CHEM 0915341

Summer Semester 21/22

CHAPTER 1

FUNDAMENTALS OF TRANSPORT PROCESSES

INTRODUCTION

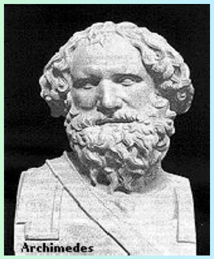
- It is always useful to examine
  - ✓ WHY we are learning this course
  - ✓ WHAT we are going to learn and
  - ✓ HOW
- So, these are the three questions that one should have a clear understanding before we even go on to a new course .

IMPORTANCE of FLUIDS

- 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
- Fluids affect every part of our lives

History

Faces of Fluid Mechanics

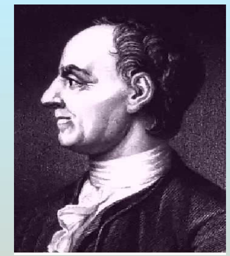


Archimedes
(C. 287-212 BC)

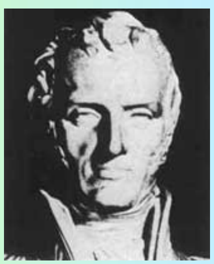
Newton
(1642-1727)

Leibniz
(1646-1716)

Bernoulli
(1667-1748)

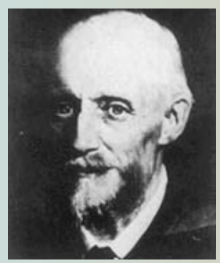


Euler
(1707-1783)

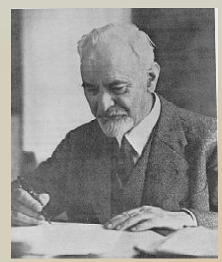


Navier
(1785-1836)

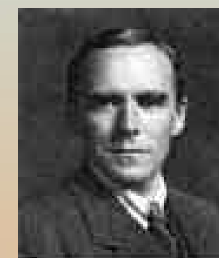
Stokes
(1819-1903)



Reynolds
(1842-1912)



Prandtl
(1875-1953)



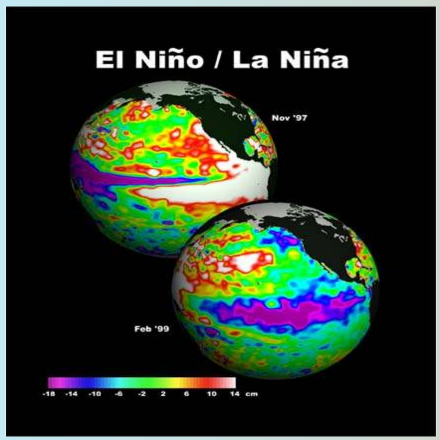
Taylor
(1886-1975)

