Pressure measurement

Lecture 15

Pressure Measurement

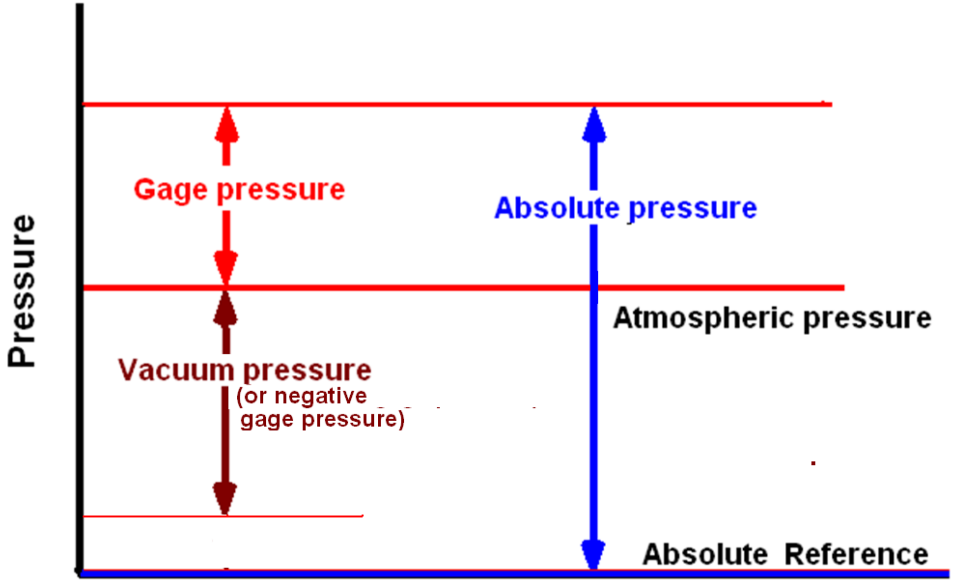
- Pressure is defined as the" the normal force exerted on a unit area"
- It always act normal to the surface

Types of Pressure

Absolute pressure : Reference pressure is taken as absolute zero pressure.

Gage pressure : Reference pressure is taken as atmospheric pressure

Vacuum pressure : The absolute pressure below the atmospheric pressure.



Static Pressure : Measured by the instrument when the fluid is at rest. It does not depends on the orientation of the measurement.

Stagnation pressure : Pressure measured when the fluid is brought to rest isentropically.

Dynamic pressure or velocity pressure : Corresponds to kinetic energy of the fluid. i.e. it is the kinetic energy per unit volume of a fluid particle. Mainly depends on the orientation of the pressure measurement.

Dynamic pressure = Stagnation pressure – static pressure.

Methods of pressure measurement

- Gravitational Types
- Dead weight testers (mostly for calibration)
- Liquid column - Manometers
- Direct - Elastic deflection gage types
- Force measurement device such as load cells
- Electro-mechanical sensors
- Electrical resistance gage
- Thermal sensors
- Ion Exchange sensors

Units involved in pressure measurements

$1\ N/m^2$	$= 1$ pa
1 mm of H_2O	$= 10$ Pa
1 mm of Hg	$= 133.3$ Pa
1 mm of Hg	$= 1$ torr
1 bar	$= 10^5$ pa
1 atm	$= 1.01325$ bar
1 bar	$= 14.508$ psi
1 bar	$= 2088\ ib/ft^2$

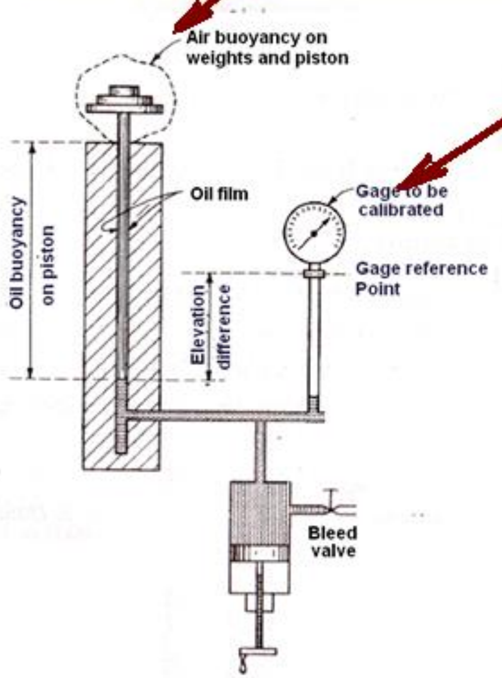
Dead Weight Tester

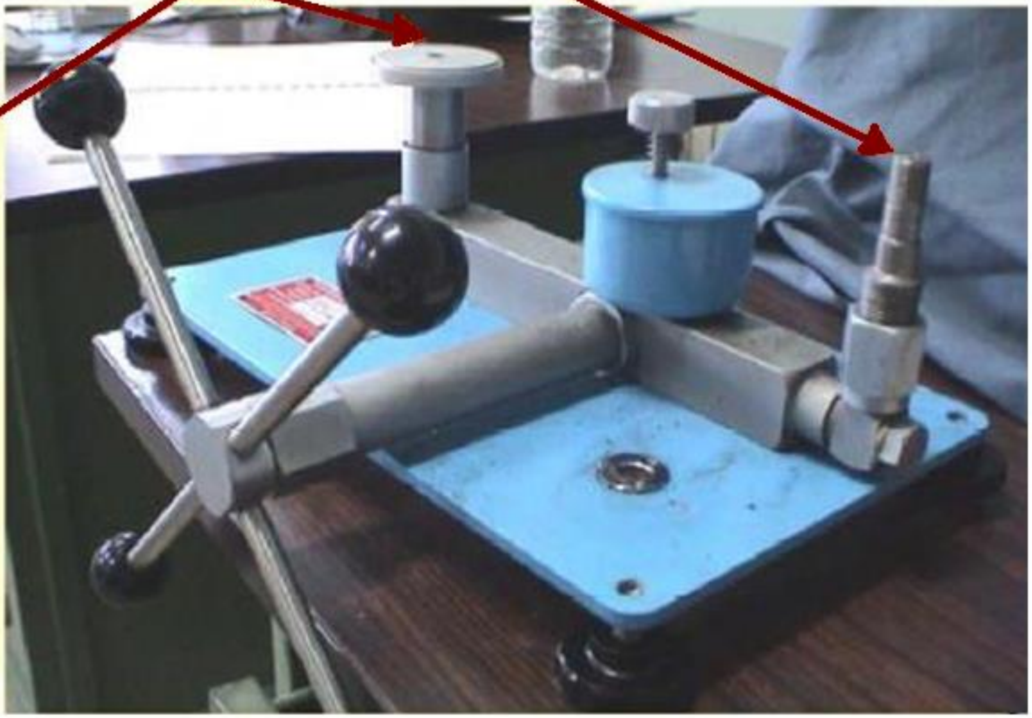
- Dead weight gauges – primary devices based on the definition of pressure
- The pressure is derived from force and area of application
- They are employed as standards for calibration
- Gauge to be calibrated is connected to a chamber filled with fluid whose pressure can be adjusted with a pump and bleed valve
- Vertical piston - cylinder to which various standard weights may be applied on it
- Pressure is slowly built up till the piston and weights are seen to float
- Fluid “gauge” pressure must equal the dead weight divided by the piston area

