Introduction to FLUID MECHANICS

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.

What is a Fluid?

Fluid: A substance in the liquid or gas phase.

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.

- 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.

Stress: Force per unit area.

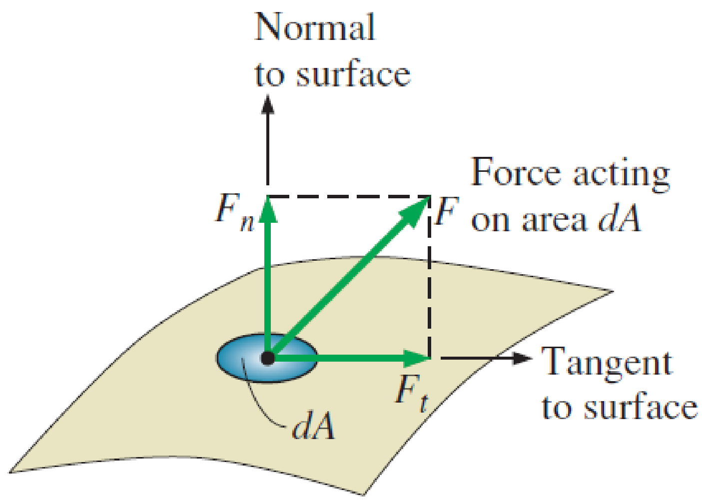
Normal stress: The normal component of a force acting on a surface per unit area.

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.



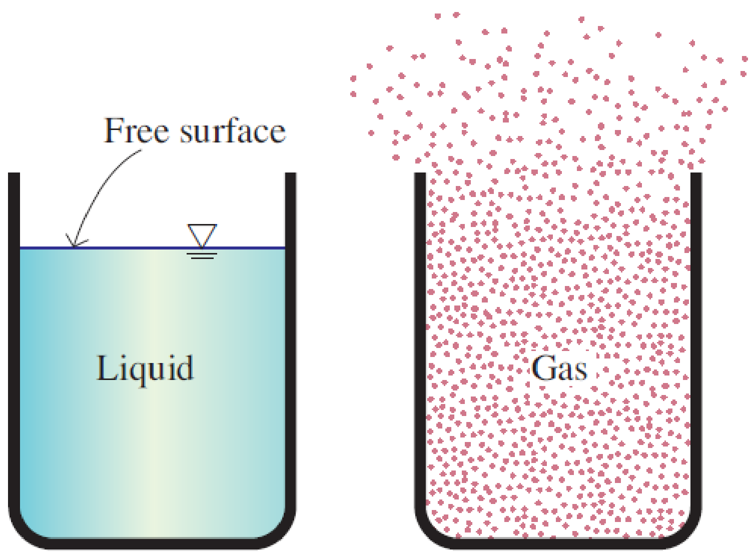
$$\text{Normal stress: } \sigma = \frac{F_n}{dA}$$

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

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.

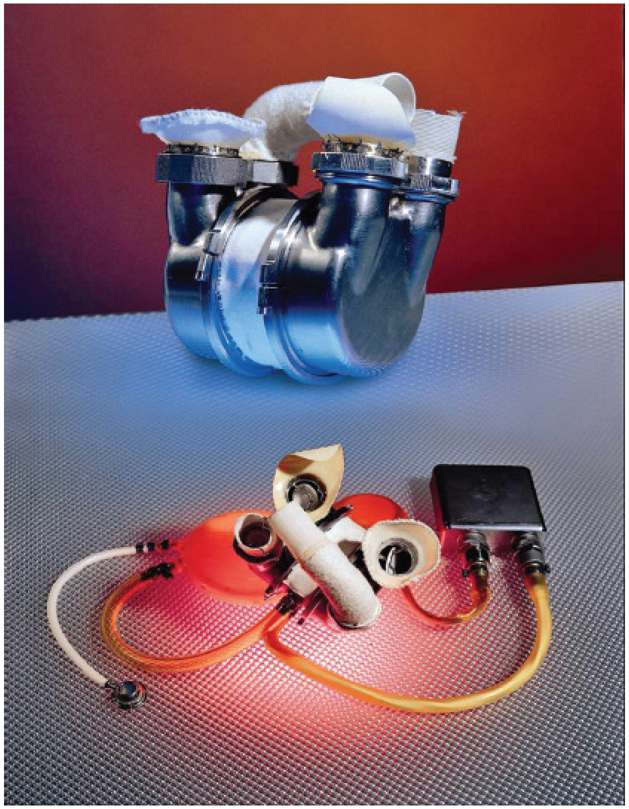
In a **liquid**, groups of molecules can move relative to each other, but the volume remains relatively constant because of the strong cohesive forces between the molecules. As a result, a liquid takes the shape of the container it is in, and it forms a free surface in a larger container in a gravitational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



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

Application Areas of Fluid Mechanics



Fluid dynamics is used extensively in the design of artificial hearts. Shown here is the Penn State Electric Total Artificial Heart.

Natural flows and weather

Power plants

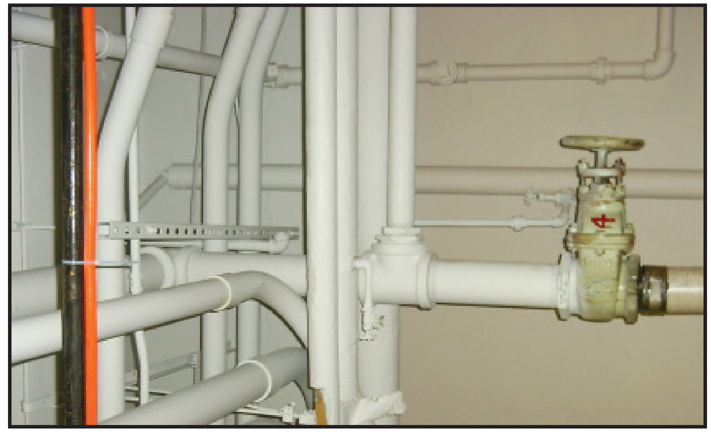
Boats

Aircraft and spacecraft

Human body

Cars

Wind turbines



Piping and plumbing systems

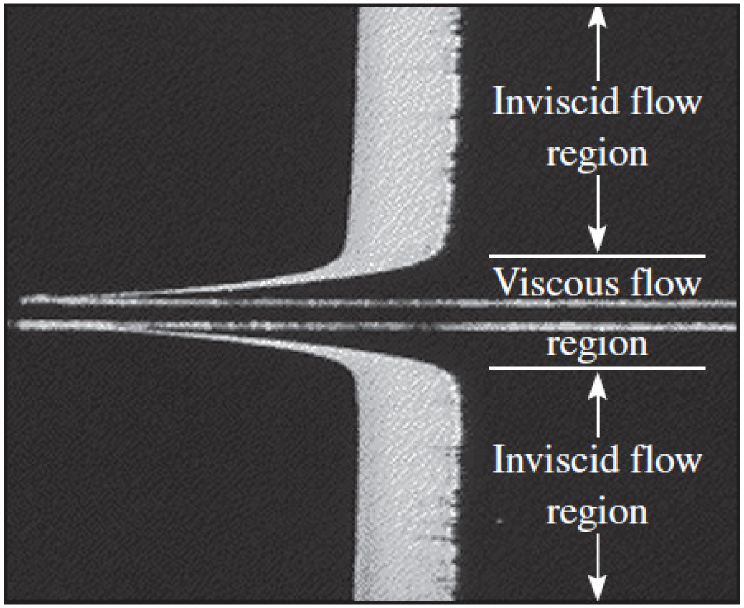
Industrial applications

CLASSIFICATION OF FLUID FLOWS

Viscous versus Inviscid Regions of Flow

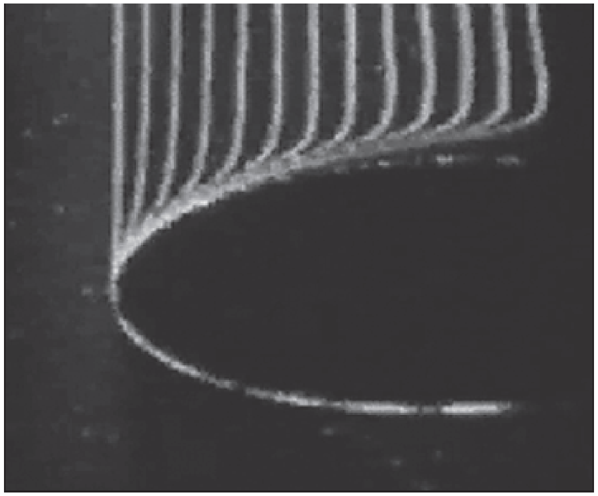
Viscous flows: Flows in which the frictional effects are significant.