Weather & Climate

Tornadoes

Thunderstorm

Global Climate



Hurricanes

Vehicles

Aircraft

Surface ships

High-speed rail

Submarines

Environment

Air pollution

River hydraulics

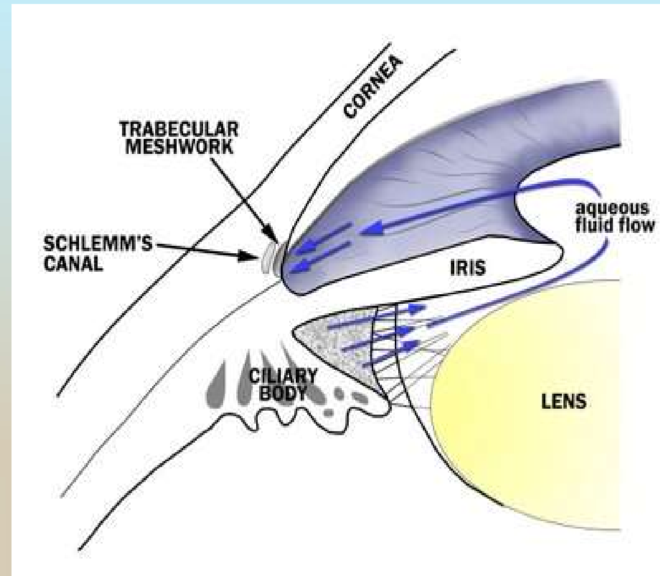
Physiology and Medicine

Blood pump

A BVS blood pump

Ventricular assist device

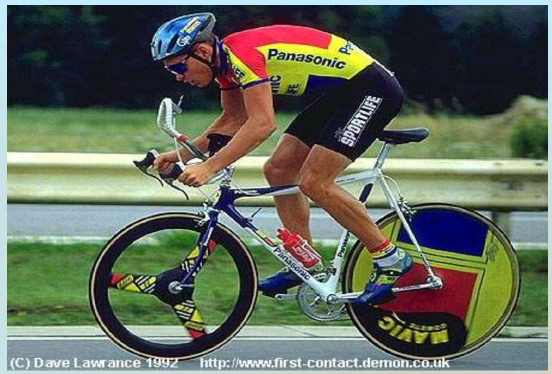
Fluid channels in eye



Sports & Recreation

Water sports

Cycling

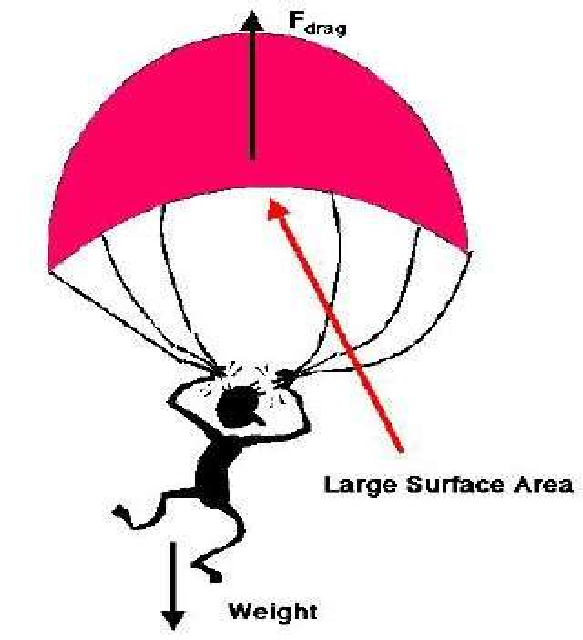


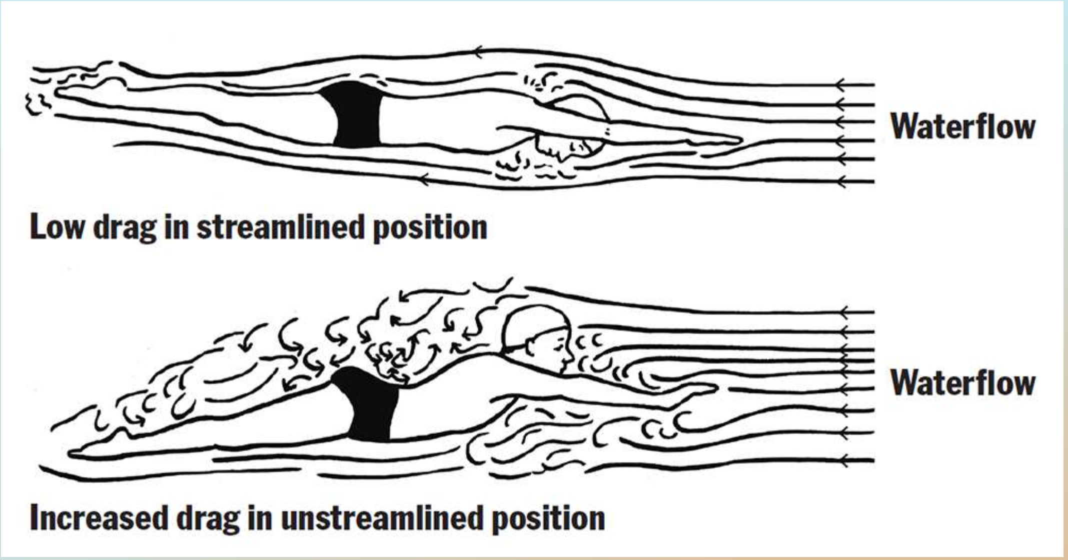
Offshore racing

Auto racing

Surfing

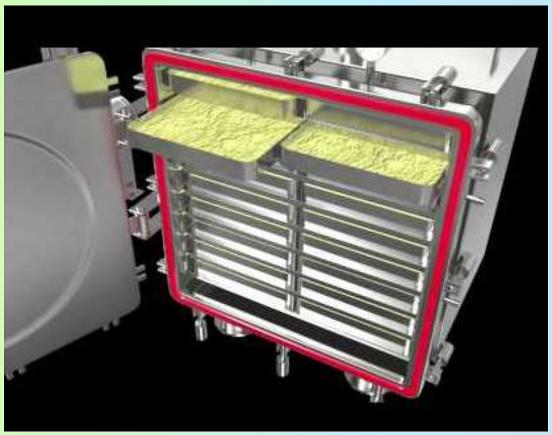
SPORTS


F_{drag}
Large Surface Area
Weight

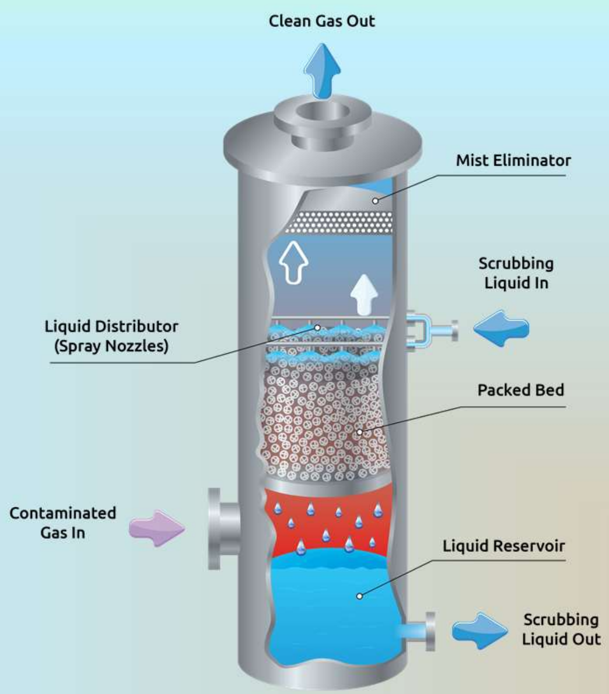

Waterflow
Low drag in streamlined position
Waterflow
Increased drag in unstreamlined position

LAB SCALE PIPE LINE SYSTEM

UNIT OPERATIONS



TRAY DRIER



PACKED BED

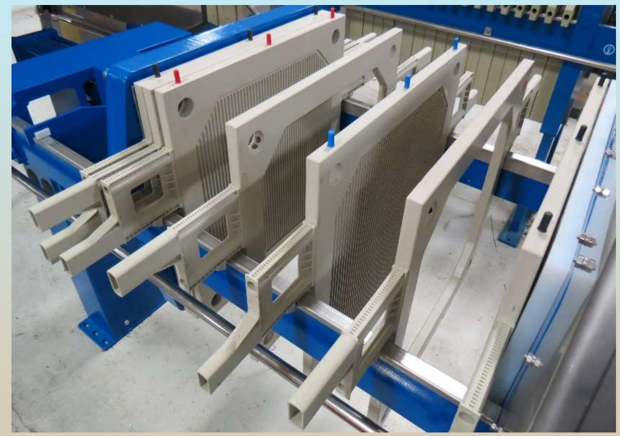
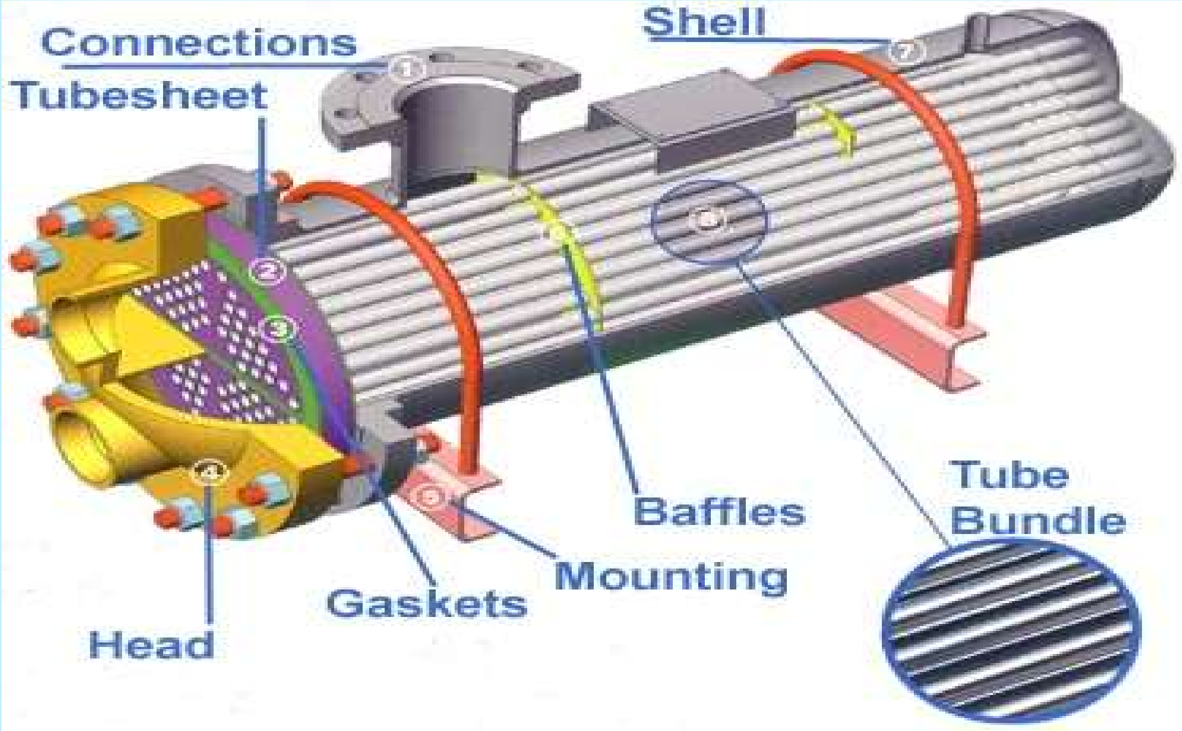
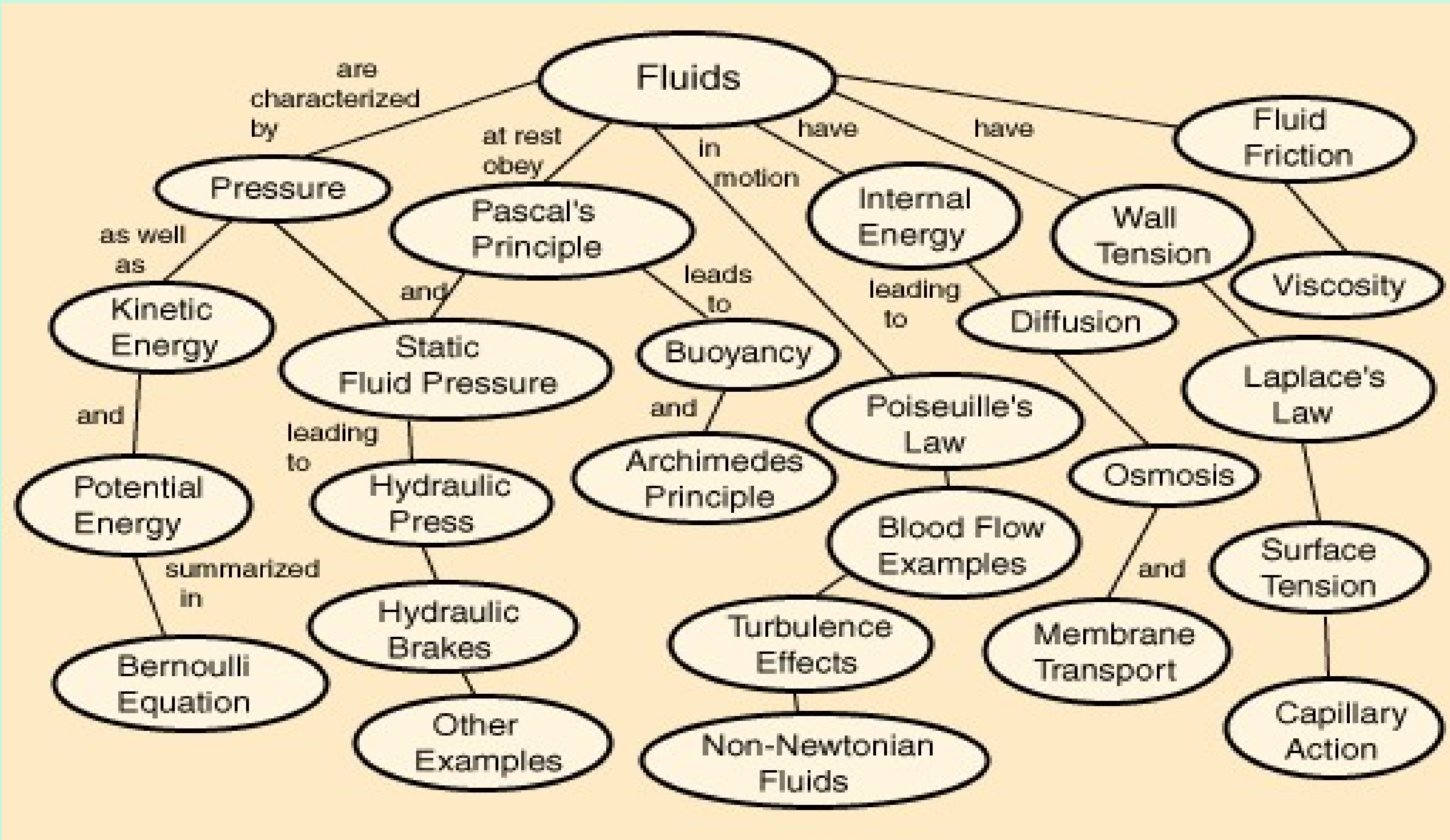