Dead weight tester available at IITG

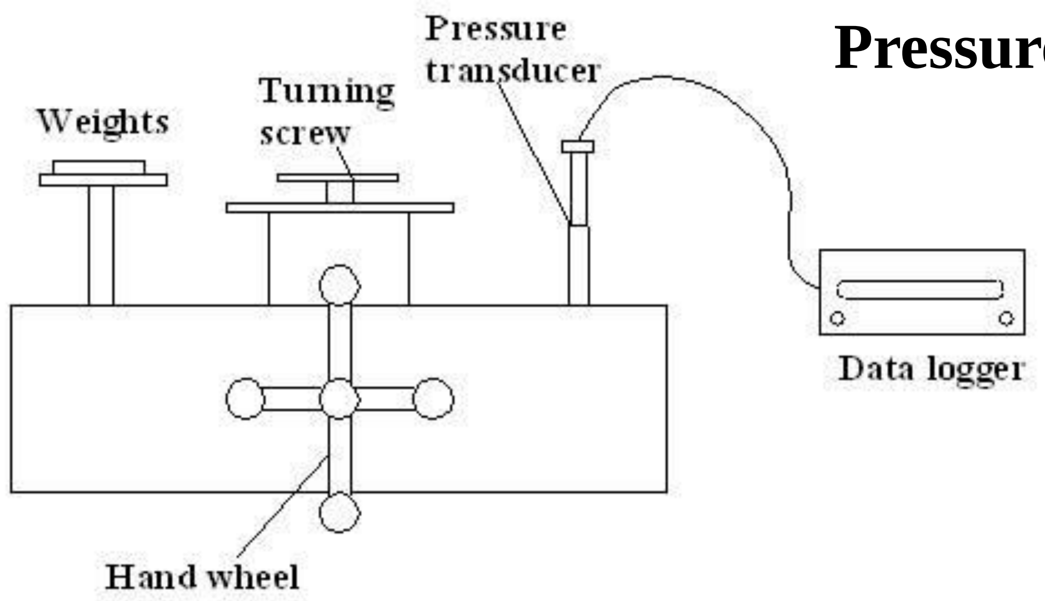
Piston loaded with dead weights

Device to be calibrated





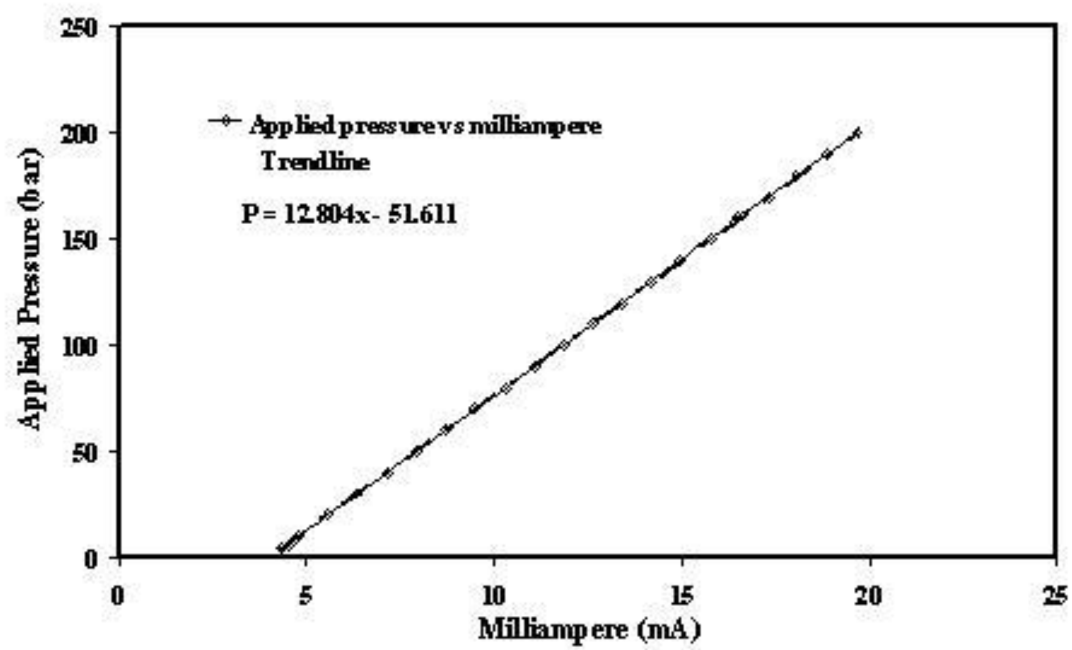
Pressure transducer calibration



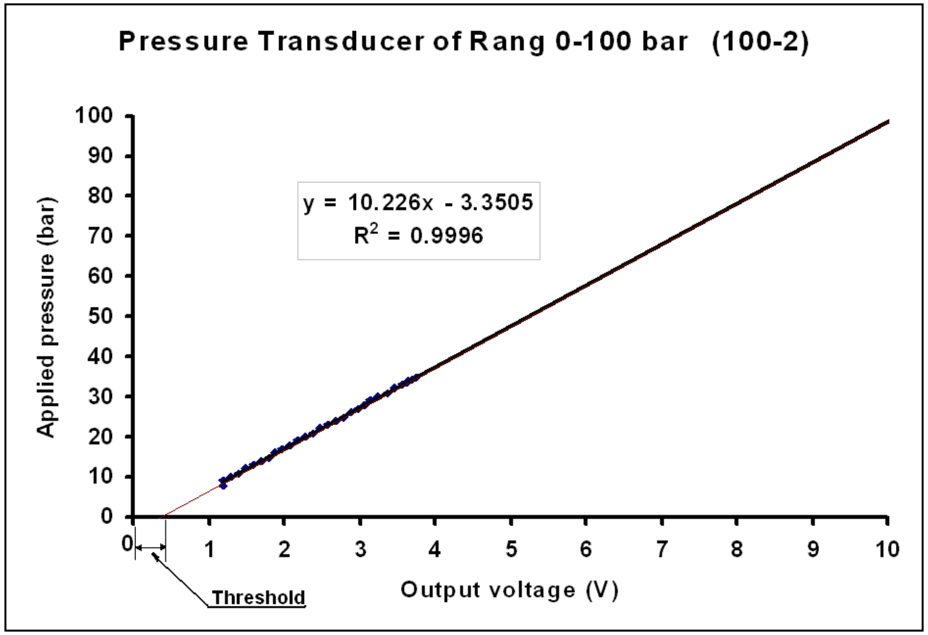
Make : Keller, Swiss

Model : 21 SC

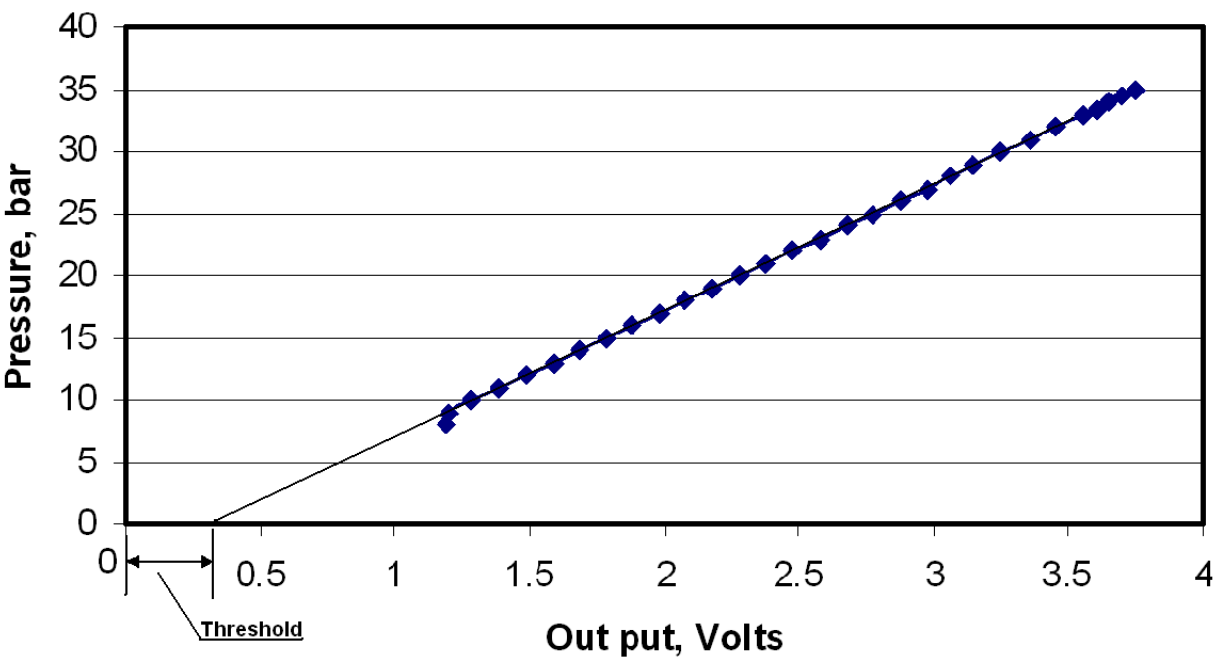
Range 0 - 200 bar



mA	Atual value	Measu. value
4	0	0.395
8	50	50.821
12	100	102.037
16	150	153.25
20	200	204.469



Threshold Error for range (0-10 bar)



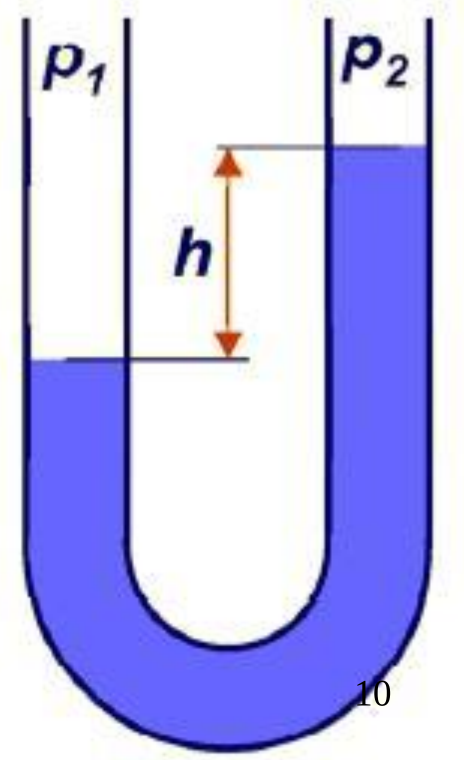
Manometers

- It is a deflection type instrument
- Unknown pressure is balanced by the weight of a fluid column
- Common type is the U- tube manometer
- Water, mercury and alcohol are most commonly used fluids

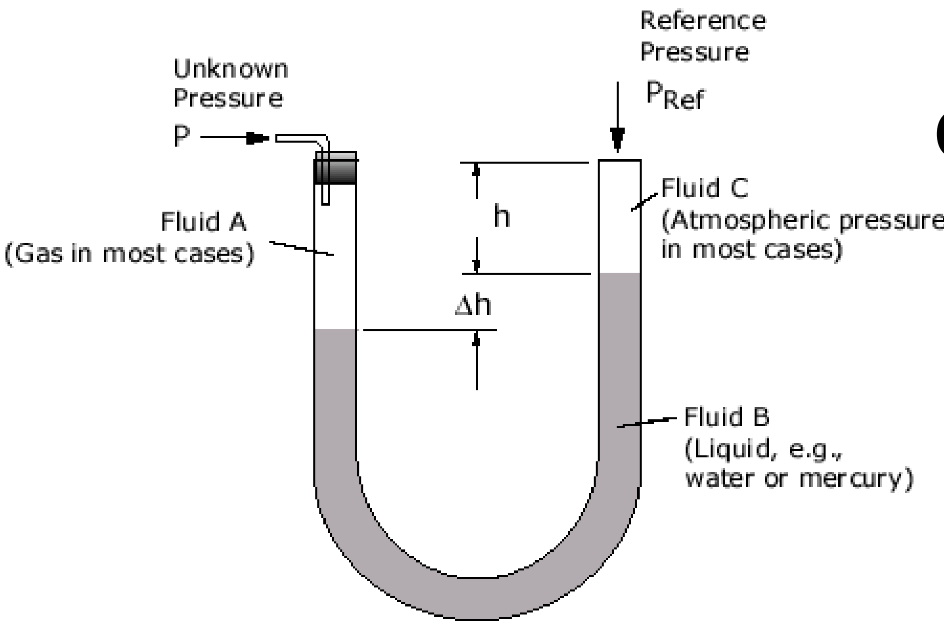
$$h = \frac{p_1 - p_2}{\rho g}$$

If the mano-metric fluid density is different from flowing liquid then,

$$h = \frac{p_1 - p_2}{(\rho_m - \rho_f)g}$$



The U Tube contains water or mercury in a U-shaped tube, and is usually used to measure gas pressure. One end of the U tube is exposed to the unknown pressure field and the other end is connected to a reference pressure source (usually atmospheric pressure), shown in the schematic below.

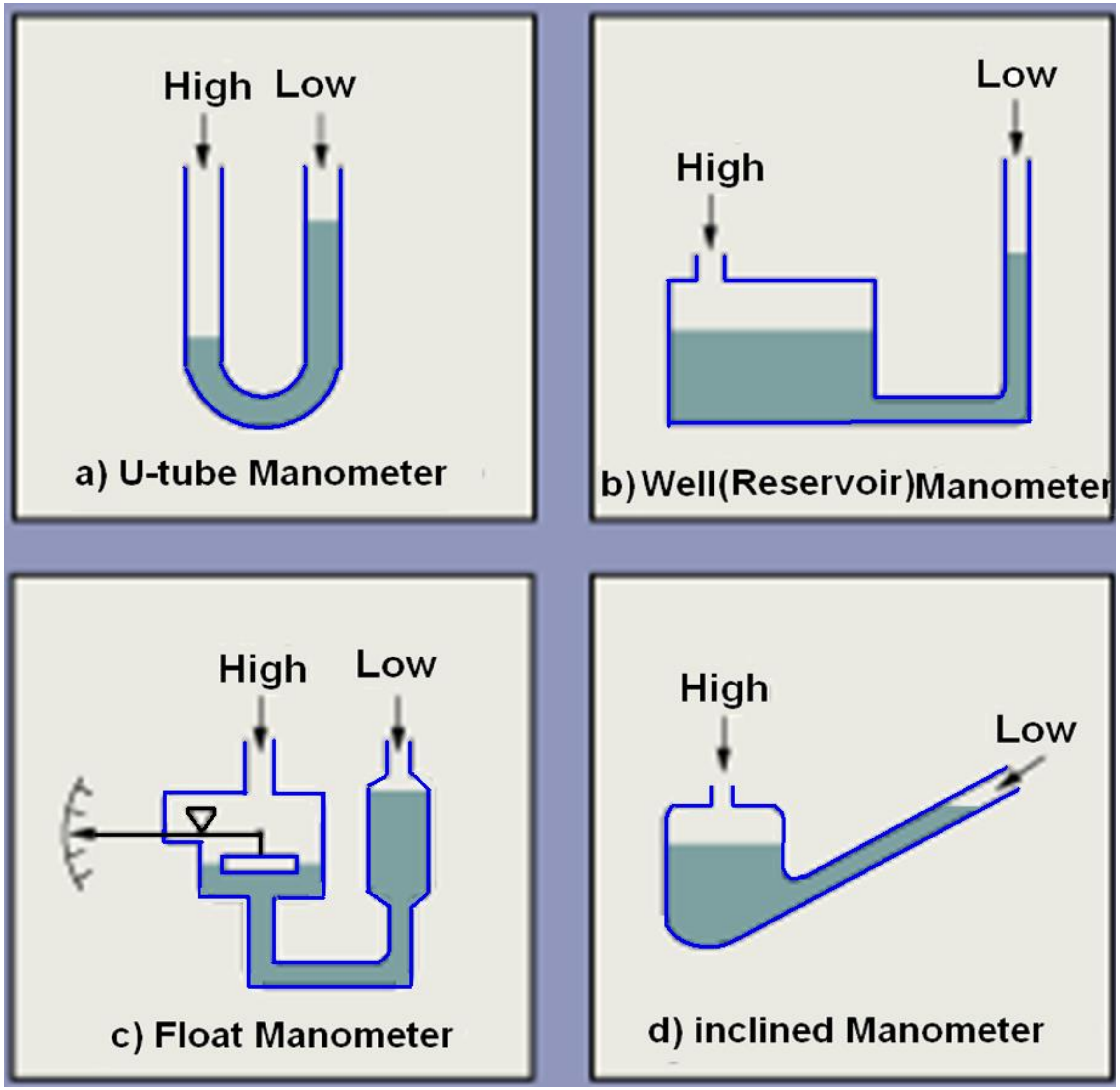


Generalized U type Manometer

$$p + \rho_A g\left(h + \Delta h\right) = \rho_B g\Delta h + \rho_C gh + p_{\mathrm{Re}\,f}$$

$$\Rightarrow p = p_{\mathrm{Re}\,f} + \left(\rho_B - \rho_A\right) g\Delta h + \left(\rho_C - \rho_A\right) gh$$