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.

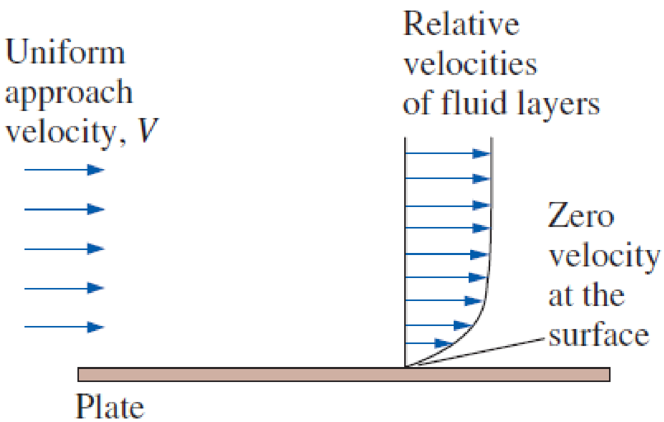


The flow of an originally uniform fluid stream over a flat plate, and the regions of viscous flow (next to the plate on both sides) and inviscid flow (away from the plate).

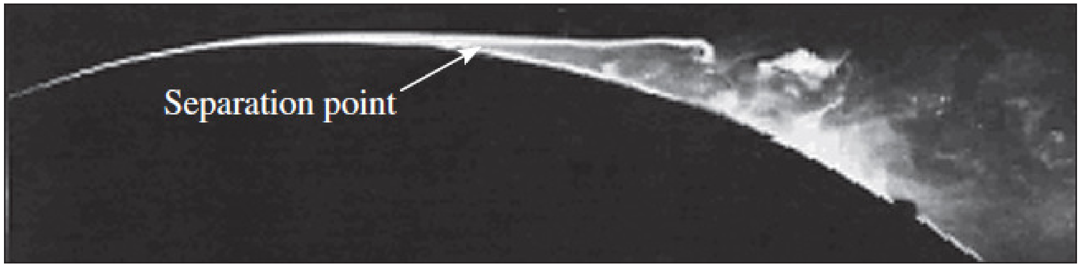
THE NO-SLIP CONDITION



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.



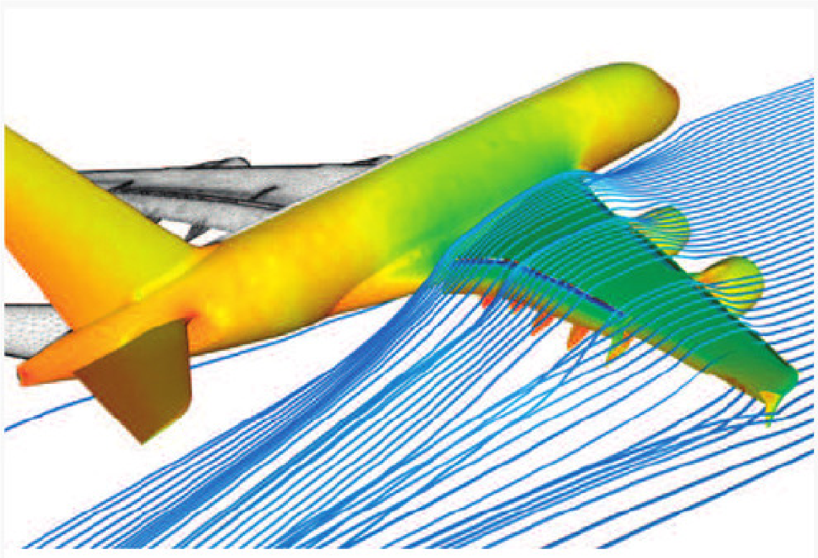
Flow separation during flow over a curved surface.

Boundary layer: The flow region adjacent to the wall in which the viscous effects (and thus the velocity gradients) are significant.

Internal versus External Flow

External flow: The flow of an unbounded fluid over a surface such as a plate, a wire, or a pipe.

Internal flow: The flow in a pipe or duct if the fluid is completely bounded by solid surfaces.



External flow over the wing, and the turbulent wake region behind.

- 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.

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)

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

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

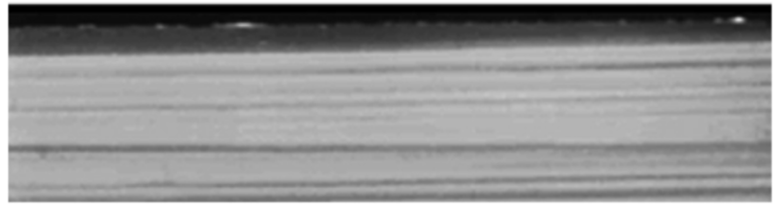
Ma = 1	**Sonic flow**
Ma < 1	**Subsonic flow**
Ma > 1	**Supersonic flow**
Ma >> 1	**Hypersonic flow**

Laminar versus Turbulent Flow

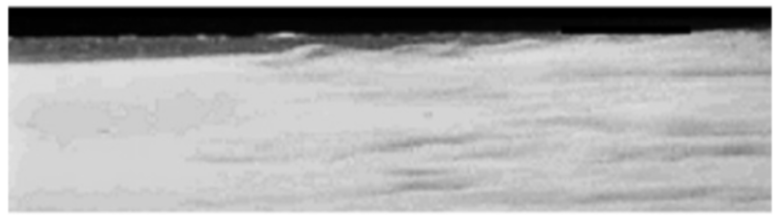
Laminar flow: The highly ordered fluid motion characterized by smooth layers of fluid. The flow of high-viscosity fluids such as oils at low velocities is typically laminar.

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.

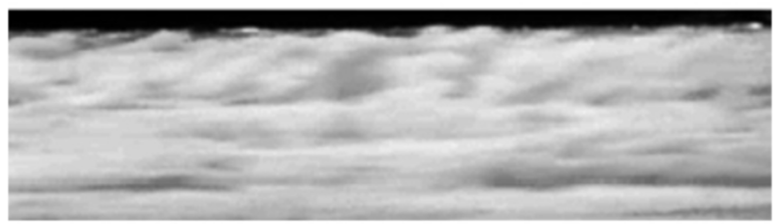
Transitional flow: A flow that alternates between being laminar and turbulent.



Laminar



Transitional



Turbulent

Laminar, transitional, and turbulent flows over a flat plate.

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.

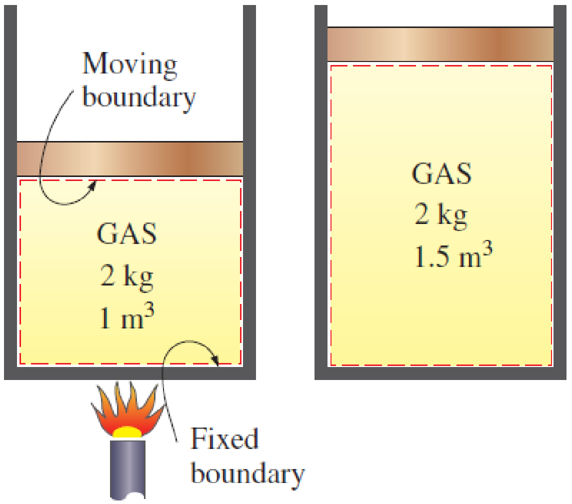
Natural flow: Fluid motion is due to natural means such as the buoyancy effect, which manifests itself as the rise of warmer (and thus lighter) fluid and the fall of cooler (and thus denser) fluid.

Steady versus Unsteady Flow

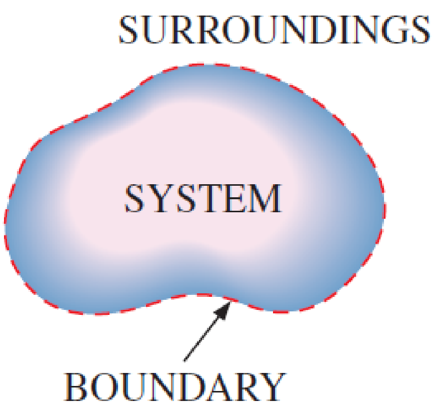
- The term **steady** implies *no change at a point with time*.
- The opposite of steady is **unsteady**.
- The term **uniform** implies *no change with location* over a specified region.
- The term **periodic** refers to the kind of unsteady flow in which the flow oscillates about a steady mean.
- Many 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-flow devices**.