PLATE FILTER

Shell and Tube Heat Exchanger



All these are related with fluid mechanics and statics



EXAMPLE OF A PRODUCTION LINE

The main unit operations usually present in a typical food-processing line:

1. Flow of fluid: when a fluid is moved from one point to another by pumping, gravity, etc.
2. Heat transfer: in which heat is either removed or added (heating; cooling; refrigeration and freezing).
3. Mass transfer: whether or not this requires a change in state. Processes that use mass transfer include drying, distillation, evaporation, crystallization, and membrane processes.
4. Other operations requiring energy: such as *mechanical separation* (filtration, centrifugation, sedimentation, and sieving); *size adjustment by size reductions* (slicing, dicing, cutting, grinding) *or size increase* (aggregation, agglomeration, gelation); and *mixing*, which may include solubilizing solids, preparing emulsions or foams, and dry blending of dry powders (flour, sugar, etc.).

Food Factory Processing Line

DIMENSIONALLY HOMOGENEOUS EQUATIONS

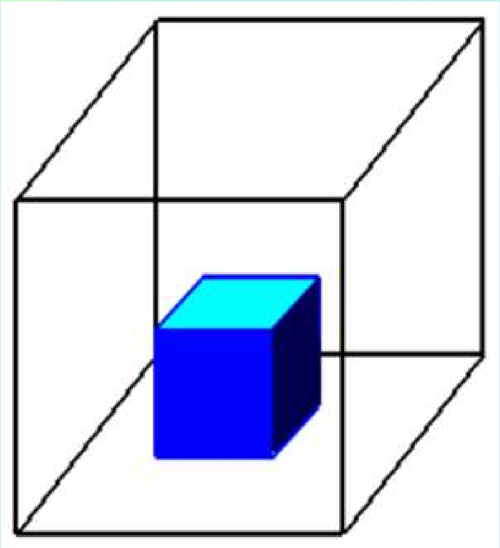
- All theoretical equations in mechanics (and in other physical sciences) are dimensionally homogeneous; i.e., each additive term in the equation has the same dimensions.
- Example is the equation from physics for a body falling with negligible air resistance:

$$S = S_0 + V_0 t + \tfrac{1}{2} g t^2$$

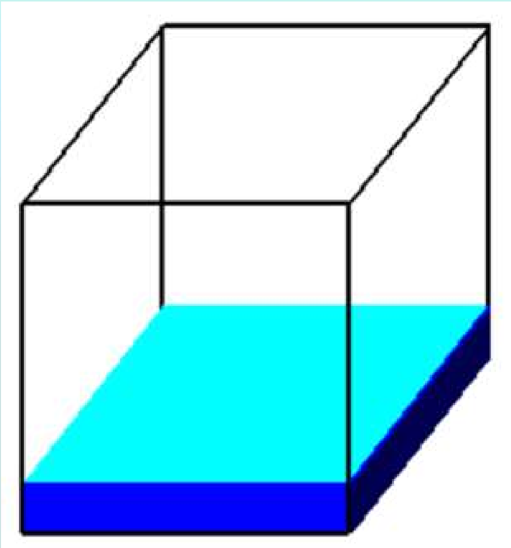
where S_0 is initial position, V_0 is initial velocity, and g is the acceleration of gravity.

- Each term in this relation has dimensions of length {L}.
- However, many empirical formulas in the engineering literature, arising primarily from correlations of data, are dimensionally inconsistent. Referred as dimensional equations.
- Defined units for each term must be used with it.

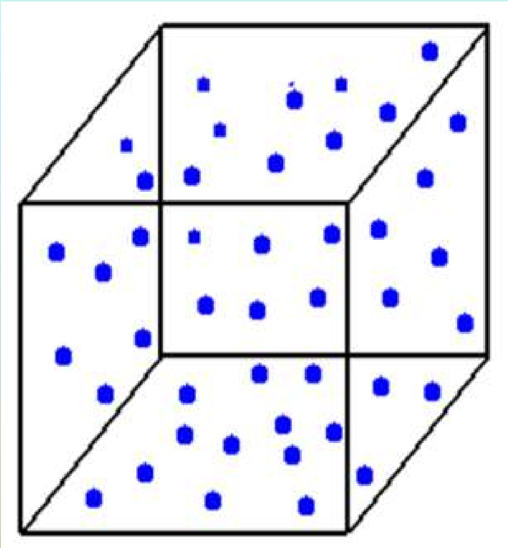
THREE STATES OF MASS



Solid
Holds Shape
Fixed Volume



Liquid
Shape of Container
Free Surface
Fixed Volume



Gas
Shape of Container
Volume of Container

FLUID MODELING

- A fluid can be modeled in one of two ways:
  - ✓ As a collection of individual, interacting molecules (Molecular Model) or
  - ✓ As a continuum in which properties are defined to be continuous throughout space (Continuum Model)
- Macroscale fluid mechanics is based on continuum model. But if the molecules are sparsely distributed relative to the length scale of the flow, assuming continuity of fluid and flow properties may lead to wrong results

Statics vs Dynamics

Statics

Dynamics

FLIUD SCIENCE BRANCHES

- **Continium mechanics**:
  - ✓ Branch of engineering science that studies behavior of solids and fluids
- **Fluid mechanics**:
  - ✓ Branch of engineering science that studies behavior of fluids
- **Fluid statics**:
  - ✓ Deals with fluids in the equilibrium state of no shear stress (study of fluids *at rest)*
- **Fluid dynamics**:
  - ✓ Deals with the fluids when portions of the fluid are in motion relative to other parts. (study of fluids in motion)

FLUID PROPERTIES

- A fluid is a substance that flows under the action of shearing forces or it is a substance that deforms continuously under the application of shear stress, no matter how small that stress may be.
- Fluids are gases and liquids. If a fluid is at rest, we know that the forces on it are in balance.
- A solid can resist a shear stress, a fluid cannot.
- The two most important parameters characterizing a fluid are density and viscosity.
- Density (ρ) is the mass per unit volume [kg/m^3]
- Dynamic Viscosity (η) is a property of fluid flow that indicates the resistance of flow. In other words, viscosity is the fluid property that causes shear stress when the fluid is moving; without viscosity in a fluid, there would be no fluid resistance.

DENSITY

- The density of a fluid is defined as its mass per unit volume.
- It is denoted by the Greek symbol, ρ.

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

Kg.m^{-3} — ρ; kg — m; m^3 — V

$$\rho_{water} = 998 \text{ kg.m}^{-3}$$

$$\rho_{air} = 1.2 \text{ kg.m}^{-3}$$

- If the density is constant (most liquids), the fluid is incompressible.
- If the density varies significantly (e.g. some gases), the fluid is compressible.
- (Although gases are easy to compress, the flow may be treated as incompressible if there are no large pressure fluctuations)

PRESSURE

- Pressure is the force per unit area, where the force is perpendicular to the area.

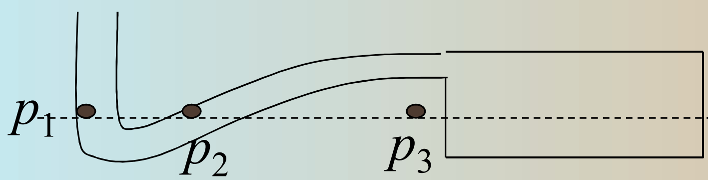
$$P = \frac{F}{A}$$

P: $N.m^{-2}$ (Pa); F: N; A: m^2

- Pressure in a fluid acts equally in all directions
- Pressure in a static liquid increases linearly with depth

$$\Delta p = \rho g \, \Delta h$$

- The pressure at a given depth in a continuous, static body of liquid is constant.