Other types


High
Low
a) U-tube Manometer
Low
High
b) Well(Reservoir)Manometer
High
Low
c) Float Manometer
High
Low
d) inclined Manometer

Cistern or Well type Manometer

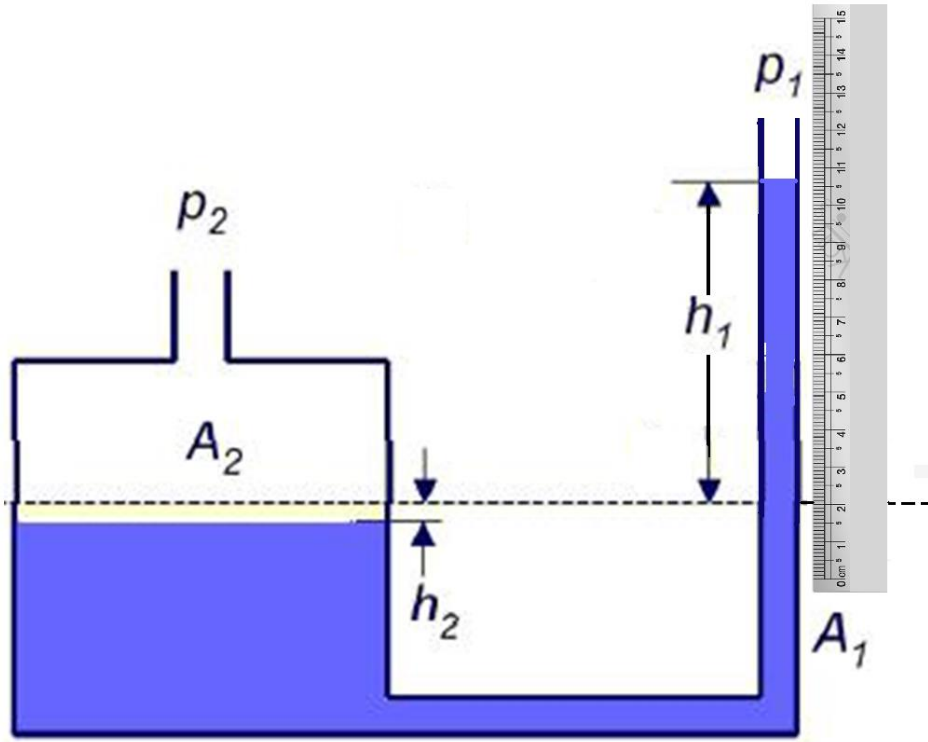
$$P_1 + \rho g(h_1 + h_2) = P_2$$

$$(P_2 - P_1) = \rho g(h_1 + h_2)$$

$$A_2 h_2 = A_1 h_1$$

$$h_2 = \frac{A_1}{A_2} h_1$$

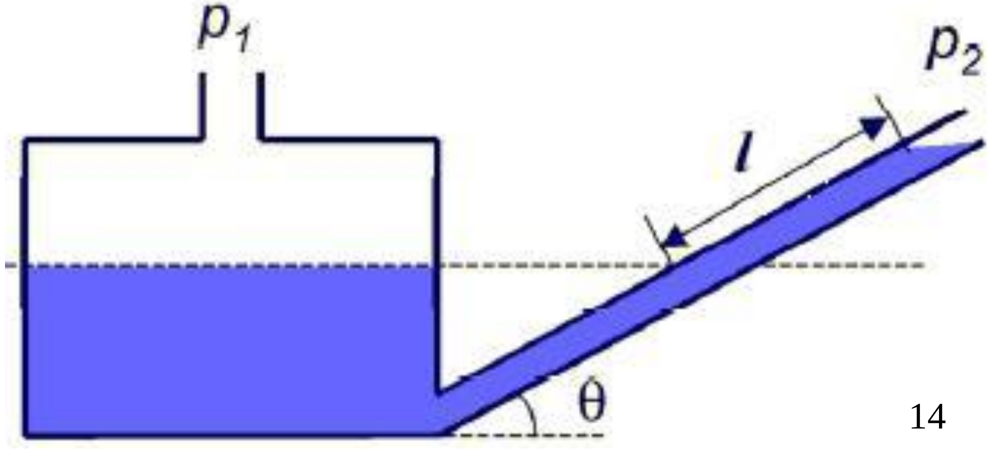
$$P_2 - P_1 = \rho g h_1 \left(1 + \frac{A_1}{A_2} \right)$$



<u>Sensitivity Enhancement methods</u>

- **One leg of a well manometer inclined to obtain longer liquid column**
- **Too shallow angles lead to manual errors**
- **Sensitivity enhanced by 1/sin θ**

$$\rho g l \sin\theta = p_1 - p_2$$



Sensitivity Enhancement in U Tube Manometer

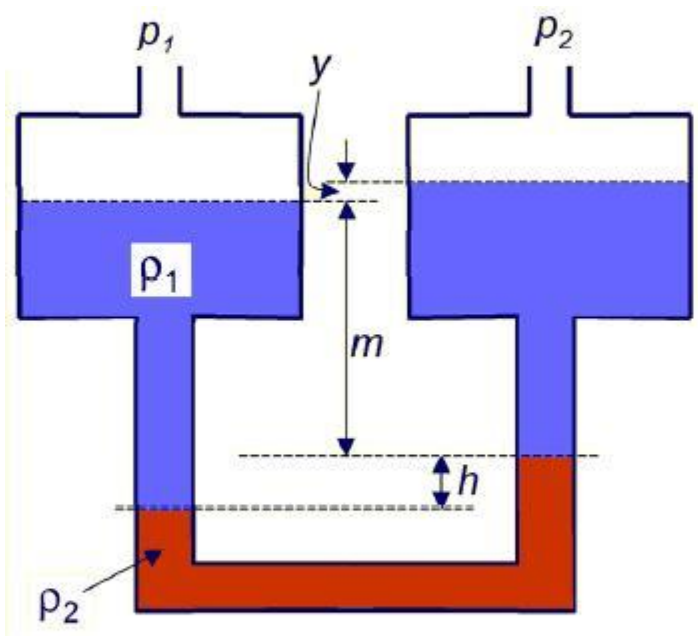
Sensitivity magnification = 1/[(ρ_2-ρ_1)]

Example : $CaCl_2$ solution (SG = 1.15) and Benzyl alcohol (SG = 1.05)

Magnification (M) = 1/(1.15-1.05) = 10

In case of Water and kerosene   M = 1/(1-0.7) = 3.33

Smaller the difference in density, higher the magnification.



$$A.y = a.h \Rightarrow y = h\frac{a}{A}$$

$$p_1 - p_2 = gh(\rho_2 - \rho_1)$$

$$h = \frac{p_1 - p_2}{g(\rho_2 - \rho_1)}$$

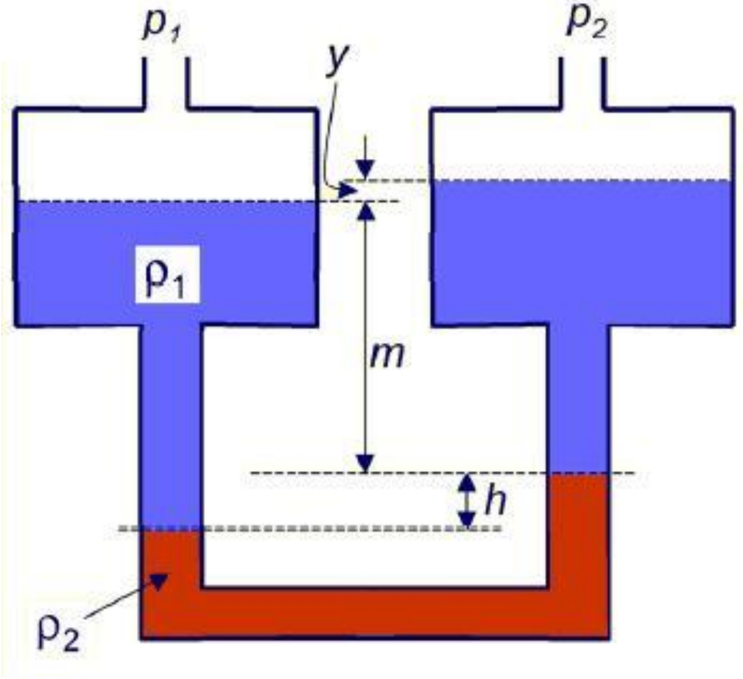
$$p_1 + \rho_{air} g.y + \rho_1 g.m + \rho_1 g.h = p_2 + \rho_1 g.y + \rho_1 g.m + \rho_2 g.h$$

$$p_1 - p_2 = gh(\rho_2 - \rho_1) + \rho_1 g.y + \rho_{air} g.y$$

$$A.y = a.h \Rightarrow y = h\frac{a}{A}$$

$$p_1 - p_2 = gh(\rho_2 - \rho_1)$$

$$h = \frac{p_1 - p_2}{g(\rho_2 - \rho_1)}$$



Multi-tube Manometer

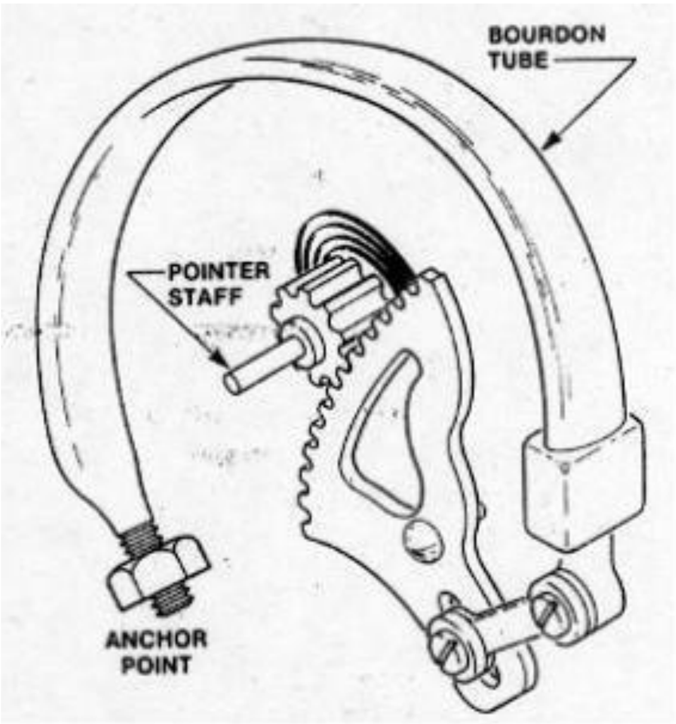
- For measuring pressures at several locations simultaneously.
- For freezing the values at a particular time instant, pinch cork /valve can be used.

Analysis of Manometer

- **For higher ranges, high density fluid is preferred**
- **For higher sensitivity, lighter fluid is preferred**
- **In general, manometer is used for static measurements, however, due to oscillations of the liquid column it is necessary to known the response of the system with some known input functions.**

BOURDON TUBE

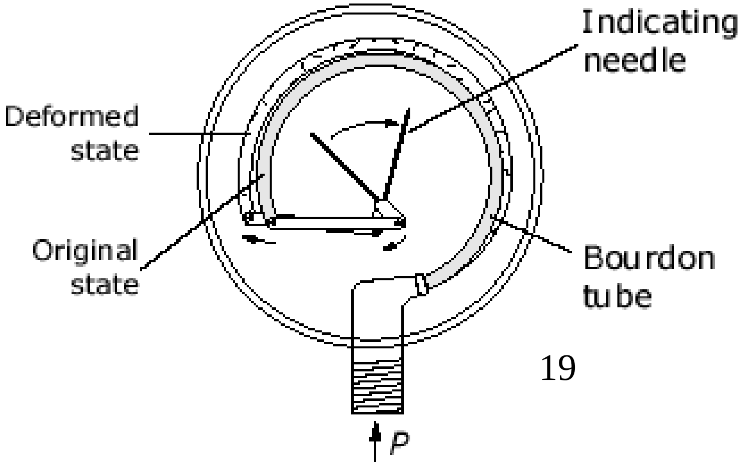
A typical Bourdon tube contains a curved tube of non circular cross section that is open to external pressure input on one end and is coupled mechanically to an indicating needle on the other end, as shown schematically below.