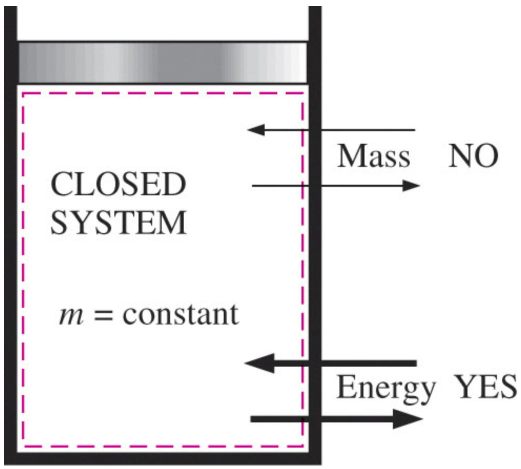
SYSTEM AND CONTROL VOLUME

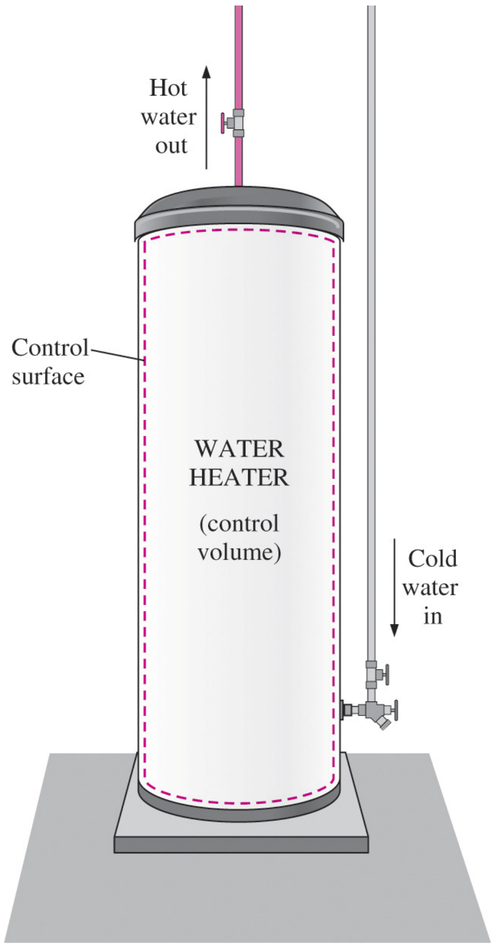
- **System**: A quantity of matter or a region in space chosen for study.
- **Surroundings**: The mass or region outside the system
- **Boundary**: The real or imaginary surface that separates the system from its surroundings.
- The boundary of a system can be *fixed* or *movable.*
- Systems may be considered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



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

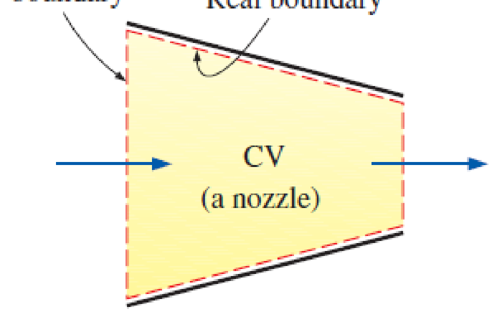




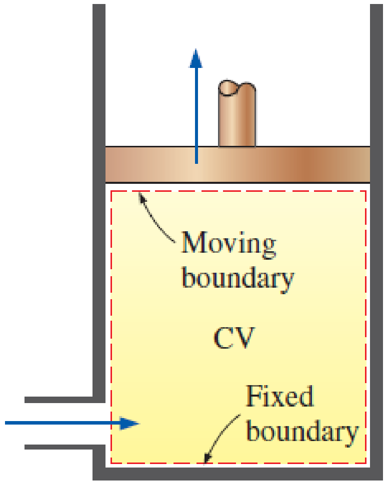


An open system (a control volume) with one inlet and one exit.

- **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 (CV) with real and imaginary boundaries



(*b*) A control volume (CV) with fixed and moving boundaries as well as real and imaginary boundaries

Unit of Pressure

- Pressure is an expression of force exerted on a surface per unit area. The SI unit of pressure is the Pascal [Pa], equivalent to one newton per meter squared $[\frac{N}{m^2}]$
- Consider an enclosed chamber filled with a gas and surrounded by a vacuum. The pressure exerted on the walls of the chamber by the gas depends on three factors: (1) the amount of gas in the chamber, (2) the temperature of the gas, and (3) the volume of the chamber.

The ideal gas equation

P∀ = mRT ... where R is the specific gas constant $[\frac{kJ}{kgK}]$

R=$\frac{\overline{R}}{M}$ $where$ $\overline{R}$: universal gas constant=8.3143$[\frac{kJ}{kmolK}]$, M: molecular mass $[\frac{\text{kg}}{\text{kMol}}]$

m: mass [kg], T: Absolute temprature [K], P: pressure[kPa]

∀: volume $[m^3]$

Real Gas

Generalized Compressibility Chart

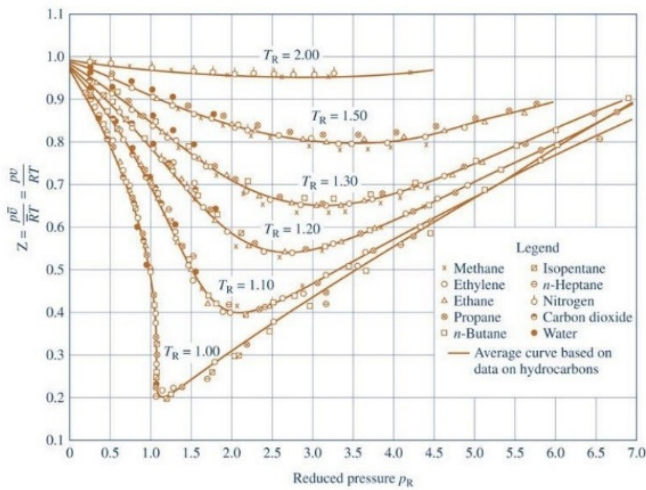
- In this chart, the compressibility factor, Z, is plotted versus the ***reduced pressure***, p_R, and ***reduced temperature*** T_R, where

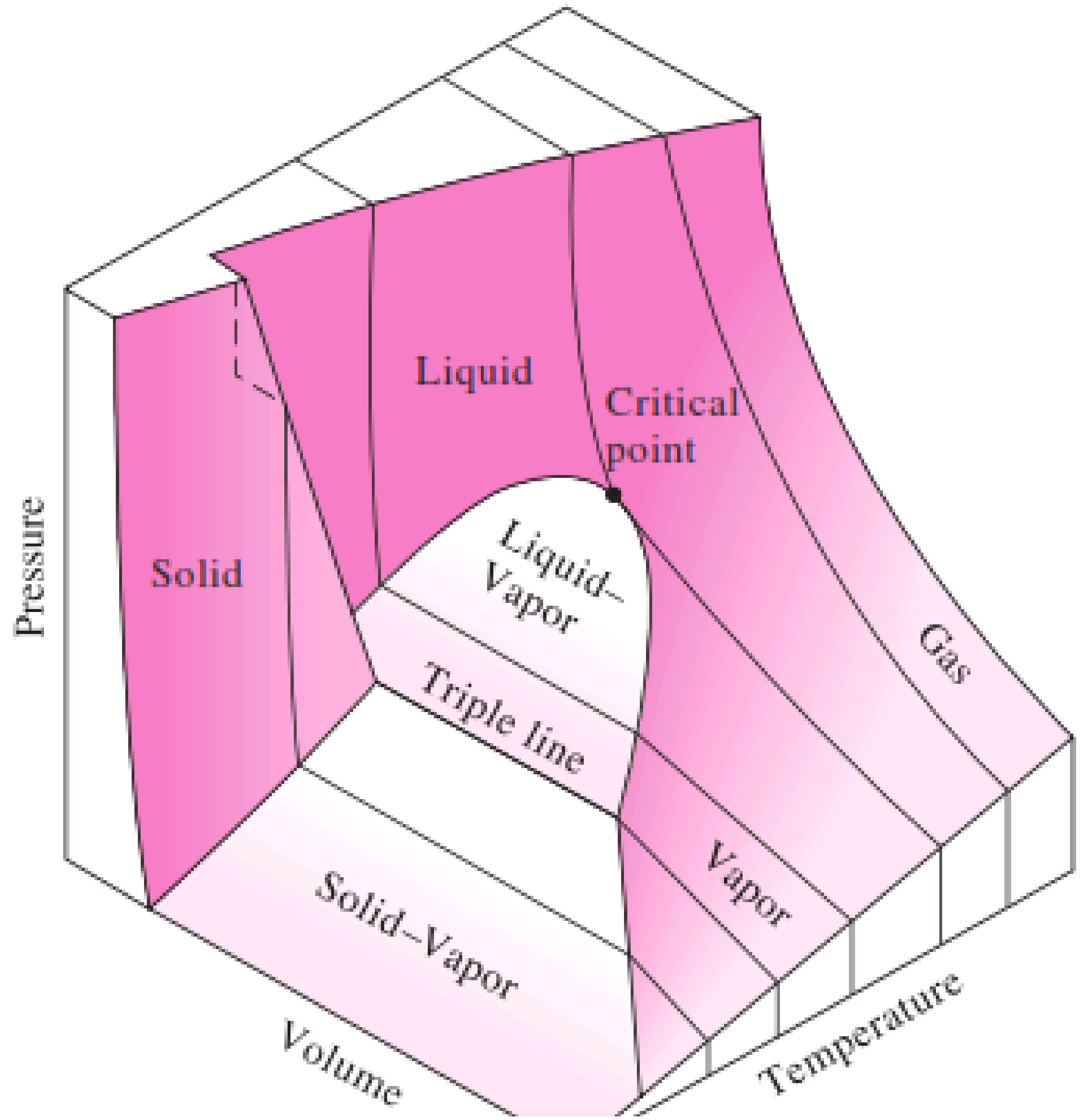
$$Z = \frac{p\bar{v}}{\bar{R}T}$$ $$p_R = p/p_c$$ $$T_R = T/T_c$$