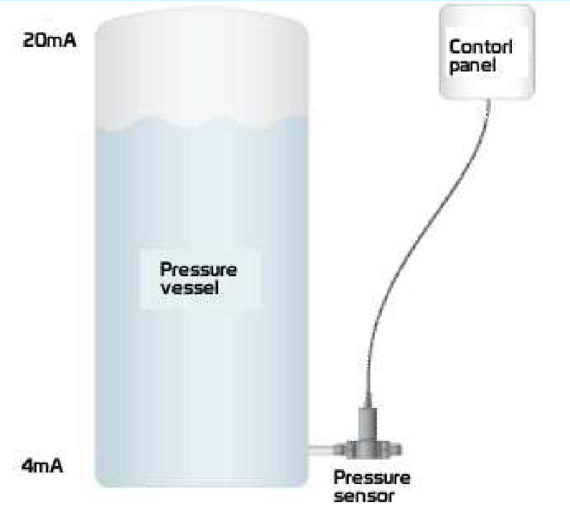
$$p_1 = p_2 = p_3$$

PRESSURE FIELD

- Pressure is a scalar field:

$$p = p(x; y; z; t)$$

- The value of p varies in space, but p is not associated with a direction.
- The pressure at any point in a stationary fluid is independent of direction.
- A pressure sensor will not detect different values of pressure when the orientation of the sensor is changed at a fixed measurement point.



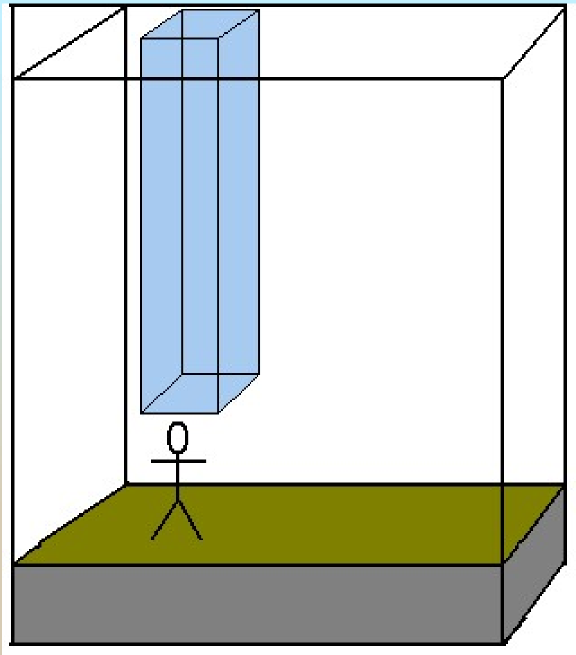
Differential pressure transmitter measuring vented tank

ATMOSPHERIC PRESSURE

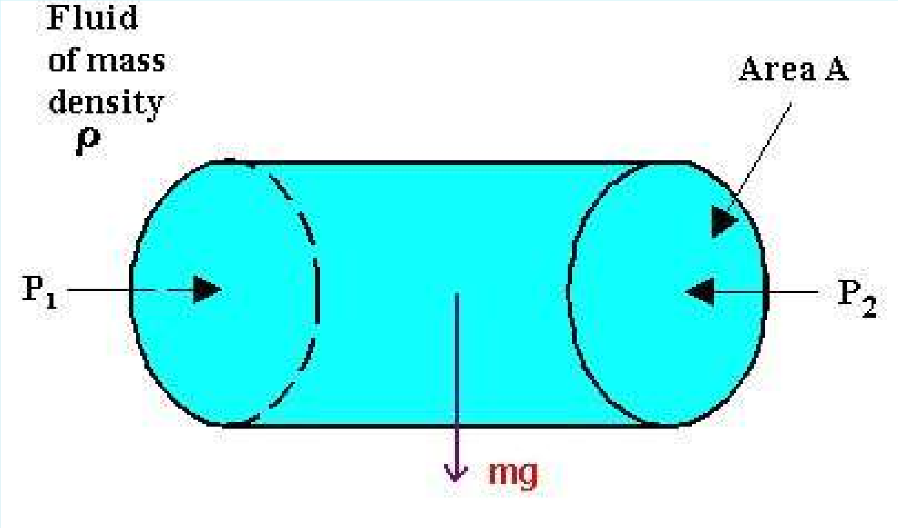
- Pressure = Force per Unit Area
- Atmospheric Pressure is the weight of the column of air above a unit area.
- For example, the atmospheric pressure felt by a man is the weight of the column of air above his body divided by the area the air is resting on:
- P = (Weight of column)/(Area of base)
- Standard Atmospheric Pressure:

  1 Atmosphere (atm) = 14.7 lbs/in^2 (psi) = 760 Torr (mm Hg) = 1013.25 millibars = 101.3 kPa

  1 Pa = 1 N/m^2



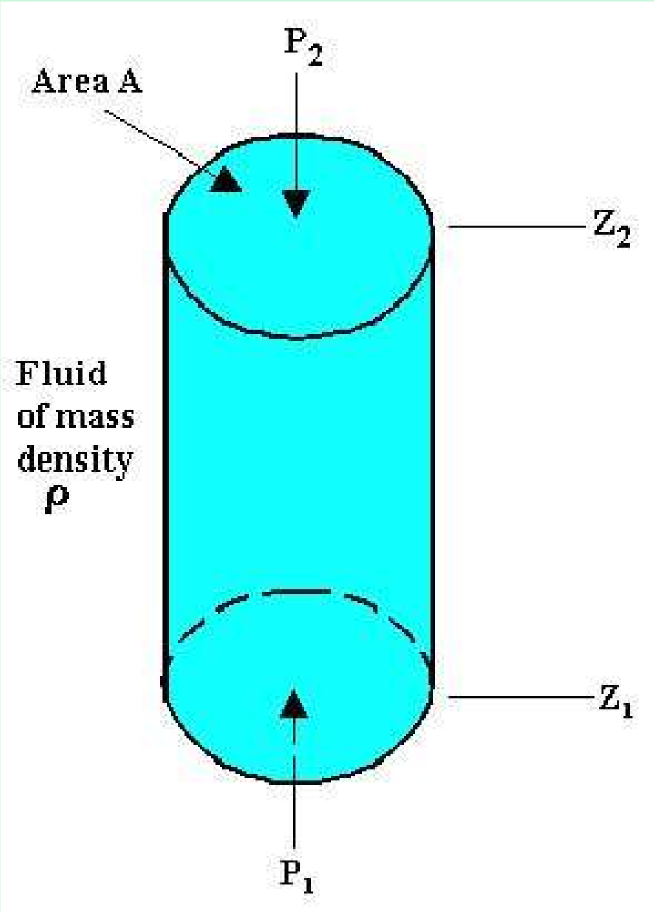
EQUALITY OF PRESSURE AT THE SAME LEVEL IN A STATIC FLUID



$$\sum F_{horizontal} = p_1 A - p_2 A = 0$$

$$p_1 = p_2$$

VARIATION OF PRESSURE WITH ELEVATION



$$\sum F_{vertical} = p_1 A - p_2 A - mg = 0$$

$$p_1 A - p_2 A = \rho A (z_2 - z_1) g$$

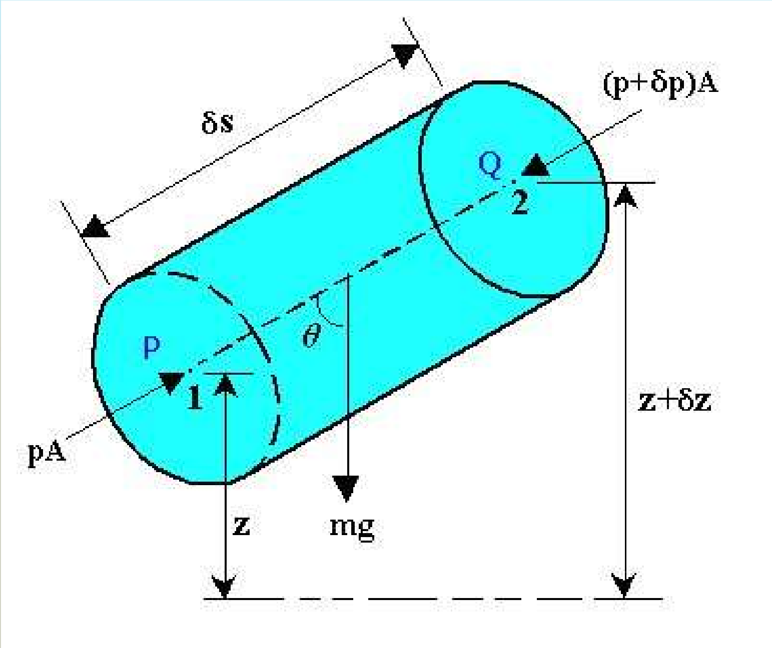
$$p_1 - p_2 = \rho (z_2 - z_1) g$$

GENERAL VARIATION OF PRESSURE IN A STATIC FLUID DUE TO GRAVITY

$$p\,A-(p+\delta p)A-\rho\,g\,A\,\delta s\cos\theta=0$$

$$\delta p=-\rho\,g\;\delta s\cos\theta$$

$$\frac{\delta p}{\delta s}=-\rho\,g\;\cos\theta$$



- For vertical direction: $\theta = 0$

$$\frac{dp}{dz}=-\rho\,g=-\gamma$$

VARIATION OF PRESSURE IN AN INCOMPRESSIBLE FLUID (LIQUID)

$$dp = -\rho\, g\, dz$$

$$\int_{p_1}^{p_2} dp = -\int_{z_1}^{z_2} \rho\, g\, dz$$

- For liquids: ρ = constant

$$p_2 - p_1 = -\rho\, g\left(z_2 - z_1\right)$$

VARIATION OF PRESSURE IN AN COMPRESSIBLE FLUID (GAS)

$$dp = -\rho\, g\, dz \quad \Rightarrow \quad \int_{p_1}^{p_2} dp = -\int_{z_1}^{z_2} \rho\, g\, dz$$