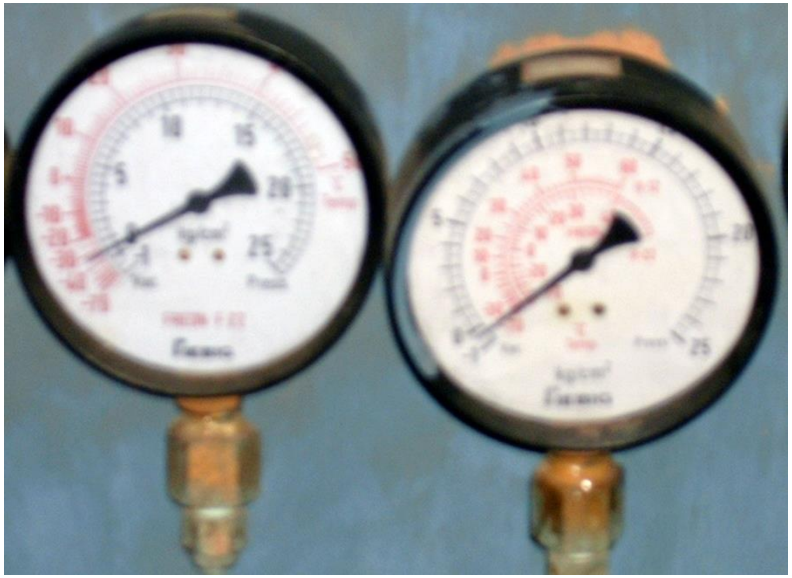
Tube of non-circular cross section

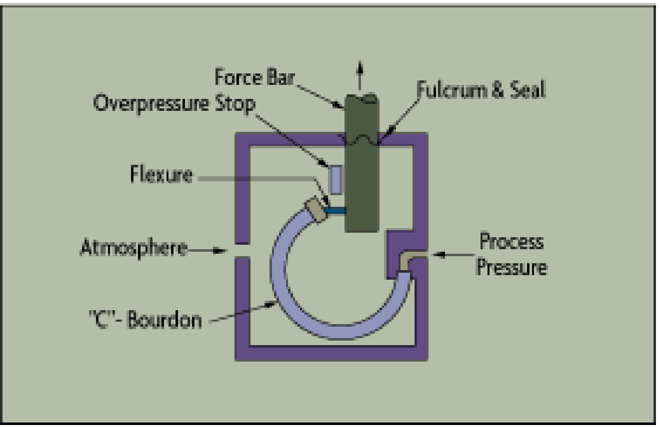
Applied force attempt to attain a circular cross section.

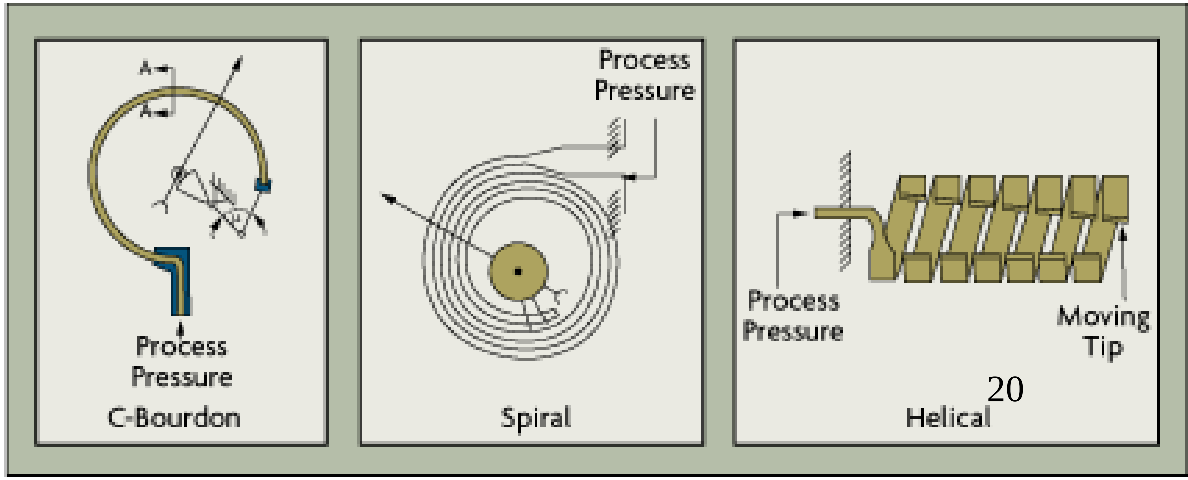
Types: C, Spiral and Helical



Illustrations







For better accuracy and sensitivity electrical – resistance strain gages may be installed on the bourdon tube for sensing the elastic deformation.

<u>Advantages:</u>

Portable, Convenient and no leveling required

<u>Disadvantages:</u>

Limited to static or quasi-static measurements. Accuracy may be insufficient for many applications.

Pressure measurement

Lecture 16

Pressure Measurement in the Moving Fluids

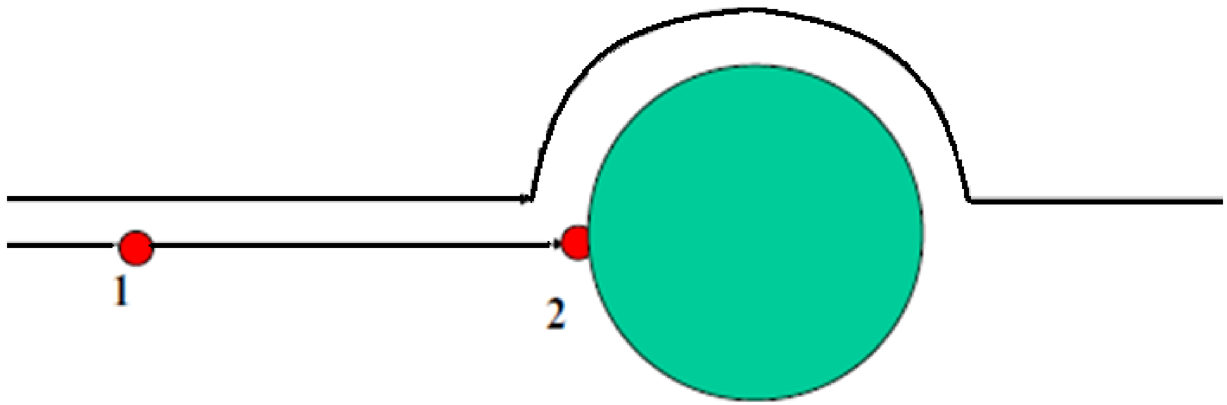
Subsonic flow

- Total (point)
- Static (static)
- Dynamic (kinetic)

Supersonic flow

- Total
- Static

Pressure Measurement in Moving Fluids



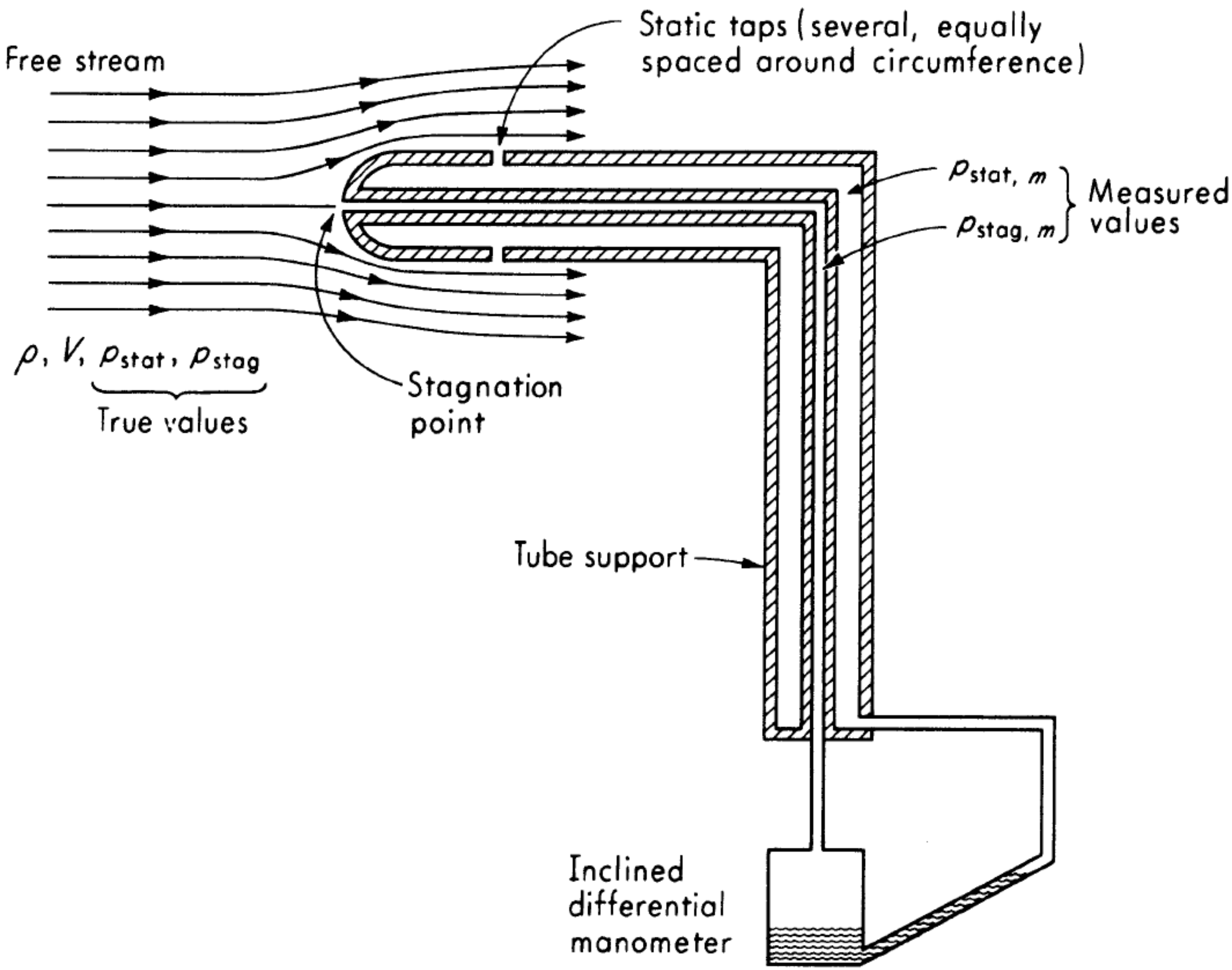
$$P_1 + \frac{\rho V_1^{\,2}}{2} = P_2 + \frac{\rho V_2^{\,2}}{2}$$

$$V_2 = 0$$

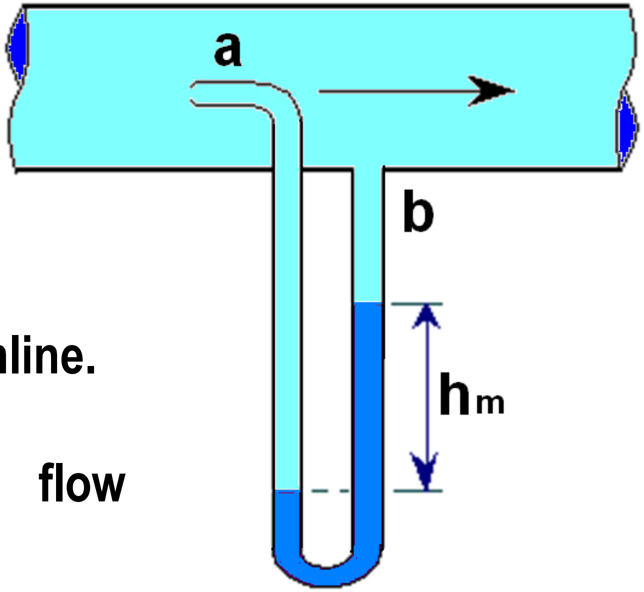
$$\Rightarrow P_2 = P_t = P_1 + \frac{\rho V_1^{\,2}}{2}$$