$\bar{R}$ is the universal gas constant

$$\bar{R} = \begin{cases} 8.314 \text{ kJ/kmol·K} \\ 1.986 \text{ Btu/lbmol·°R} \\ 1545 \text{ ft·lbf/lbmol·°R} \end{cases}$$

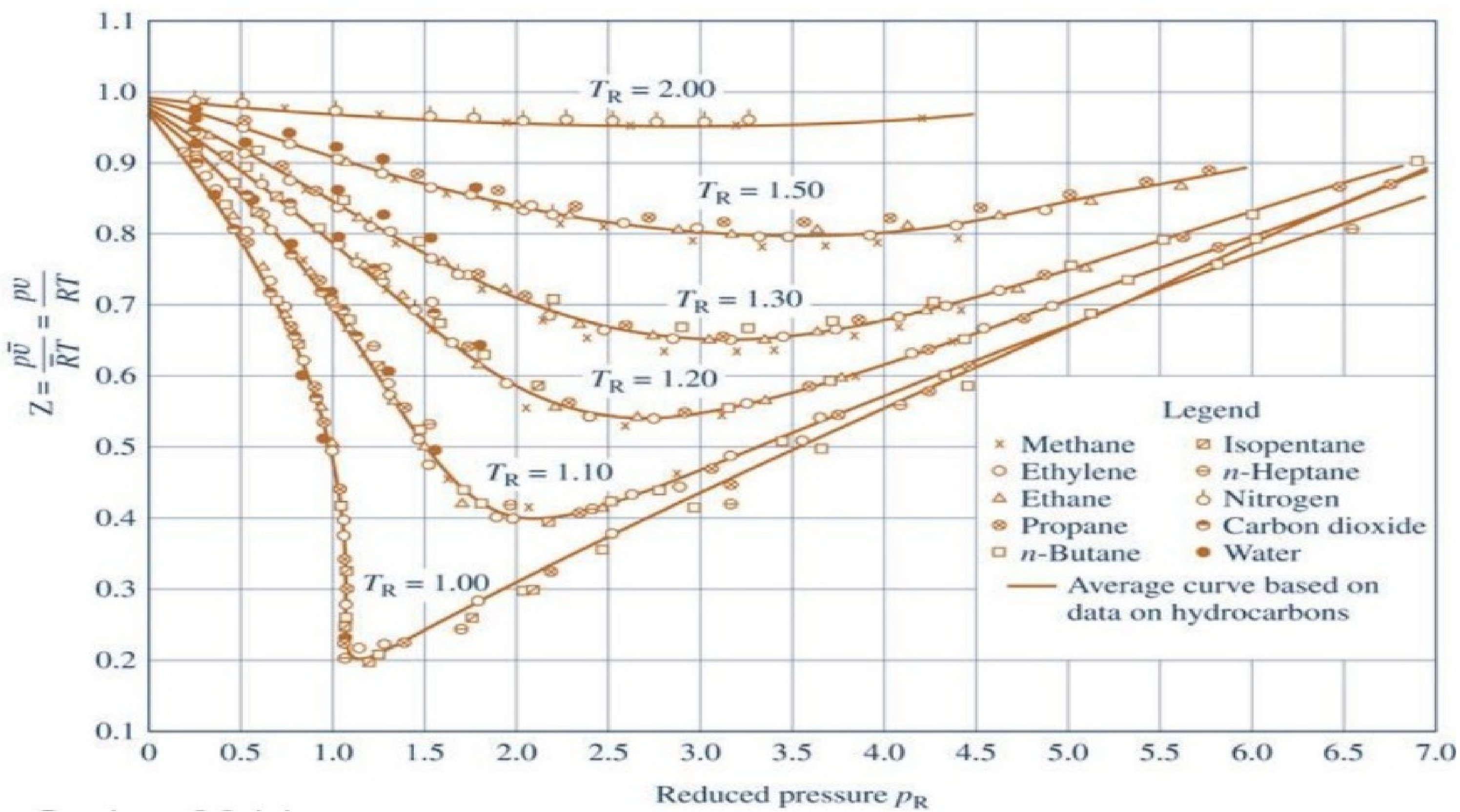
The symbols p_c and T_c denote the temperature and pressure at the critical point for the particular gas under consideration.

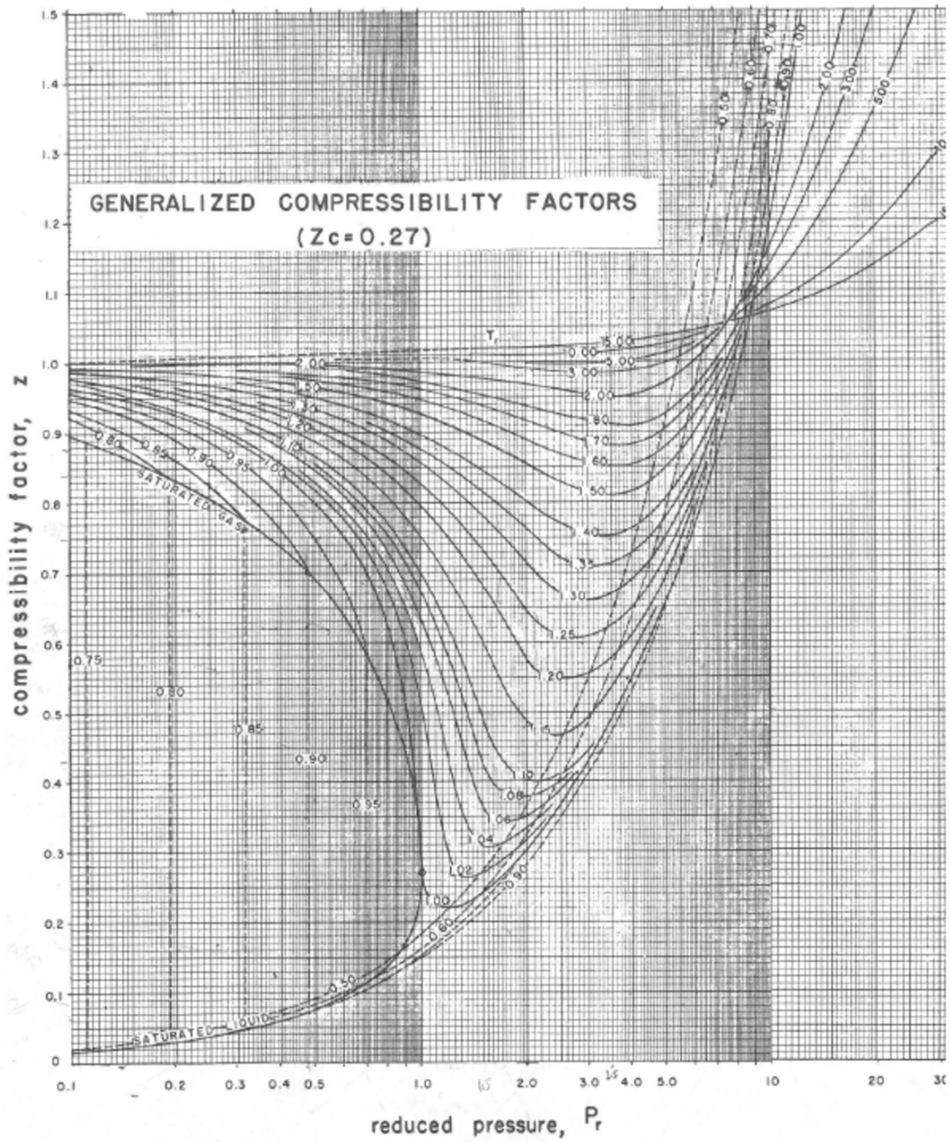



Liquid
Critical point
Solid
Liquid–Vapor
Triple line
Gas
Vapor
Solid–Vapor
Pressure
Volume
Temperature