ρ is variable, e.g. for an ideal gas: $\rho = \dfrac{p}{RT}$

$$\frac{dp}{p} = -\frac{g}{RT}\, dz \quad \Rightarrow \quad \ln\frac{p_2}{p_1} = -\frac{g}{R}\int_{z_1}^{z_2} \frac{dz}{T}$$

$$\int_{p_1}^{p_2} \frac{dp}{p} = -\int_{z_1}^{z_2} \frac{g}{RT}\, dz$$

need to know T=T(z)

VARIATION OF PRESSURE IN AN COMPRESSIBLE FLUID (GAS)

- Case of uniform temperature: $T = T_o$

$$p_2 = p_1 \exp\left[-\frac{g(z_2 - z_1)}{RT_o}\right]$$

- Case of linear temperature variation: $T = T_o - \beta z$

at $z_1 = 0$ (sea level)

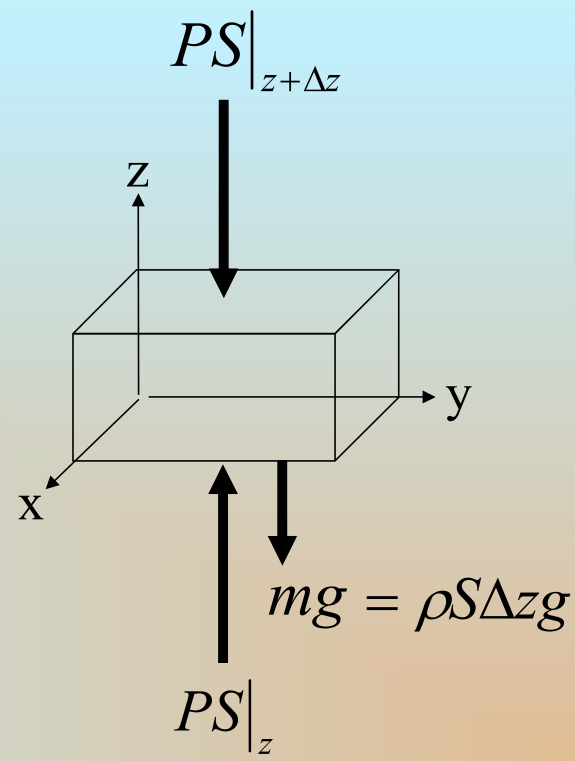
$T = T_o$

$p_1 = p_o$

$$\Longrightarrow \quad p_2 = p_o\left(1 - \frac{\beta z_2}{T_o}\right)^{\frac{g}{\beta R}}$$

WHAT ARE THE Z-DIRECTION FORCES?

- Let P_z and $P_{z+\Delta z}$ denote the pressures at the base and top of the cube, where the elevations are z and z+Δz respectively.



PRESSURE DISTRIBUTION FOR A FLUID AT REST

- A force balance in the z direction gives:

$$\sum F_z = 0 = PS\big|_z - PS\big|_{z+\Delta z} - \rho S \Delta z g$$

$$\frac{P_{z+\Delta z} - P_z}{\Delta z} = -\rho g$$

- For an infinitesimal element ($\Delta z \rightarrow 0$)

$$\frac{dP}{dz} = -\rho g$$

INCOMPRESSIBLE FLUID

- Liquids are incompressible (density is constant):

$$P_2 - P_1 = -\rho g (z_2 - z_1)$$

- When we have a liquid with a free surface the pressure P at any depth below the free surface is:

$$P = \rho g h + P_o$$

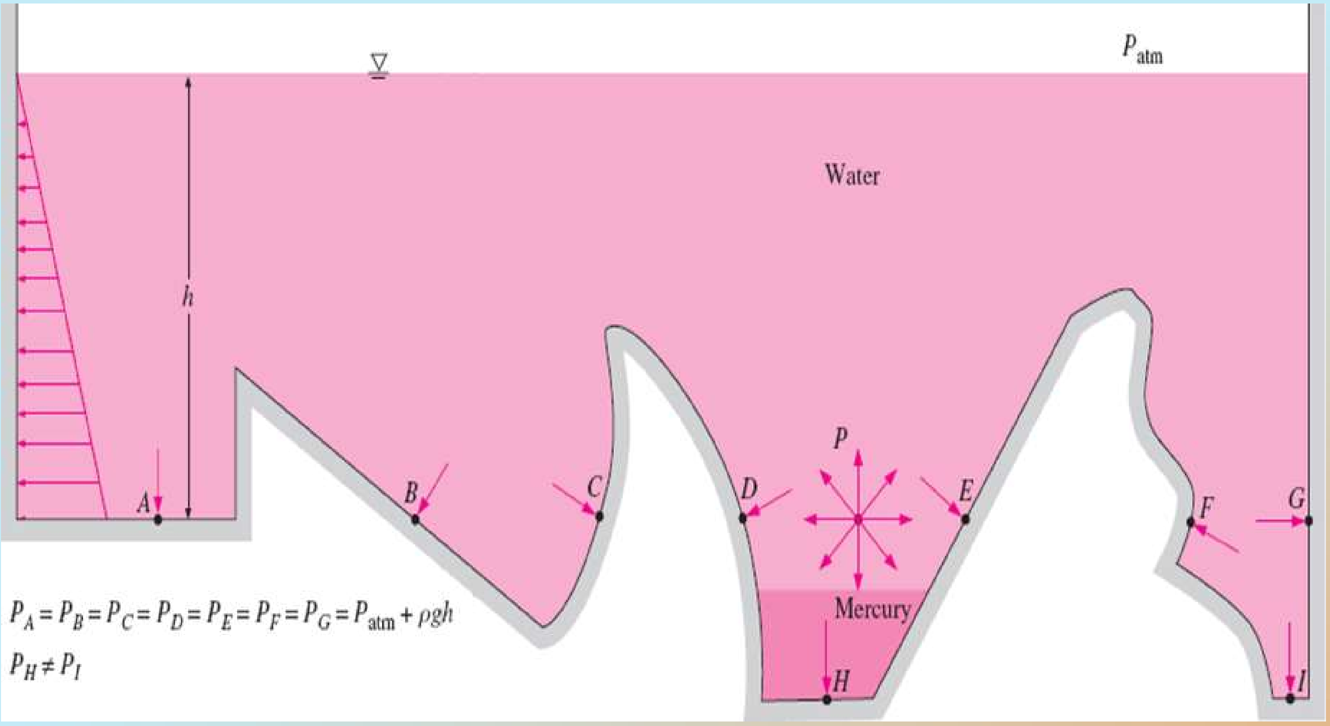
P_o is the pressure at the free surface ($P_o = P_{atm}$)

SOME PRESSURE LEVELS

▪ **10 Pa** - The pressure at a depth of 1 mm of water ▪ **10 kPa** - The pressure at a depth of 1 m of water, or the drop in air pressure when going from sea level to 1000 m elevation ▪ **10 MPa** - A "high pressure" washer forces the water out of the nozzles at this pressure ▪ **10 GPa** - This pressure forms diamonds	▪ **1 bar** - 100,000 Pa ▪ **1 millibar** - 100 Pa ▪ **1 atmosphere** - 101,325 Pa ▪ **1 mm Hg** - 133 Pa ▪ **1 inch Hg** - 3,386 Pa

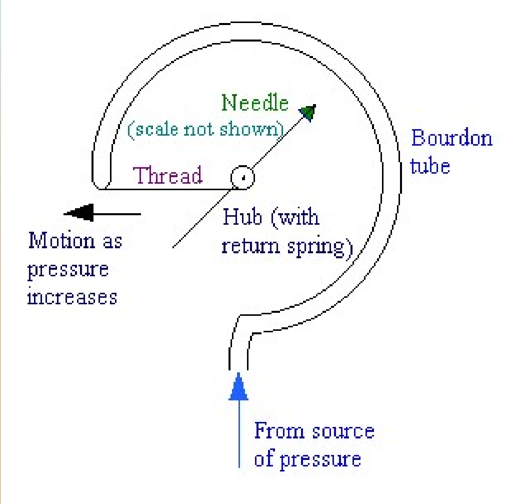
- The bar is common in the industry. One bar is 100,000 Pa, and for most practical purposes can be approximated to one atmosphere even if 1 Bar = 0.9869 atm

- 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.