Pressure Measurement in the Moving Fluids

- **Static Pressure: measured perpendicular to the stream line**
- **Dynamic Pressure: Equivalent of the kinetic energy of the fluid**
- **Stagnation pressure is when the fluid is brought to rest isentropically.**
- **Total (stagnation, impact) pressure is the sum of the static and dynamic pressures**


Static taps (several, equally spaced around circumference)
Free stream
$p_{stat,\,m}$
$p_{stag,\,m}$
Measured values
ρ, V, p_{stat}, p_{stag}
True values
Stagnation point
Tube support
Inclined differential manometer

Simple Pitot tube

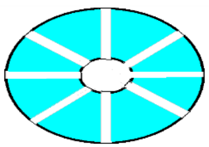


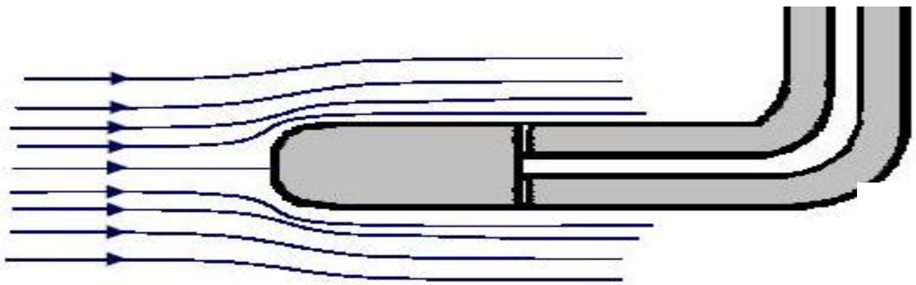
- device to measure the local velocity along a streamline.
- two tubes: impact tube “a” and static tube “b”,
- impact tube opening is perpendicular to the flow direction.
- Static tube opening is parallel to the direction of flow. .

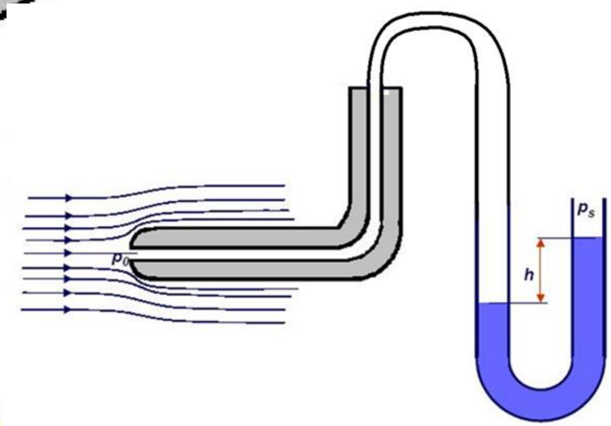
- static tube measures the static pressure, since there is no velocity component perpendicular to its opening.
- The impact tube measures both the static pressure and impact pressure (due to kinetic energy). In terms of heads the impact tube measures the static pressure head plus the velocity head

Static Probe

- For Static Pressure
- 4, 6, or 8 circumferential holes



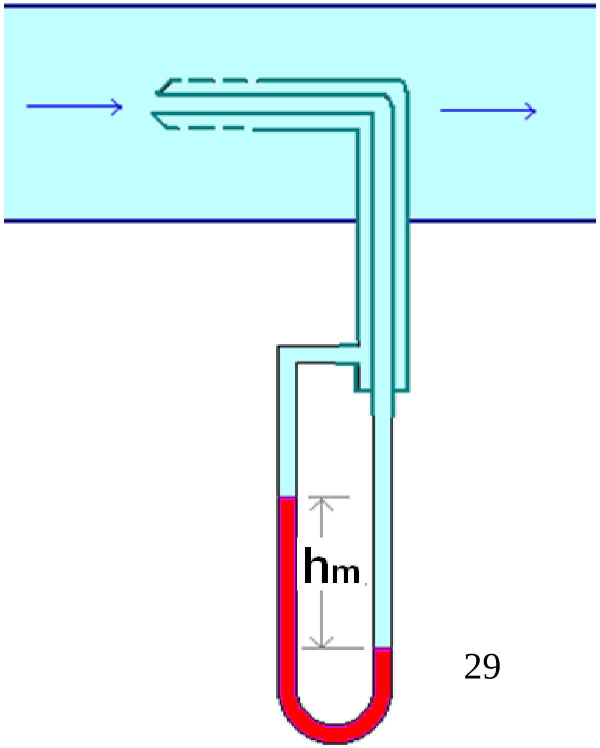




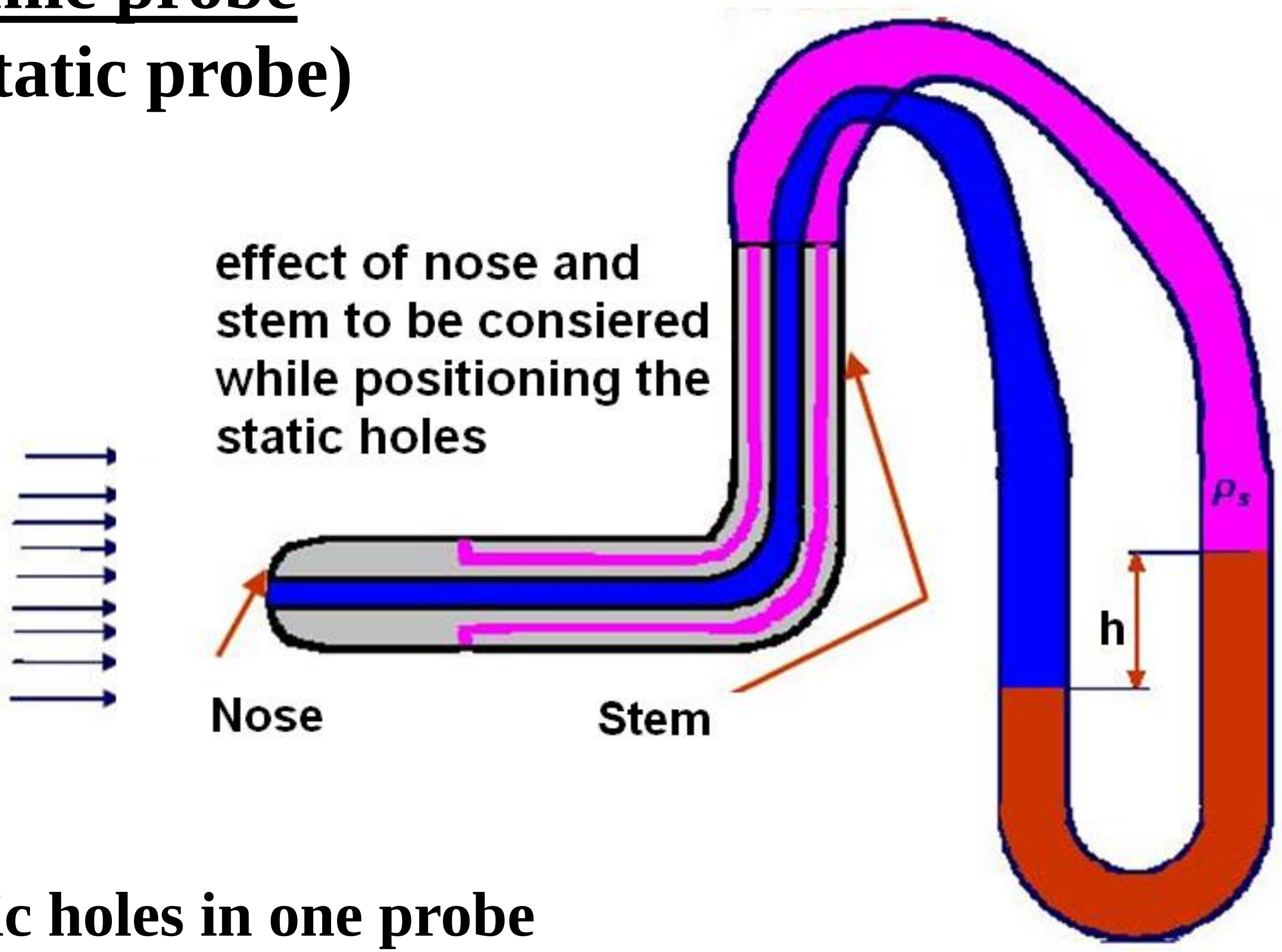
- Two co-axial tubes
- The inner tube faces the flow, other tube is open to the stream only
- Small static orifices
- Pressure connections to the manometer

Pitot-static tube

A device, essentially a tube set parallel to the direction of fluid-stream movement and attached to a manometer, used to measure the total pressure of the fluid stream.



Dynamic probe
(Pitot-static probe)



Pitot and static holes in one probe
Positioning of static holes is crucial to accuracy

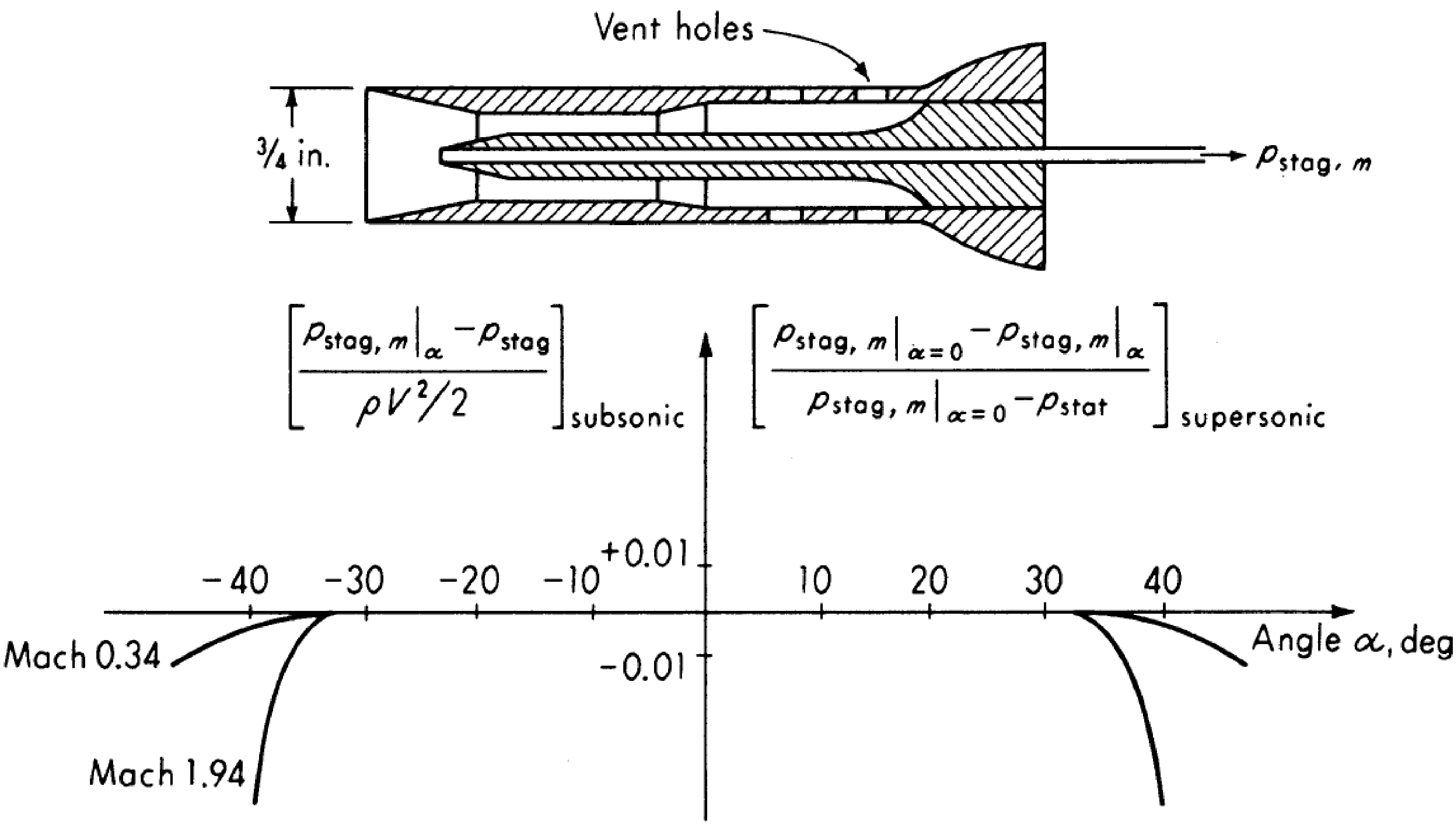
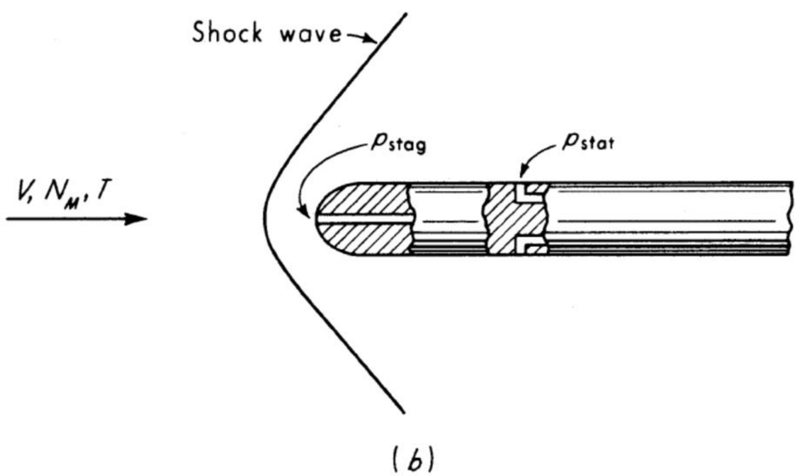