Generalized Compressibility Chart

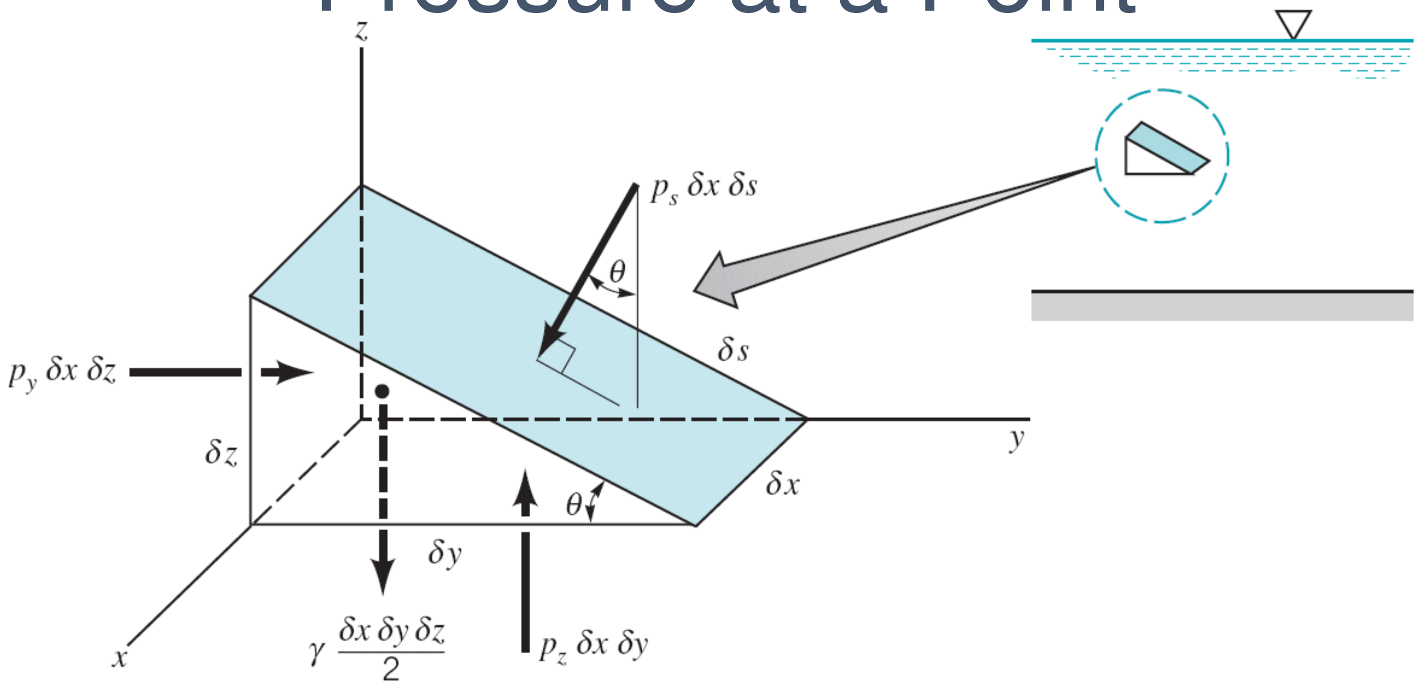
► The p-$\overline{v}$-T relation for 10 common gases is shown in the generalized compressibility chart.





Generalized compressibility chart.

Pressure at a Point



Forces on an arbitrary wedge-shaped element of fluid.

Pascal's Law

The equations of motion (Newton's second law, $\mathbf{F} = m\mathbf{a}$) in the y and z directions are, respectively,

$$\sum F_y = p_y \,\delta x\, \delta z - p_s \,\delta x\, \delta s \sin\theta = \rho \frac{\delta x\, \delta y\, \delta z}{2} a_y$$

$$\sum F_z = p_z \,\delta x\, \delta y - p_s \,\delta x\, \delta s \cos\theta - \gamma \frac{\delta x\, \delta y\, \delta z}{2} = \rho \frac{\delta x\, \delta y\, \delta z}{2} a_z$$

where p_s, p_y, and p_z are the average pressures on the faces, γ and ρ are the fluid specific weight and density, respectively, and a_y, a_z the accelerations. Note that a pressure must be multiplied by an appropriate area to obtain the force generated by the pressure. It follows from the geometry that

$$\delta y = \delta s \cos\theta \qquad \delta z = \delta s \sin\theta$$

so that the equations of motion can be rewritten as

$$p_y - p_s = \rho a_y \frac{\delta y}{2}$$

$$p_z - p_s = (\rho a_z + \gamma) \frac{\delta z}{2}$$

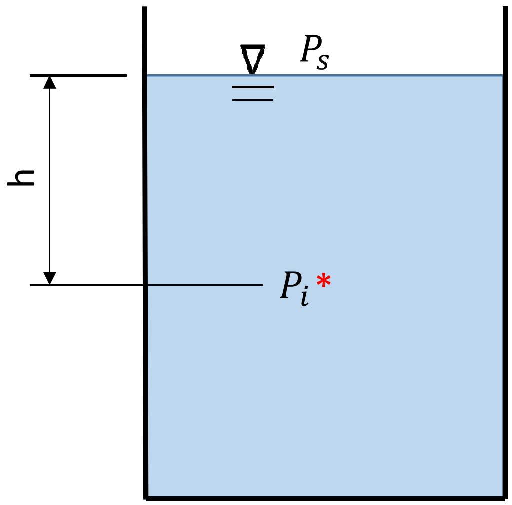
Since we are really interested in what is happening at a point, we take the limit as δx, δy, and δz approach zero (while maintaining the angle θ), and it follows that

$$p_y = p_s \qquad p_z = p_s$$

or $p_s = p_y = p_z$. The angle θ was arbitrarily chosen so we can conclude that *the pressure at a point in a fluid at rest, or in motion, is independent of direction as long as there are no shearing stresses present*. This important result is known as **Pascal's law**, named in honor of Blaise Pascal (1623–1662), a French mathematician who made important contributions in the field of hydrostatics.

$$p_y = p_z = p_z = p_s$$

Hydro-static Pressure:



$$\boldsymbol{P_i = P_s + \rho_l g h}$$

where; P_i: Pressure in liquid at point i

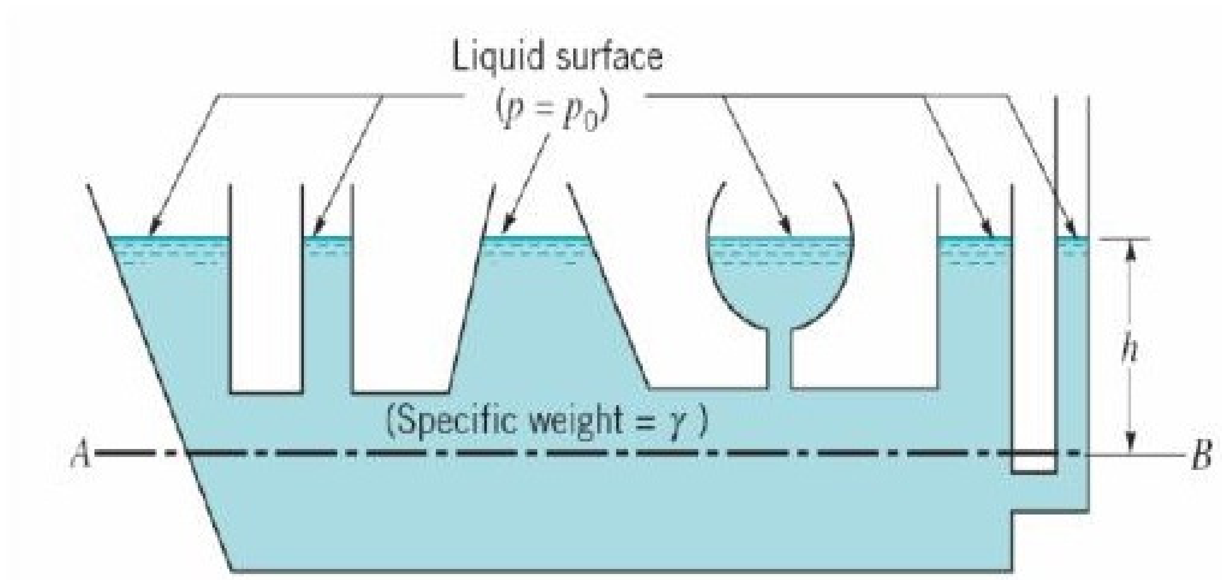
P_s: *Pressure at the free surface*

ρ_l: *Density of liquid*

g: Gravitational acceleration

h: location dimension for point i relative to the free surface in the vertical direction