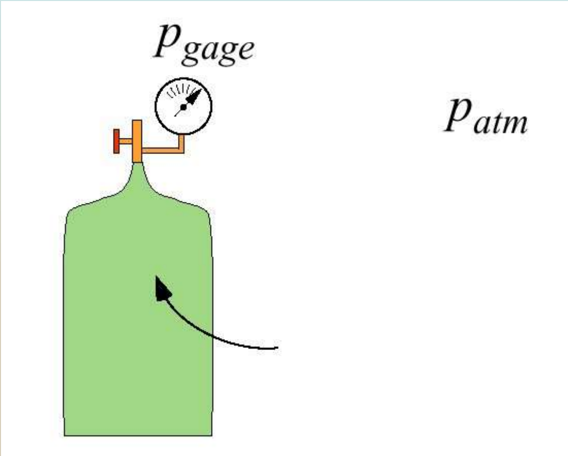
BOURDON GAUGE

- The pressure to be measured is applied to a curved tube, oval in cross section. Pressure applied to the tube tends to cause the tube to straighten out, and the deflection of the end of the tube is communicated through a system of levers to a recording needle.
- This gauge is widely used for steam and compressed gases.
- The pressure indicated is the difference between that communicated by the system to the external (ambient) pressure, and is usually referred to as the gauge pressure.



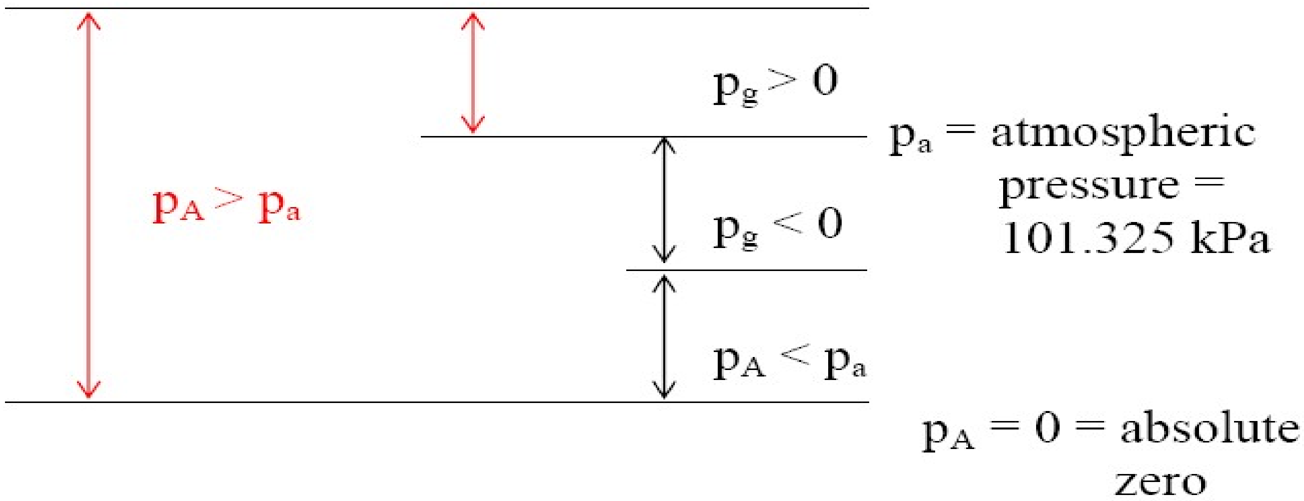
PRESSURE SCALES

- Absolute pressure: p_{abs} is measured relative to an absolute vacuum; it is always positive. (The pressure of a fluid is expressed relative to that of vacuum (=0)
- Gauge pressure: p_{gauge} is measured relative to the current pressure of the atmosphere; it can be negative or positive. (Pressure expressed as the difference between the pressure of the fluid and that of the surrounding atmosphere.) Usual pressure gauges record gauge pressure.