Fig. 7.6 *Special stagnation probe.*

Non-uniform flow

The probe of finite size intercepts the steam lines of different velocities and stagnation pressure measured corresponds to average velocity.



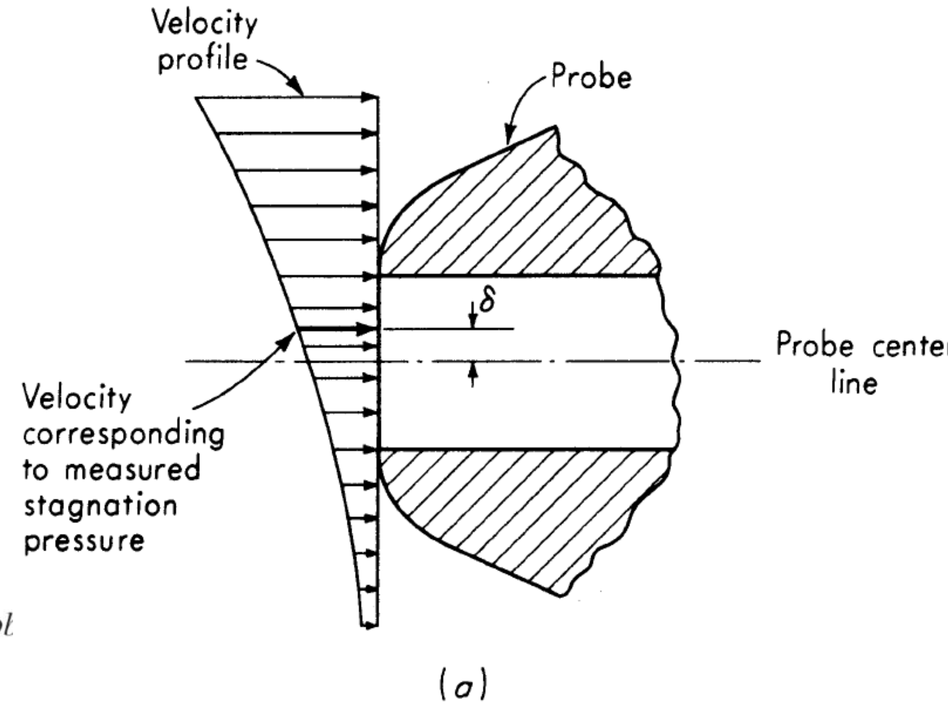
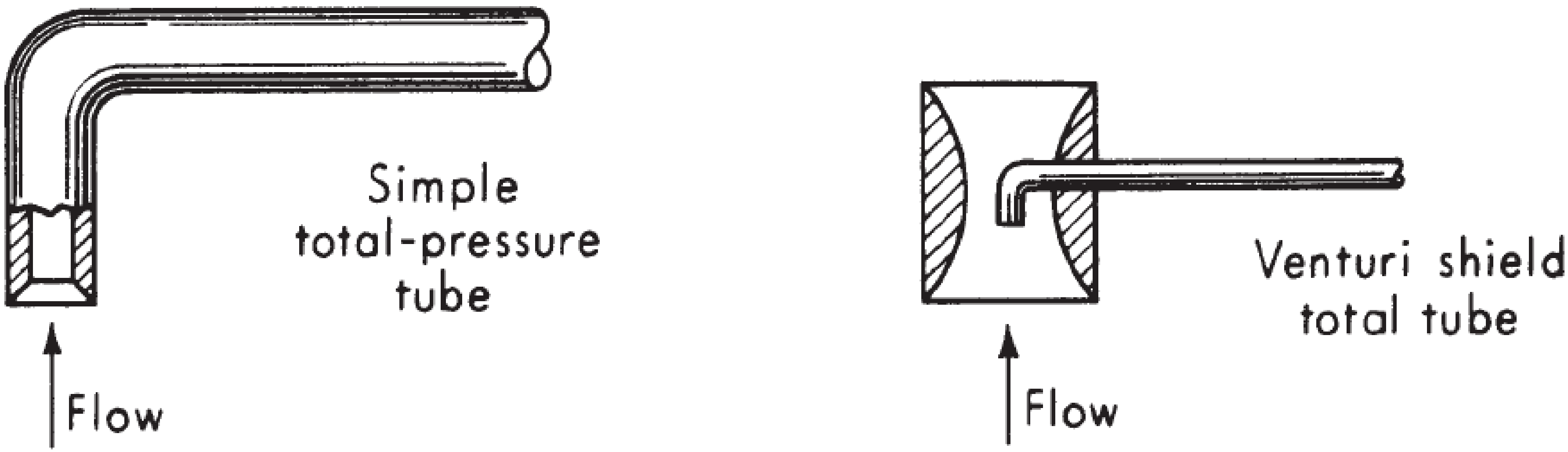


Fig. 7.7 *Nonuniform-velocity profile and supersonic prol*


Simple
total-pressure
tube
Flow
Venturi shield
total tube
Flow

(b) (c)

Nose forces streamlines to bend around it. So if the static holes are closer to the nose, the streamlines my not be parallel to the probe. The measured static pressure would be lesser by a fraction of the dynamic pressure

$$P_{s,measured} = P_{s,actual} - K_1\left(\tfrac{1}{2}\rho V^2 \right)$$

Stem stagnates the flow. So, if the static holes are near the stem, the effect of stagnation would reflect in the static pressure. The measured static pressure would be higher by a fraction of the dynamic pressure.

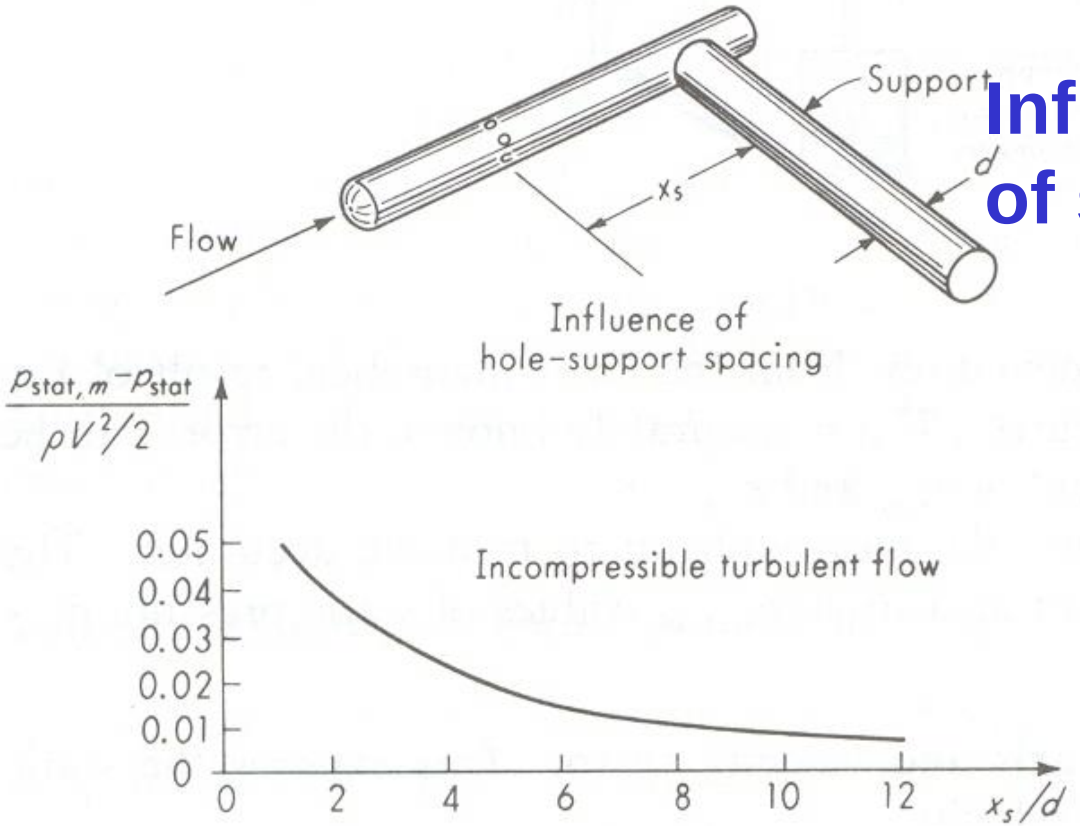
$$P_{s,measured} = P_{s,actual} + K_2\left(\tfrac{1}{2}\rho V^2 \right)$$

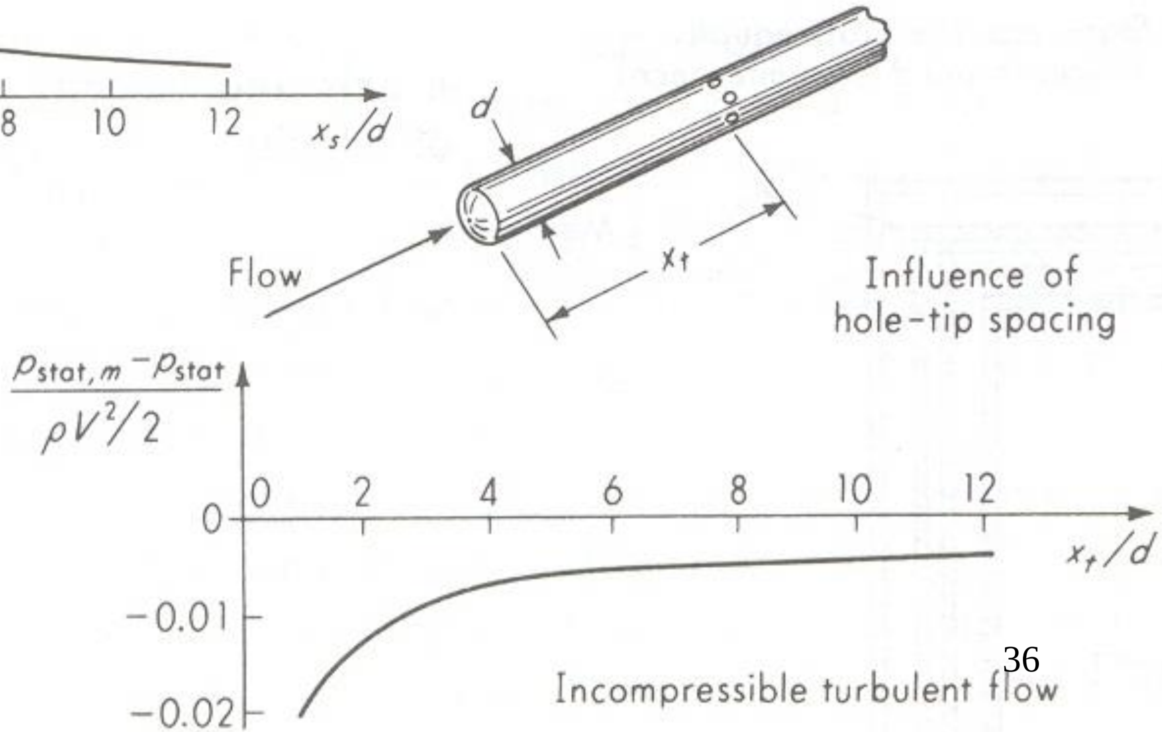
K_1 and K_2 are functions of the location of the static holes. If the location is such that $K_1 = K_2$, the effects of nose and stem would cancel each other.

