa} = 10^6 \text{ Pa}$) are commonly used. Three other pressure units commonly used in practice, especially in Europe, are bar, standard atmosphere, and kilogram-force per square centimeter:

$$1 \text{ bar} = 10^5 \text{ Pa} = 0.1 \text{ MPa} = 100 \text{ kPa} : 1 \text{ atm} = 101,325 \text{ Pa} = 101.325 \text{ kPa} = 1.01325 \text{ bars}$$

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

- **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.



Variation of Pressure with Depth:

- Pressure in a fluid at rest does not change in the horizontal direction. This can be shown easily by considering a thin horizontal layer of fluid and doing a force balance in any horizontal direction. However, this is not the case in the vertical direction in a gravity field.
- Pressure in a fluid increases with depth because more fluid rests on deeper layers, and the effect of this “extra weight” on a deeper layer is balanced by an increase in pressure.

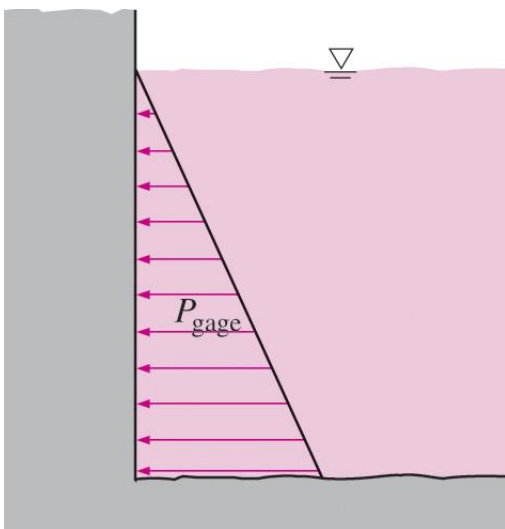
$$\Delta P = P_2 - P_1 = \rho g \Delta z = \gamma_s \Delta z$$

$$P = P_{atm} + \rho g h$$

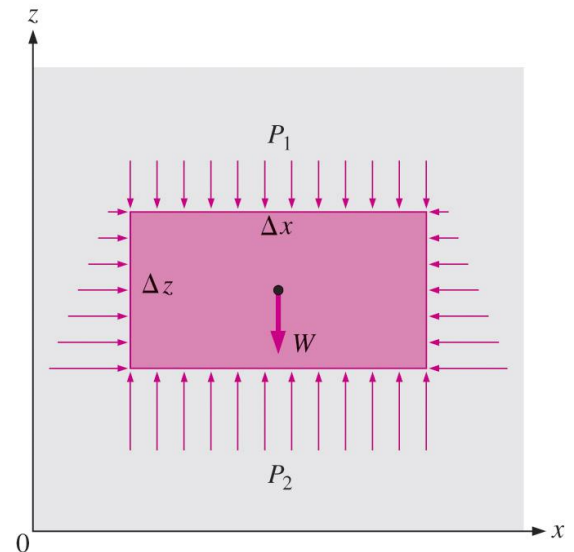
$$P_{gage} = \rho g h$$

When the variation of density with elevation is known

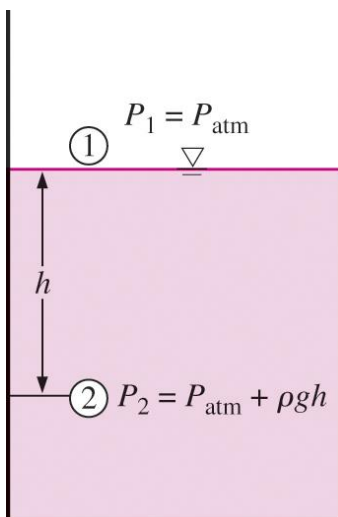
$$\Delta P = P_2 - P_1 = -\int_1^2 \rho g \Delta z$$



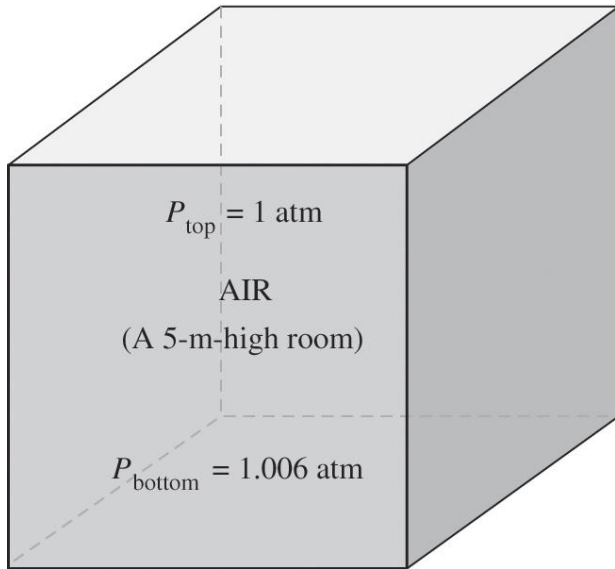
The pressure of a fluid at rest increases with depth (as a result of added weight).