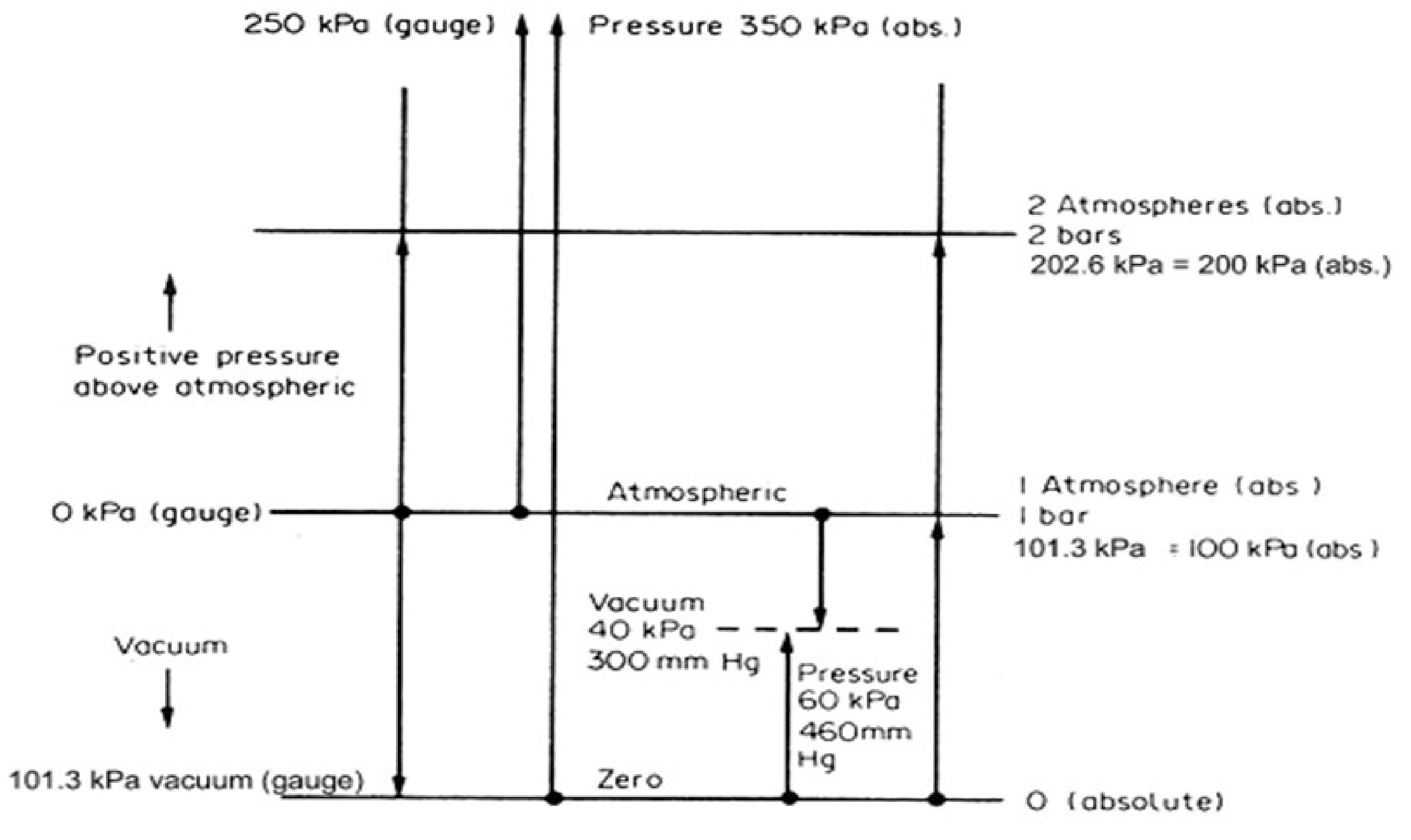
$$p_{abs} = p_{atm} + p_{gage}$$

Absolute Pressure, Gage Pressure, and Vacuum



For $p_A > p_a$, $\quad p_g = p_A - p_a$ = gage pressure

For $p_A < p_a$, $\quad p_{vac} = -p_g = p_a - p_A$ = vacuum pressure



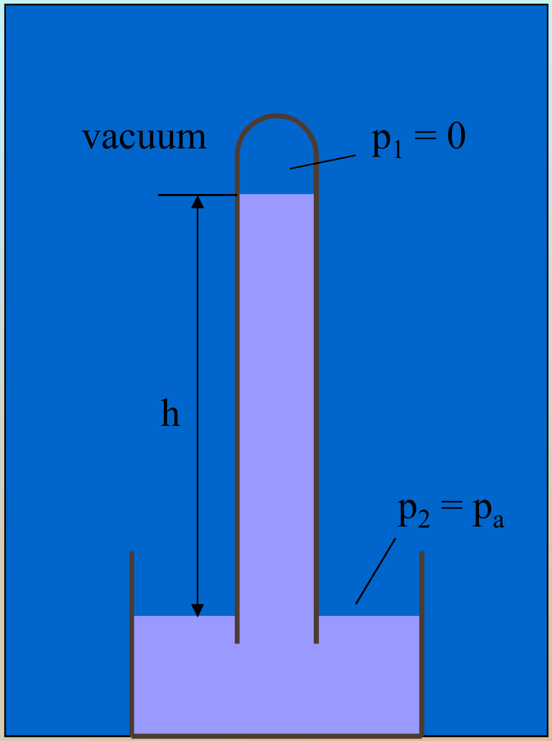
Pressure conversions

MEASURING PRESSURE: BAROMETERS

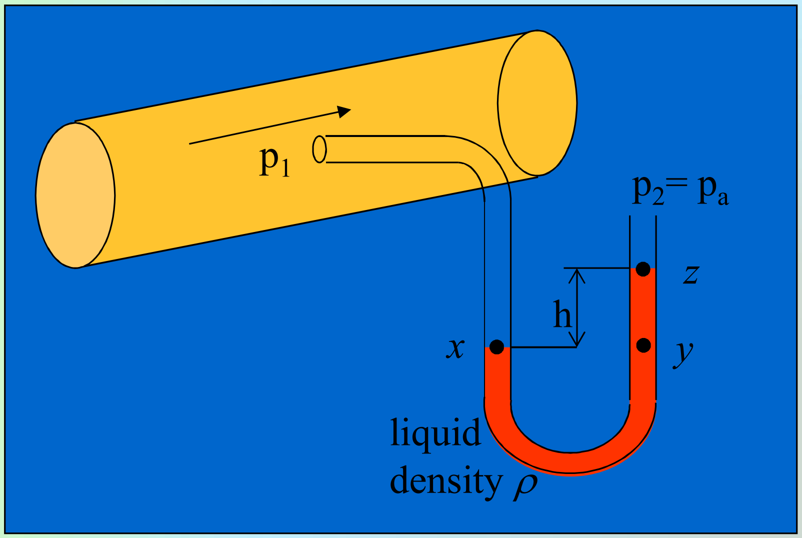
- A barometer is used to measure the pressure of the atmosphere.
- The simplest type of barometer consists of a column of fluid.

$$p_2 - p_1 = \rho g h$$

$$p_a = \rho g h$$



MEASURING PRESSURE WITH MANOMETERS



$p_1 = p_x$ (negligible pressure change in a gas)

$p_x = p_y$ (since they are at the same height)

$p_z = p_2 = p_a$

$p_y - p_z = \rho g h$

$p_1 - p_a = \rho g h$

- So a manometer measures gauge pressure.

MANOMETERS

- A somewhat more complicated device for measuring fluid pressure consists of a bent tube containing one or more **liquid of different specific gravities**. Such a device is known as *manometer*.
- In using a manometer, **generally a known pressure** (which may be atmospheric) is applied to one end of the manometer tube and the **unknown pressure to be determined is applied to the other end.**
- In some cases, however, the **difference between pressure** at ends of the manometer tube is desired rather than the actual pressure at the either end. A manometer to determine this differential pressure is known as ***differential pressure manometer***.

- The manometer in its various forms is an extremely useful type of pressure measuring instrument, but suffers from a number of limitations.
- While it can be adapted to measure very small pressure differences, it can not be used conveniently for large pressure differences - although it is possible to connect a number of manometers in series and to use mercury as the manometric fluid to improve the range. (limitation)
- A manometer does not have to be calibrated against any standard; the pressure difference can be calculated from first principles. (Advantage)

- Some liquids are unsuitable for use because they do not form well-defined menisci. Surface tension can also cause errors due to capillary rise; this can be avoided if the diameters of the tubes are sufficiently large - preferably not less than 15 mm diameter. (limitation)
- A major disadvantage of the manometer is its slow response, which makes it unsuitable for measuring fluctuating pressures. (limitation)
- It is essential that the pipes connecting the manometer to the pipe or vessel containing the liquid under pressure should be filled with this liquid and there should be no air bubbles in the liquid. (important point to be kept in mind)

MANOMETERS - MEASURE ΔP

Rules of thumb

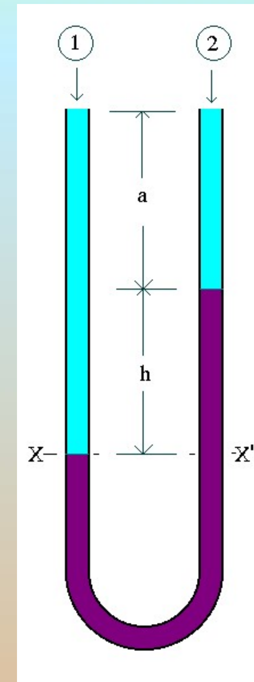
- When evaluating, start from the known pressure end and work towards the unknown end
- At equal elevations, pressure is constant in the SAME fluid
- When moving down a monometer, pressure increases
- When moving up a monometer, pressure decreases
- Only include atmospheric pressure on open ends

MANOMETERS - VARIOUS FORMS

- Simple U - tube Manometer
- Inverted U - tube Manometer
- U - tube with one leg enlarged
- Two fluid U - tube Manometer
- Inclined U - tube Manometer

SIMPLE U - TUBE MANOMETER

- The maximum value of $P_1 - P_2$ is limited by the height of the manometer.
- To measure larger pressure differences we can choose a manometer with higher density, and to measure smaller pressure differences with accuracy we can choose a manometer fluid which is having a density closer to the fluid density