The NPL (UK) standard for optimum dimension for hemispherical head (considering the outer diameter of probe as D) are:

- **Pitot hole dia ~ D/2**
- **Probe length ~ 14 D**
- **Distance of static holes from nose ~ 6D**
- **Stem height ~ 40 D**

Influences of position of static holes





Effect of Misalignment

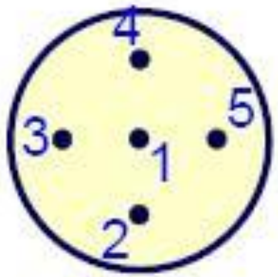
- If the Pitot head or static head is not accurately aligned with the direction o flow, it leads to error
- This is called Yaw sensitivity
- Pitot tubes are insensitive to quite large angles ~ 20^o

Yaw sensitivity of static and dynamic probes

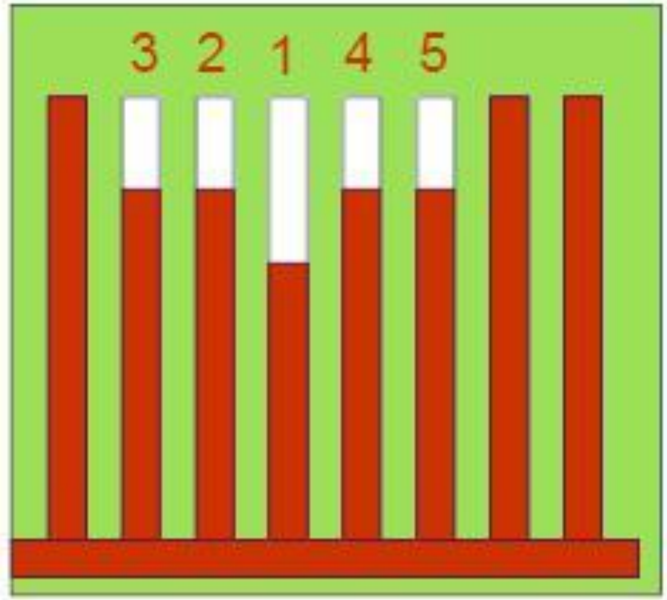
- **Static Probes: More sensitive to angular deviations than Pitot tubes**
- **Around 10% error at 25^o, < 5% at angles <15^o**
- **Pitot-static probes: depends on the type of head.**

  If alignment is uncertain at 25^o – 30^o, hemispherical nose is preferred.
- **Error incurred would be less than 5% to $\frac{1}{2}\rho V^2$**

Alignment probes



Schematic view of 5-hole probe facing the flow.



Multi-tube manometer

- Hole 1 is connected to 1, and so on. The probe is rotated until pressures 2 and 4, and 3 and 5 are equal. At this condition, probe 1 is parallel to the streamline, and hence aligned. So reading 1 gives the accurate pitot pressure.

Pressure measurement in supersonic flow

Shock stands in front of the probe. Since there is a finite total pressure loss across a shock, it has to be accounted for

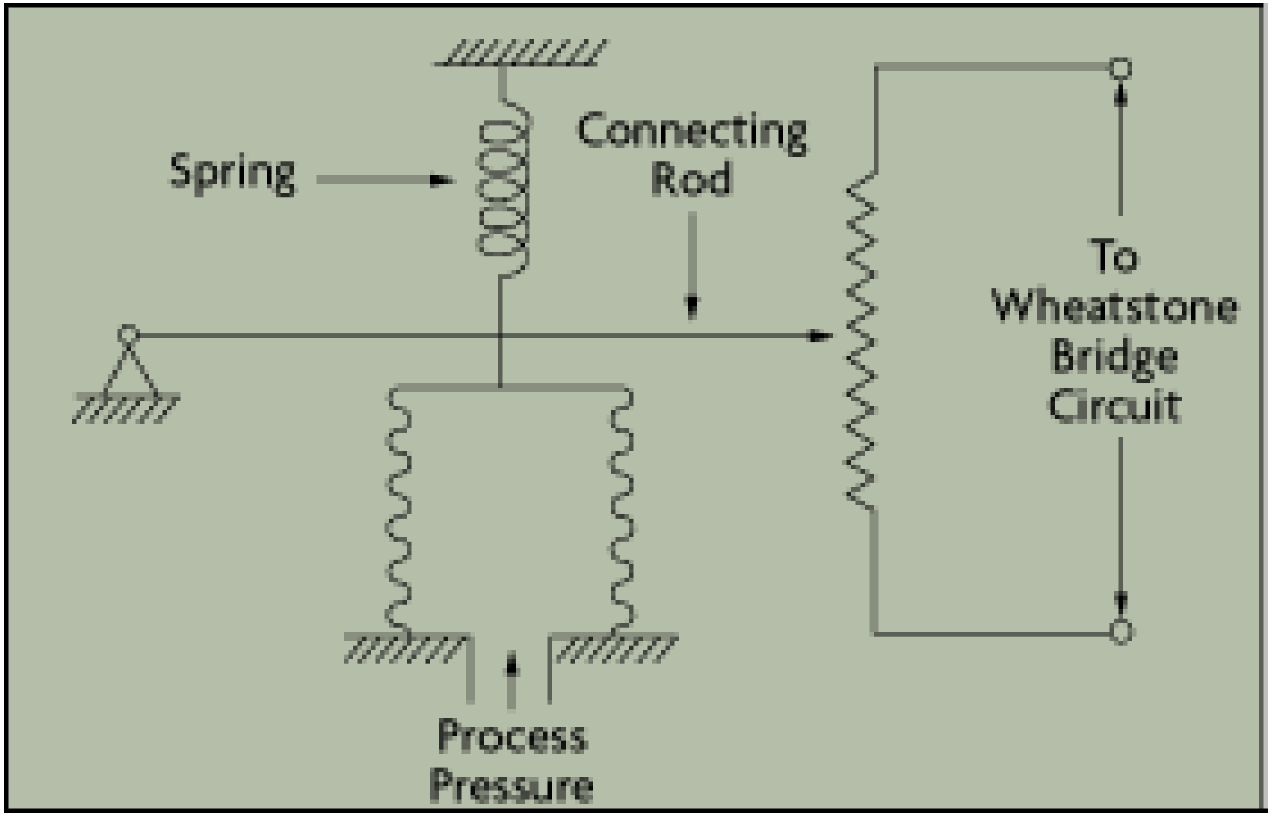
$$\frac{P_t}{P_{stat}} = M\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}}\left[\frac{2\gamma M-\gamma+1}{M^2(\gamma+1)}\right]^{1-\frac{1}{\gamma-1}}$$

$$M = \frac{V}{c};\ c = \sqrt{\gamma g R T}\ ;\ \gamma = \frac{C_p}{C_v}$$

Electro-Mechanical Sensors

Potentiometric Pressure Transducer

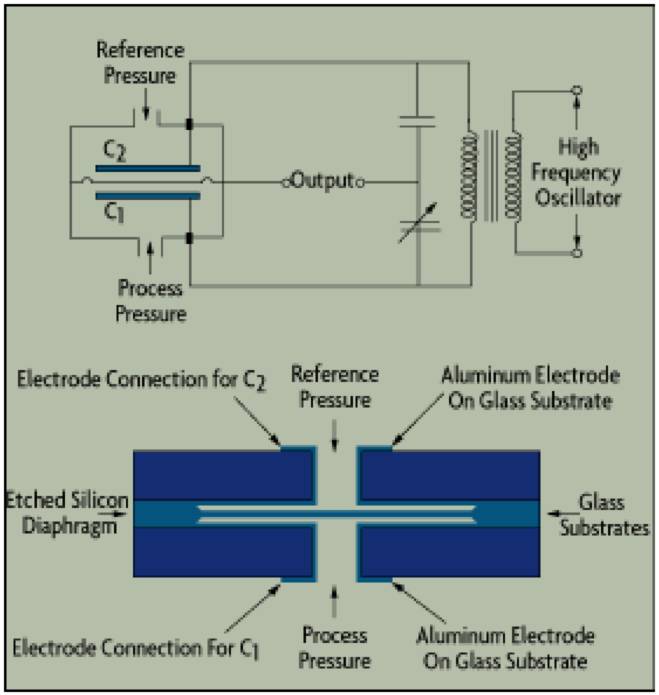
The device consists of a precision potentiometer, whose wiper arm is mechanically linked to a Bourdon or bellows element. The movement of the wiper arm across the potentiometer converts the mechanically detected sensor deflection into a resistance measurement, using a Wheatstone bridge circuit.



CAPACITANCE PRESSURE TRANSDUCERS

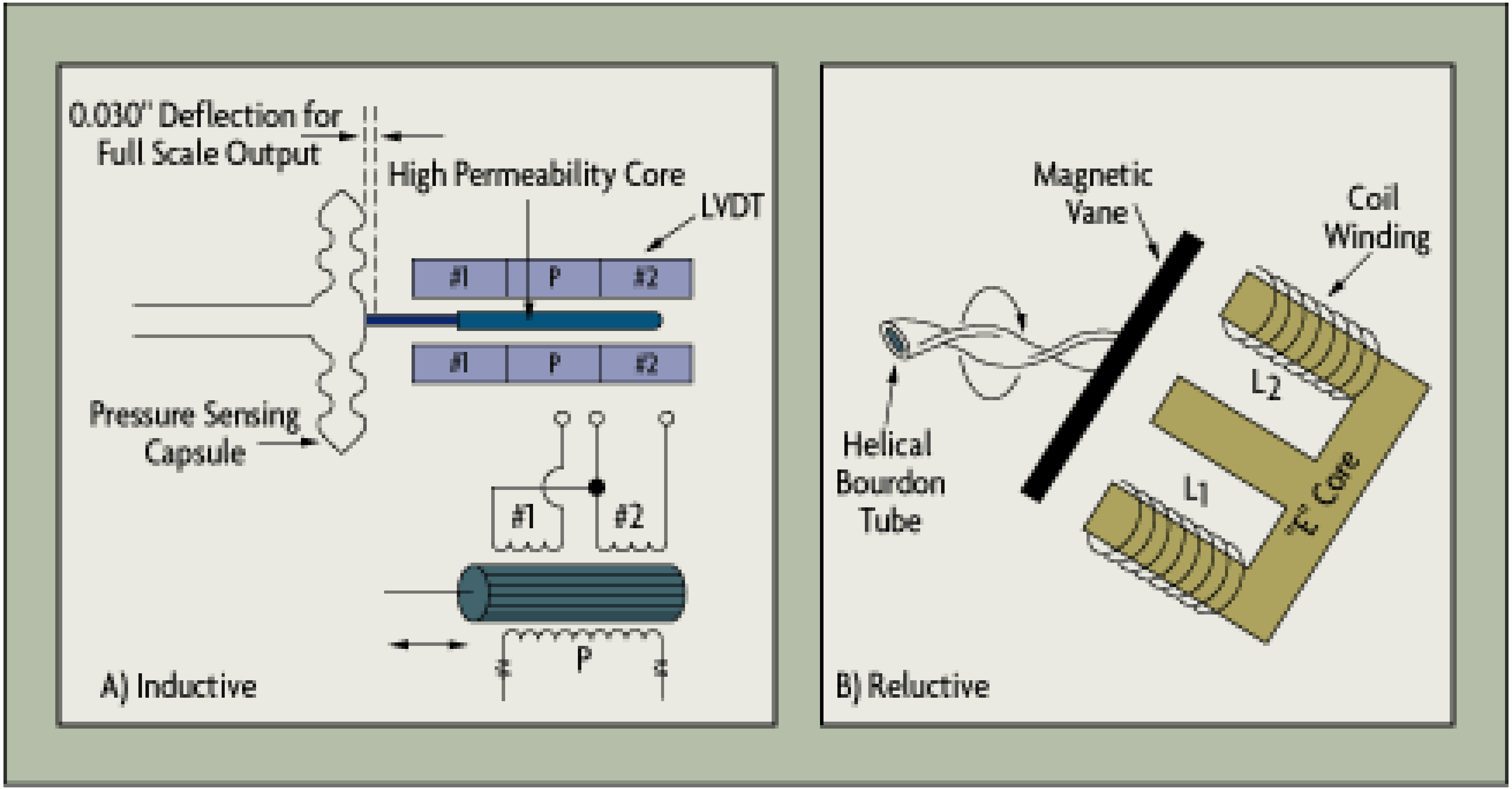
Capacitance change results from the movement of a diaphragm element. The diaphragm is usually metal or metal-coated quartz and is exposed to the process pressure on one side and to the reference pressure on the other. Depending on the type of pressure, the capacitive transducer can be either an absolute, gauge, or differential pressure transducer..