Fluid Equilibrium



Pressure is the same at all points along the line AB irrespective of height

Fluid equilibrium in a container of arbitrary shape

- Unit of pressure in USCS:

$[\frac{lb_f}{ft^2}]$ more common unit: [psi] means $[\frac{lb_f}{inch^2}]$

1[psi]= 6.89476 [kPa]

- Other common units of pressure:

Bar: 1[bar]=100[kPa]

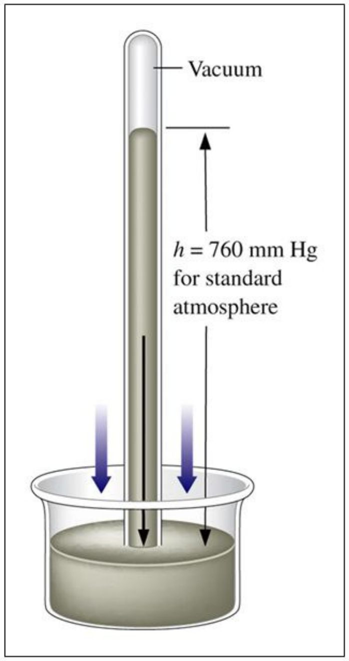
Atmosphere: 1[atm]=101.325[kPa]

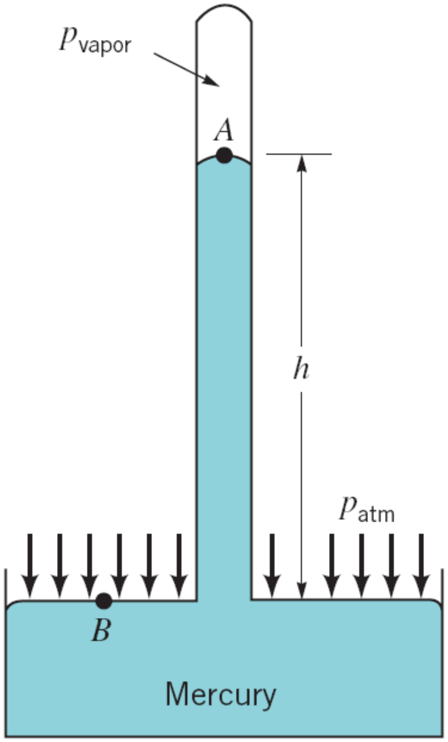
Technical Atmosphere: 1[at]≡ $\left[\frac{kg_f}{cm^2}\right]$

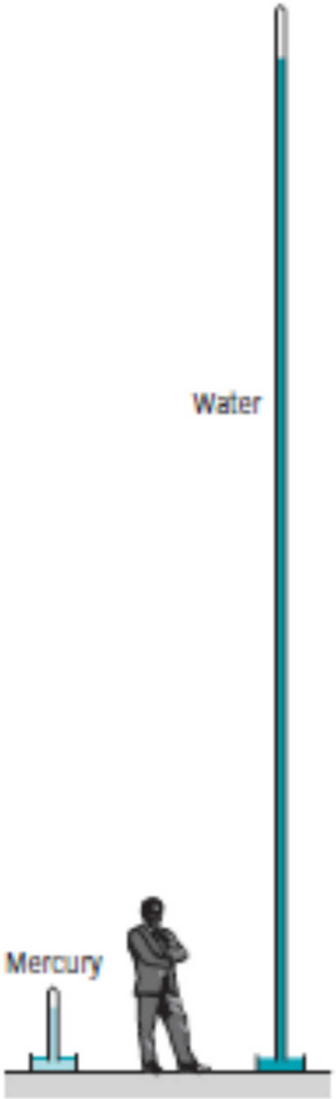
1[at]=98.067[kPa]=0.98067[bar]

One mmHg is the pressure exerted by a 1 mm vertical column of mercury (Hg) at 0 degree Celsius. One mmHg is virtually equal to 1 torr, which is defined as 1/760 of 1 atmosphere (atm) pressure (i.e., 1 atm = 760 mmHg).

Torricelli's Barometer

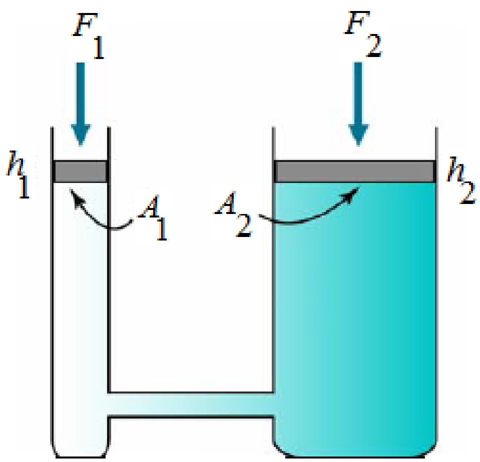






Pascal's Principle

Mechanical Advantage $\equiv \frac{F_{output}}{F_{input}}$



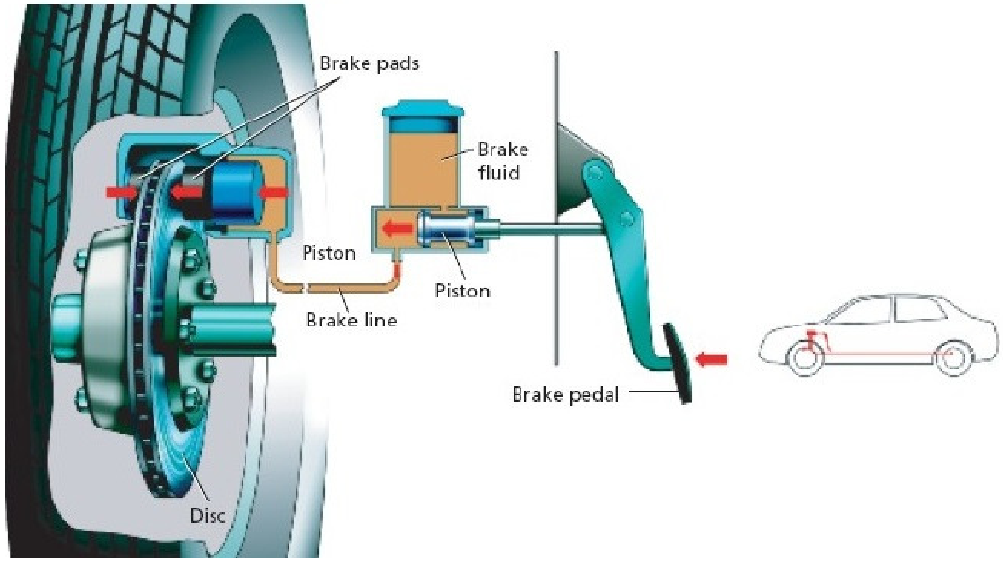
Hydraulic Press / Lift

$$\frac{F_1}{A_1} = \frac{F_2}{A_2}$$

F_1 = Force exerted on the small piston
A_1 = area of the small piston
F_2 = Force exerted on the big piston
A_2 = area of the big piston

$$MA = \frac{A_2}{A_1}$$

Car Breaks



- Absolute pressure

Absolute pressure is referred to the vacuum of free space (zero pressure)

* Gage pressure

Gage pressure is measured relative to the ambient pressure. If ambient is atmospher, changes of the atmospheric pressure due to weather conditions or altitude directly influence the output of a gage pressure sensor. A gage pressure higher than ambient pressure is referred to as positive pressure. If the measured pressure is below atmospheric pressure it is called negative or vacuum gage pressure.