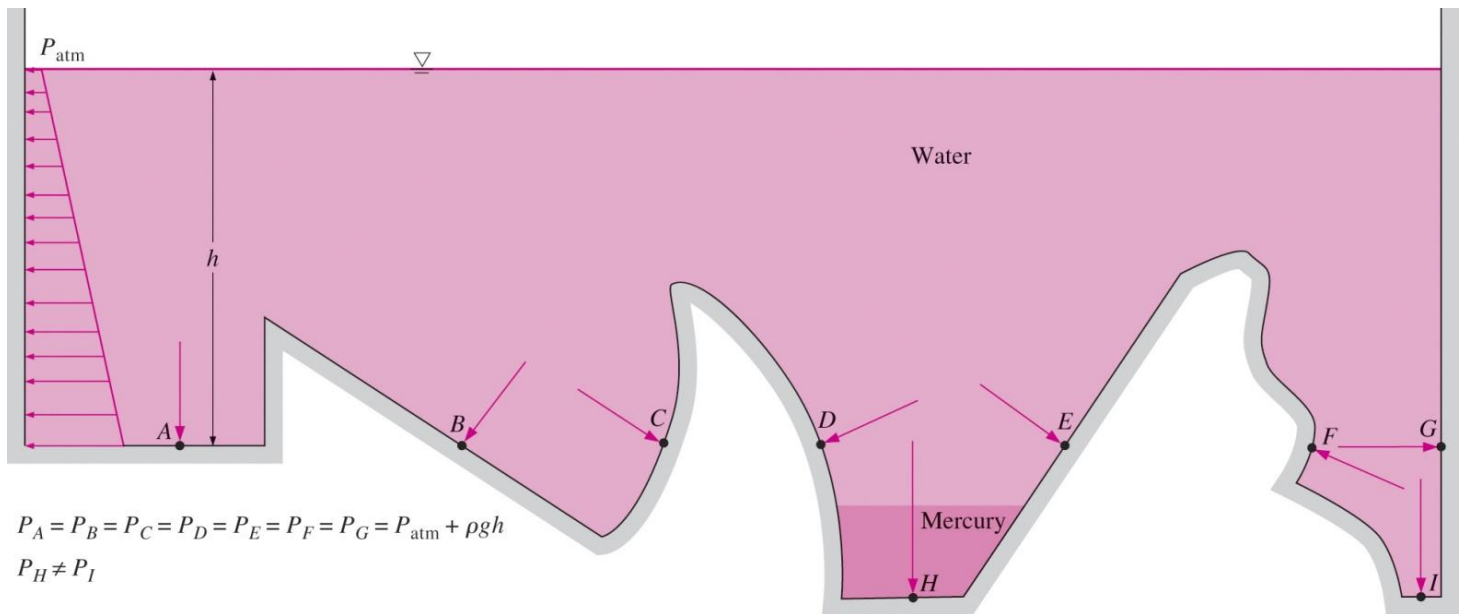
The pressure of a fluid at rest increases with depth (as a result of added weight).



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.



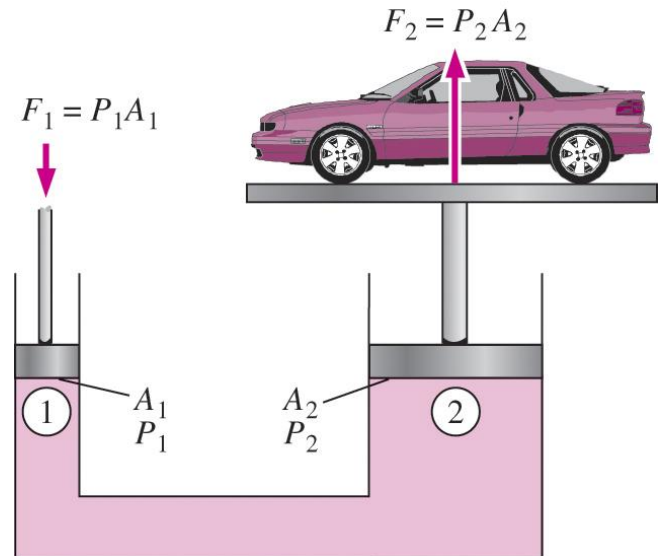
The pressure is the same at all points on a horizontal plane in a given fluid regardless of geometry, provided that the points are interconnected by the same fluid.

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

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

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.