$$p_X = p_1 + \rho g (a + h)$$

$$p_{X'} = p_2 + \rho g a + \rho_m g h$$

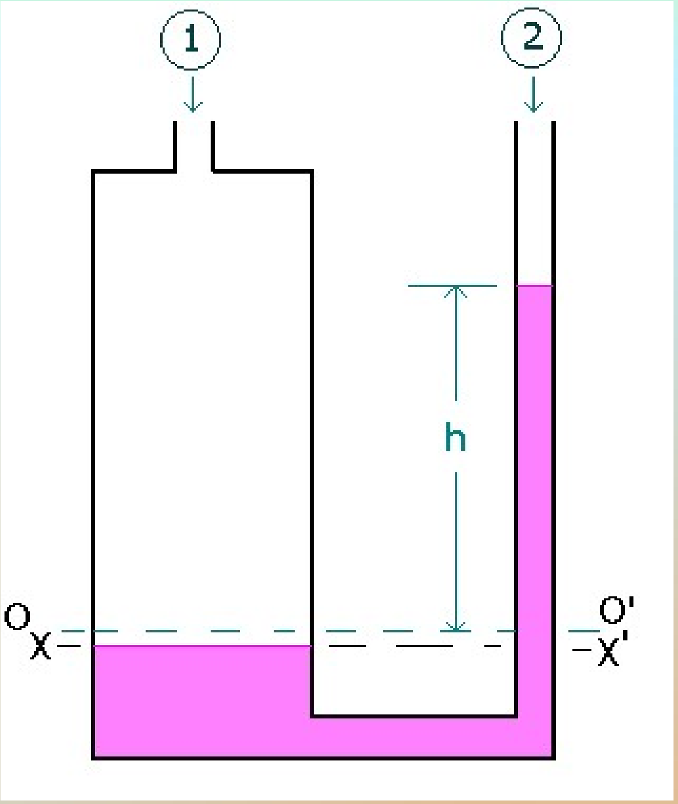
$$p_X = p_{X'}$$

$$p_1 - p_2 = (\rho_m - \rho) g h$$

U - TUBE WITH ONE LEG ENLARGED

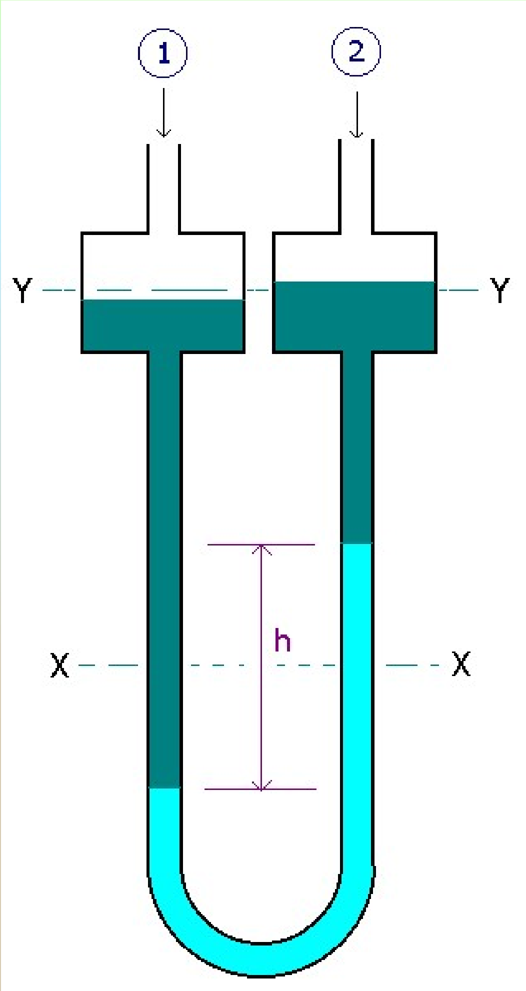
- Used for more accurate readings

$$p_1 - p_2 = (\rho_m - \rho) g\, h$$



TWO FLUID U-TUBE MANOMETER

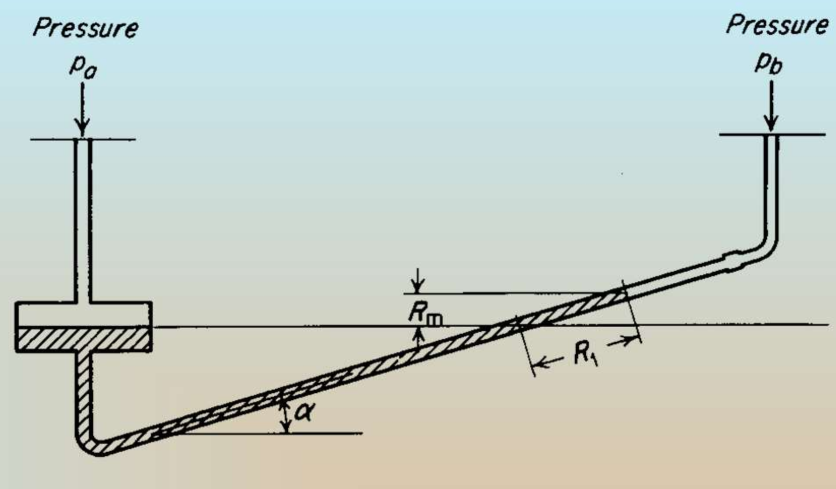
- Small differences in pressure in gases are often measured with a manometer of the form shown in the figure.



INCLINED MANOMETER

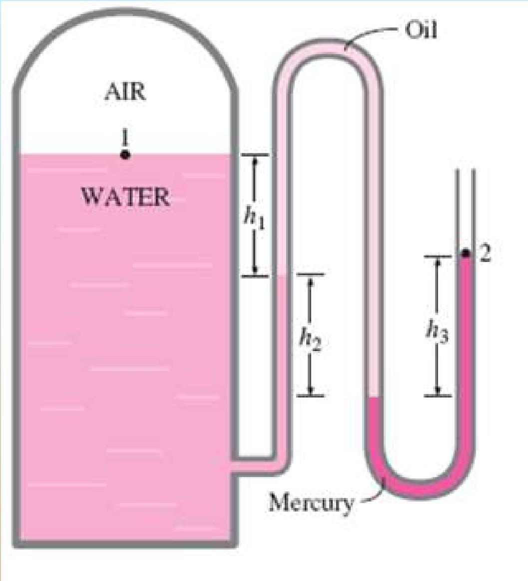
- To measure small pressure differences need to magnify R_m some way.

$$P_a - P_b = gR_1(\rho_a - \rho_b)\sin\alpha$$



EXAMPLE

The water in a tank is pressurized by air, and the pressure is measured by a multi-fluid manometer as shown in the figure. The tank is located on a mountain at an altitude of 1400 m where the atmospheric pressure is 85.6 kPa. Determine the air pressure in the tank if h_1 = 0.1 m, h_2 = 0.2 m, and h_3 = 0.35 m. Take the densities of water, oil, and mercury to be 1000, 859, and 13600 kg/m^3, respectively.

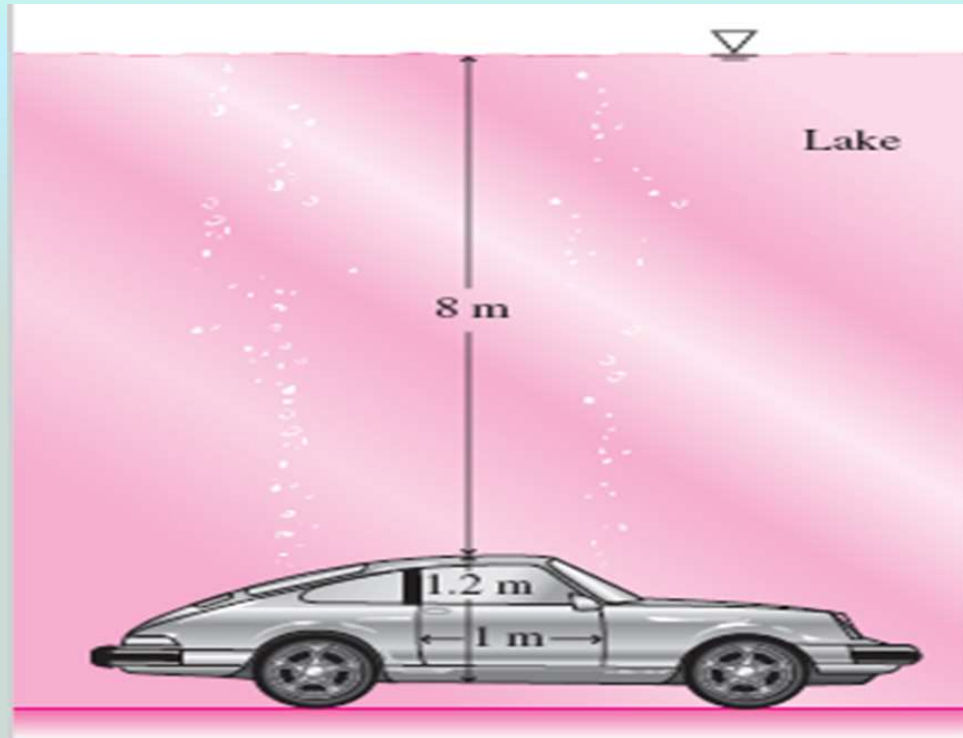


Solution: $P_1 + \rho_{water} g h_1 + \rho_{oil} g h_2 - \rho_{mercur} g h_3 = P_{atm}$

Answer = 130 kPa

EXAMPLE

A heavy car plunges into a lake during an accident and lands at the bottom of the lake on its wheels. The door is 1.2 m high and 1 m wide, and the top edge of the door is 8 m below the free surface of the water. Determine the hydrostatic force on the door and the location of the pressure center.



Assumptions:

- The bottom surface of the lake is horizontal.
- The car is well-sealed so that no water leaks inside
- The door can be approximated as a vertical rectangular plate
- The pressure in the car remains at atmospheric value since there is no water leaking in, and thus no compression of the air inside. Therefore, atmospheric pressure cancels out in the calculations since it acts on both sides of the door.
- The weight of the car is larger than the buoyant force acting on it.
- The density of lake water is 1000 kg/m^3.

Solution:

$$P_{ave} = P_C = \rho g h_C = \rho g\left(s + \frac{b}{2}\right)$$

$$= \left(1000\ kg/m^3\right)\left(9.81\ m/s^2\right)(8 + 1.2/2\ m)\left(\frac{1\ kN}{1000\ kg.m/s^2}\right)$$

$$= 84.4\ {}^{kN}/_{m^2}$$

Then the resultant hydrostatic force on the door becomes

$$F_R = P_{ave}A = \left(84.4\ kN/m^2\right)(1\ m \times 1.2\ m) = 101.3\ kN$$

$$y_P = s + \frac{b}{2} + \frac{b^2}{12(s + b/2)} = 8 + \frac{1.2^2}{2} + \frac{1.2}{12(8 + 1.2/2)} = 8.61\ m$$