*Differential pressure

Differential pressure is the difference between any two pressures p1 and p2

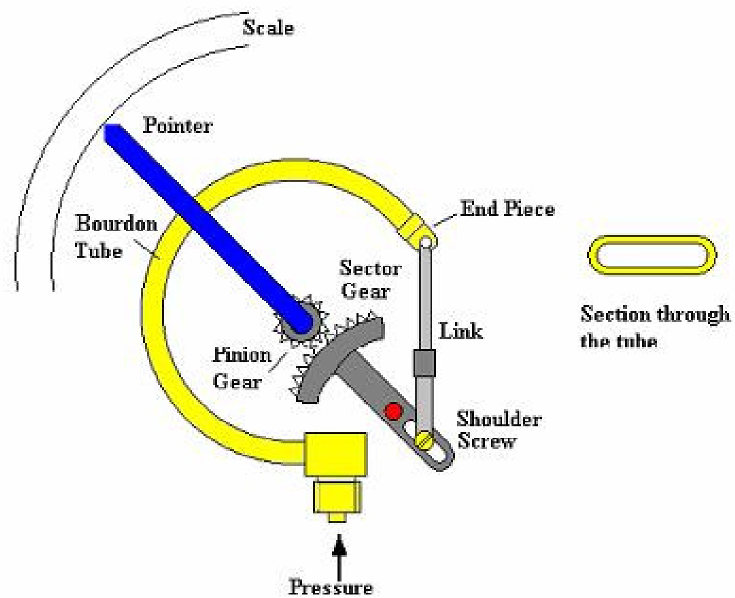
- Pressure gages measure pressure relative to the pressure of their ambient

e.g. Car tire inflation pressure=40[psi]

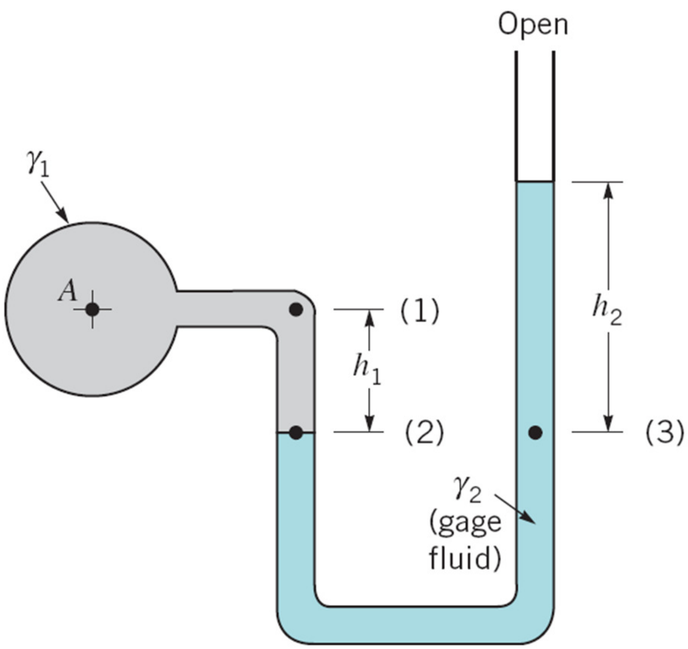
means the inside pressure- atmospheric pressure is 40[psi]

Absolute pressure of the compressed air inside of the tire=$P_{gage} + P_{atm}$

40[psi]=6.895*40=276[kPa]→ absolute pressure=276+101=377[kPa]

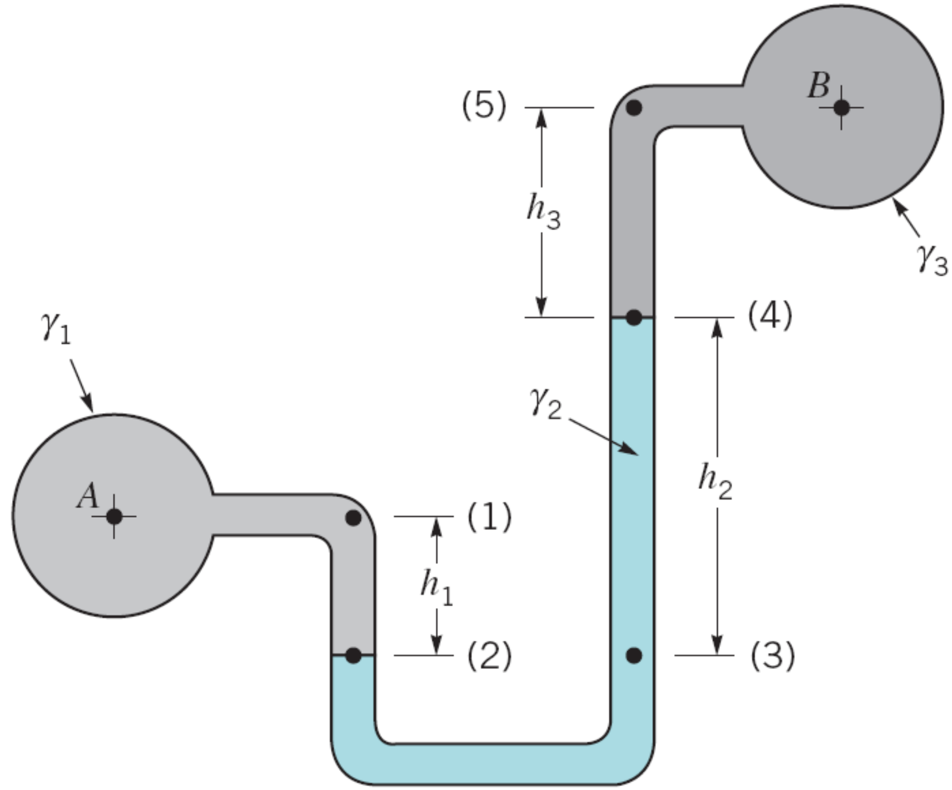


Bourdon Gage



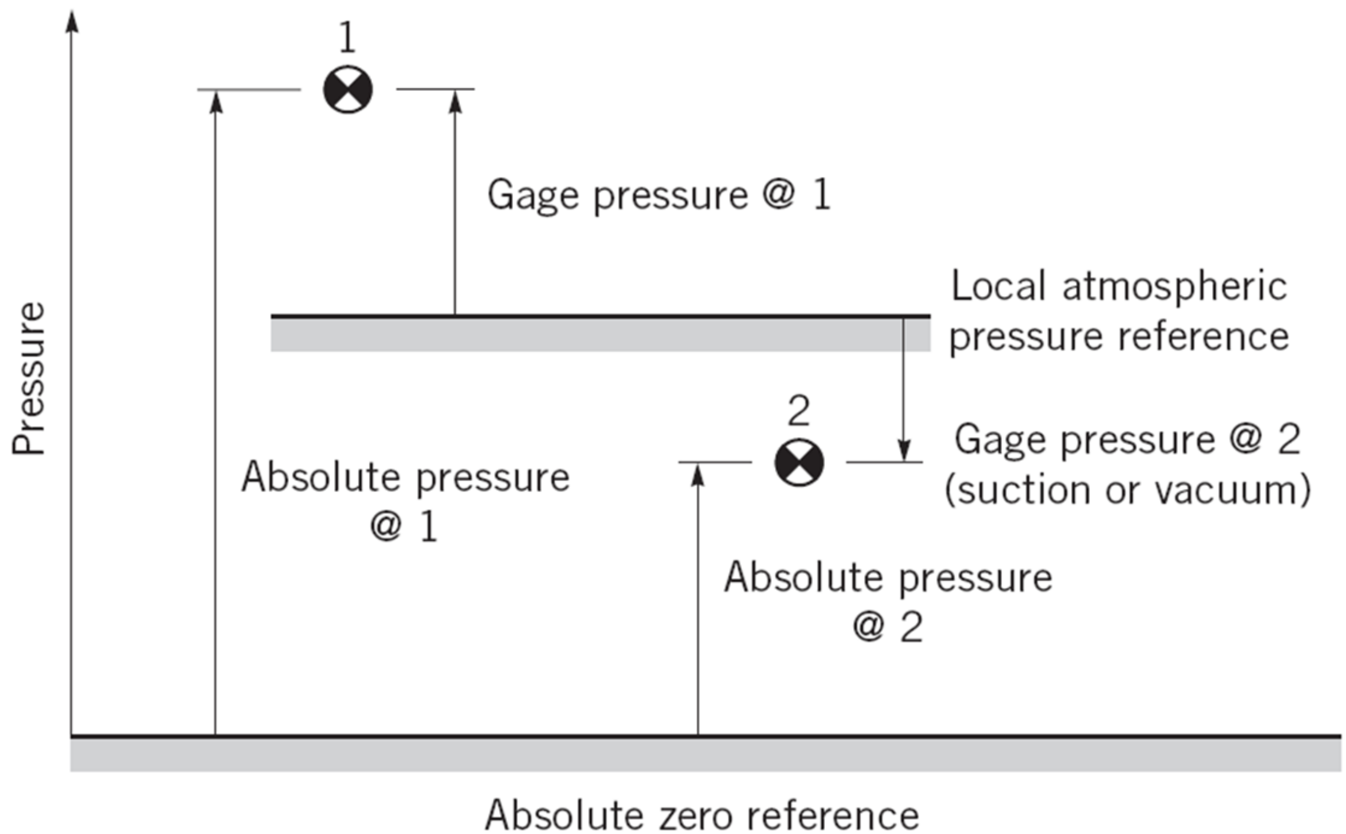
Simple U-tube manometer.