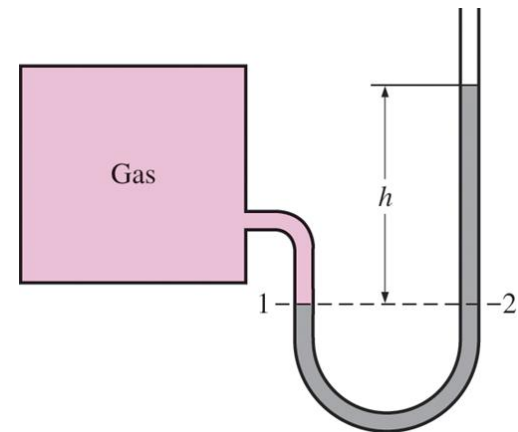


The Manometer:

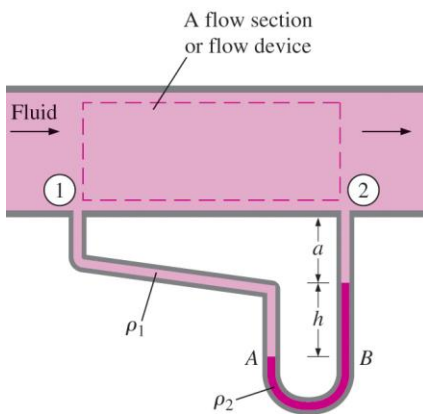
It is commonly used to measure small and moderate pressure differences. A manometer contains one or more fluids such as mercury, water, alcohol, or oil.

Consider the manometer shown in Fig. that is used to measure the pressure in the tank. Since the gravitational effects of gases are negligible, the pressure anywhere in the tank and at position 1 has the same value. Furthermore, since pressure in a fluid does not vary in the horizontal direction within a fluid, the pressure at point 2 is the same as the pressure at point 1, $P_2 = P_1$.

The differential fluid column of height h is in static equilibrium, and it is open to the atmosphere. Then the pressure at point 2 is determined directly from Eq. $P = P_{atm} + \rho gh$

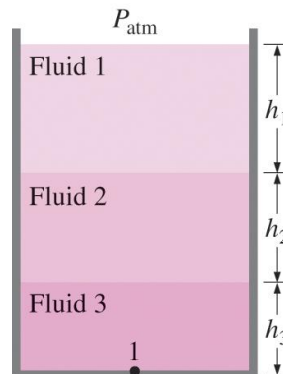


The basic manometer.



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

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



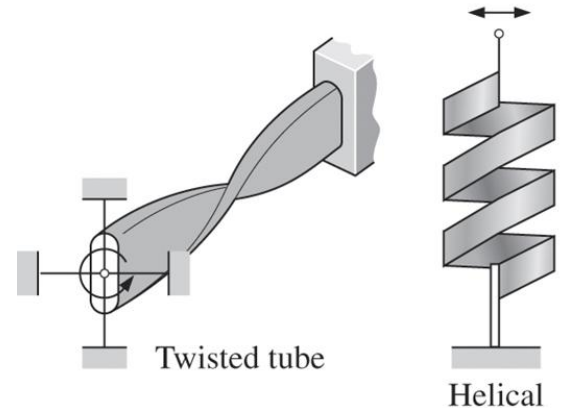
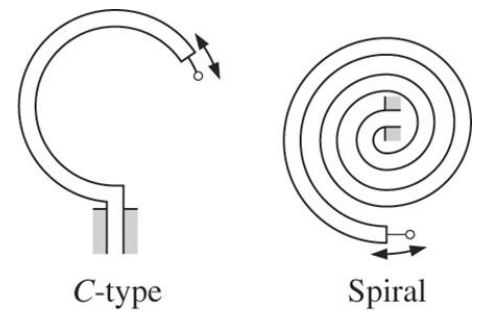
$$P_{atm} + \rho_1 gh_1 + \rho_2 gh_2 + \rho_3 gh_3 = P_1$$

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

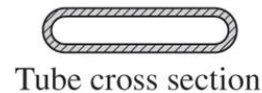
Measuring the pressure drop across a flow section or a flow device by a differential manometer.

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.

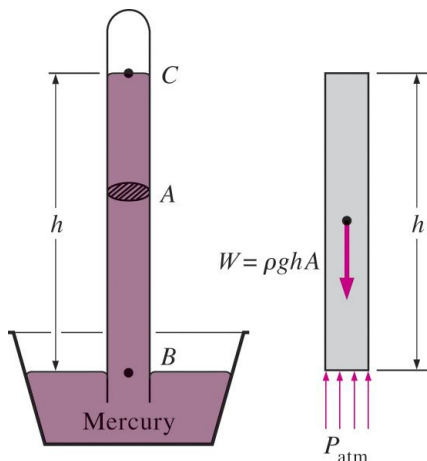


Various types of Bourdon tubes used to measure pressure.

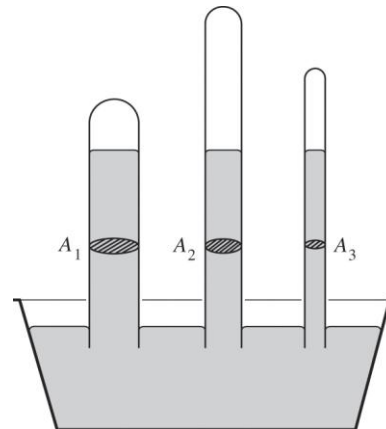


THE BAROMETER AND ATMOSPHERIC PRESSURE:

- 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 ($\rho_{\text{Hg}} = 13,595 \text{ kg/m}^3$) under standard gravitational acceleration ($g = 9.807 \text{ m/s}^2$).



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.