$$P_2 = P_3$$
$$P_A + \rho_1 g h_1 = P_{atm} + \rho_2 g h_2$$



Differential U-tube manometer

$$P_2 = P_3$$
$$P_A + \rho_1 g h_1 = P_B + \rho_3 g h_3 + \rho_2 g h_2$$



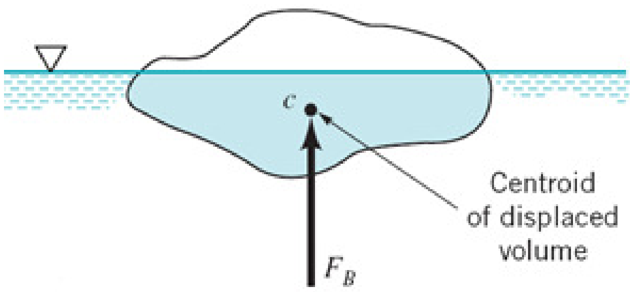
At, Atü, Atu, Ata

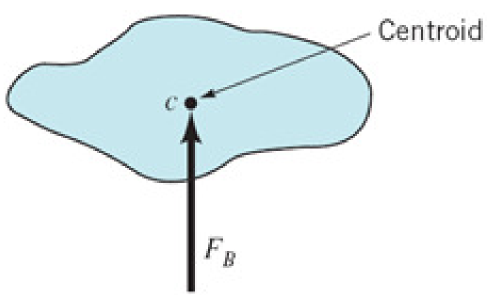
Buoyancy, Floatation

- The resultant force acting on a body that is completely submerged or floating in a fluid is called the buoyant force

Buoyancy, Floatation

Buoyant force on submerged and floating bodies.





$$F_B = \rho_f g \forall$$

Where; ρ_f: $Density\ of\ fluid$

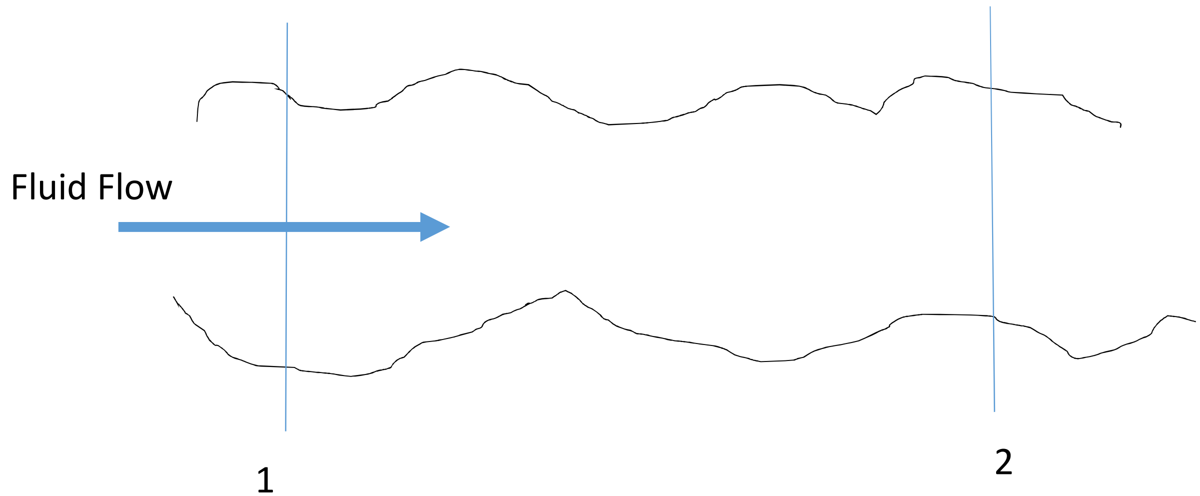
g: $Gravitational\ acceleration$

$\forall$: Volume of the submerged part of object

The buoyant force has a magnitude equal to the weight of the fluid displaced by the body and is directed vertically upward Buoyant forces passes through the centroid of the displaced volume

Elementary Fluid Dynamics – The Bernoulli Equation

- Continuity Equation: $\dot{m}_1 = \dot{m}_2$



$\dot{m}: Mass\ flow\ rate = \rho * A * V$

Where:

ρ: density of fluid

A: Cross-Sectional area

V: Flow velocity

$\dot{\forall}: Volumetric\ Flow\ rate = A * V$

$$\rho * A_1 * V_1 = \rho * A_2 * V_2$$

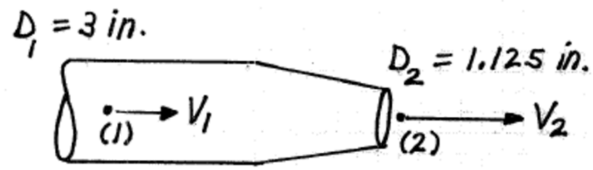
Bernoulli Equation

- For incompressible fluids, at any crossection
- $p + \frac{1}{2}\rho V^2 + \rho g z = Constant$
- Where z: altitude of the crossection

- $p_1 + \frac{1}{2}\rho_1 V_1^2 + \rho_1 g z_1 = p_2 + \frac{1}{2}\rho_2 V_2^2 + \rho_2 g z_2$

- For incompressible fluids $\rho_1 = \rho_2$

Example A fire hose nozzle has a diameter of $1\frac{1}{8}$ in. According to some fire codes, the nozzle must be capable of delivering at least 250 gal/min. If the nozzle is attached to a 3-in.-diameter hose, what pressure must be maintained just upstream of the nozzle to deliver this flowrate?



$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2$$

with $z_1 = z_2$, $p_2 = 0$

and $Q = \left(250\ \frac{gal}{min}\right)\left(231\ \frac{in^3}{gal}\right)\left(\frac{1\ ft^3}{1728\ in^3}\right)\left(\frac{1\ min}{60\ s}\right) = 0.557\ \frac{ft^3}{s}$

Thus,

$$p_1 = \frac{\gamma}{2g}\left[V_2^2 - V_1^2\right] \quad \text{where} \quad V_2 = \frac{Q}{A_2} = \frac{0.557\ \frac{ft^3}{s}}{\frac{\pi}{4}\left(\frac{1.125}{12}\right)^2 ft^2} = 80.7\ \frac{ft}{s}$$

and

$$V_1 = \frac{Q}{A_1} = \frac{0.557\ \frac{ft^3}{s}}{\frac{\pi}{4}\left(\frac{3}{12}\right)^2 ft^2} = 11.34\ \frac{ft}{s}$$

so that with $\frac{\gamma}{g} = \rho$

$$p_1 = \frac{1}{2}\left(1.94\ \frac{slugs}{ft^3}\right)\left[80.7^2 - 11.34^2\right]\frac{ft^2}{s^2}$$

$$= 6190\ \frac{lb}{ft^2} = \underline{\underline{43.0\ psi}}$$

Example A person thrusts his hand into the water while traveling 3 m/s in a motor boat. What is the maximum pressure on his hand?

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 \quad \text{with } z_1 = z_2$$

$$V_1 = 3\ \frac{m}{s}$$

$$p_1 = 0\ ,\ V_2 = 0$$

Thus,

$$p_2 = \frac{\gamma}{2g} V_1^2 = \frac{1}{2}\rho V_1^2 \quad \text{or} \quad p_2 = \frac{1}{2}\left(999\ \frac{kg}{m^3}\right)\left(3\ \frac{m}{s}\right)^2 = 4\,500\ \frac{N}{m^2} = \underline{\underline{4.50\ kPa}}$$