The deflection of the diaphragm causes a change in capacitance that is detected by a bridge circuit.



Capacitance pressure transducers are having wide operating ranges from high vacuums in the micron range to 10,000 psig (70 MPa). Differential pressures as low as 0.25 mm (0.01 inches) of water can readily be measured.

ELECTRO MAGNETIC SENSORS

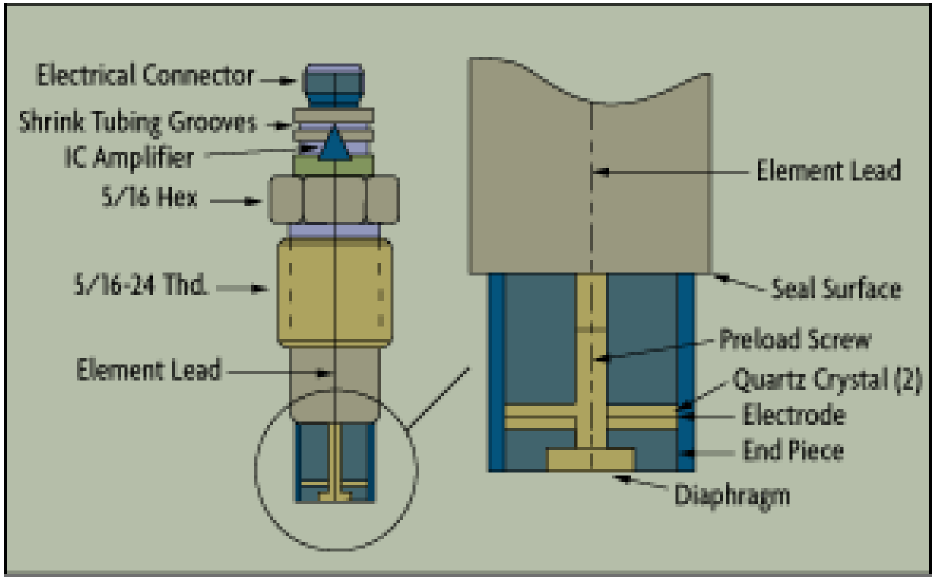


In these sensors, a change in pressure produces a movement, which in turn changes the inductance or reluctance of an electric circuit.

PIEZOELECTRIC SENSORS

- **When pressure, force or acceleration is applied to a quartz crystal, a charge is developed across the crystal that is proportional to the force applied.**

- **When pressure is applied to a crystal, it is elastically deformed. This deformation results in a flow of electric charge (which lasts for a period of a few seconds).**



➢ **The fundamental difference between these crystal sensors and static-force devices such as strain gauges is that the electric signal generated by the crystal decays rapidly. This characteristic makes these sensors unsuitable for the measurement of static forces or pressures but useful for dynamic measurements.**

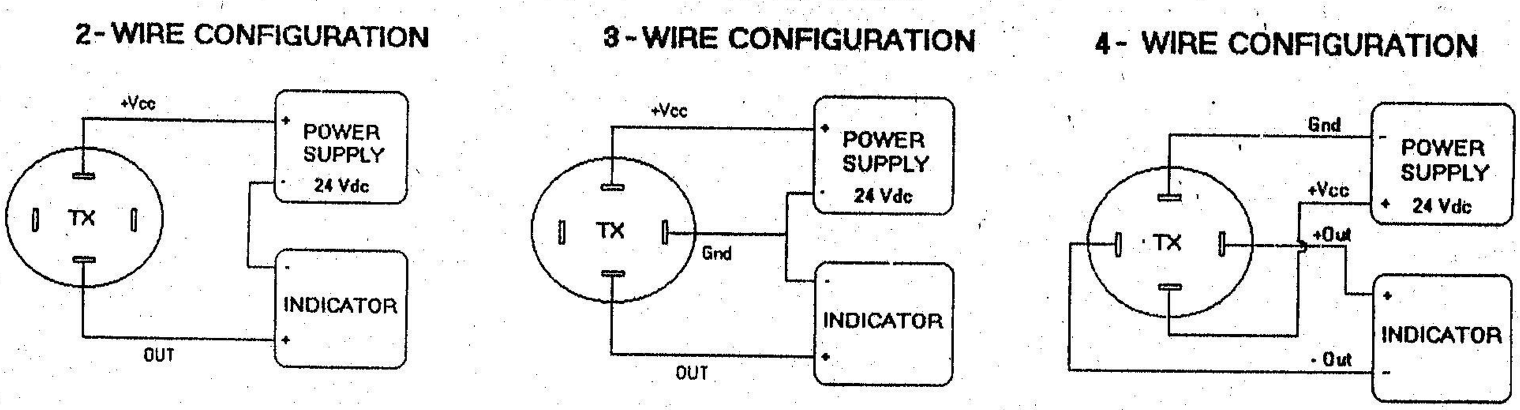
PIEZO RESISTIVE PRESSURE TRANSDUCERS

Electrical wiring diagram of peizo resistive type pressure transducers

WIRING DETAILS

NO. OF WIRES	2 – WIRE	3 – WIRE	4 – WIRE
SIGNAL OUTPUT	4 – 20 mA	0.5 – 4.5 V	0 – 100 mV
EXCITATION	8 – 28 Vdc	4.75 – 5.25 Vdc	5 – 15 Vdc

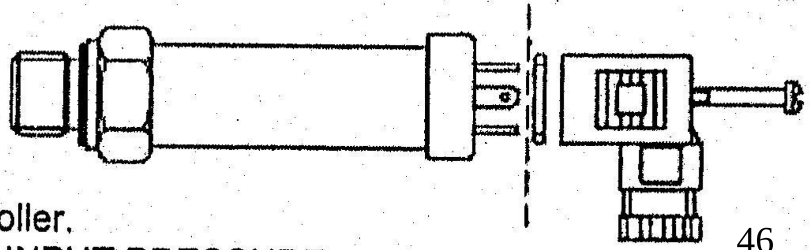
NOTE : PLEASE SEE THE PIN NUMBERS ON THE TRANSMITTER LABEL.

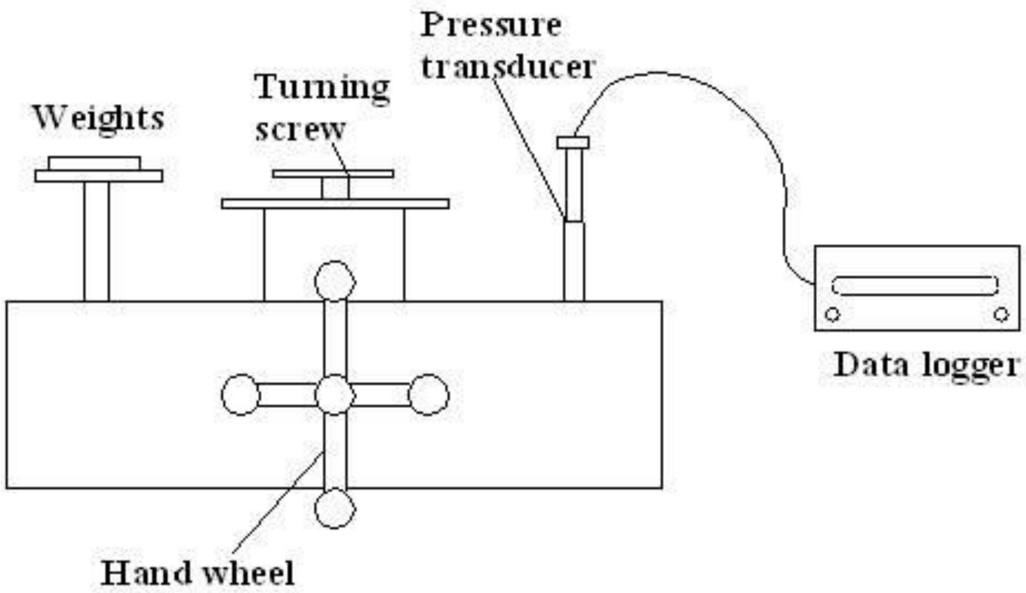


TROUBLE SHOOTING

1. NO OUTPUT AT THE OUTPUT PIN
   - Check the wiring configuration.
   - Check the input + Vcc supply.
2. NO VARIATION IN THE OUTPUT
   - Check for the leakage at pressure port.
   - Check for the span set of indicator / controller.
3. PRESSURE NOT HOLDING AT CONSTANT INPUT PRESSURE

Check for the leakage at pressure port.



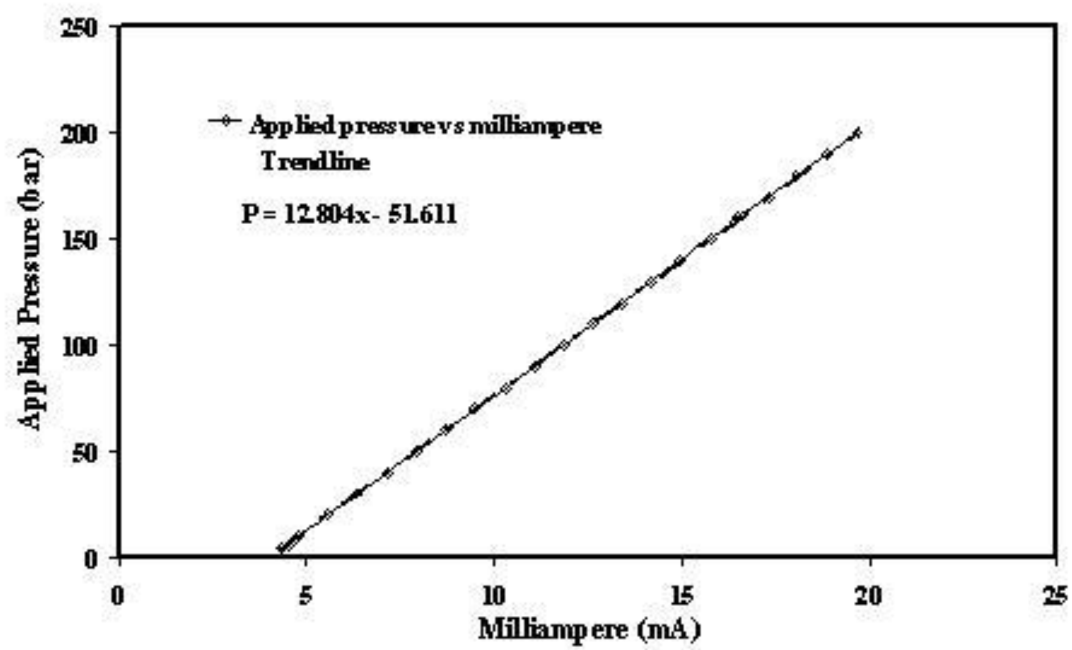


Pressure transducer calibration

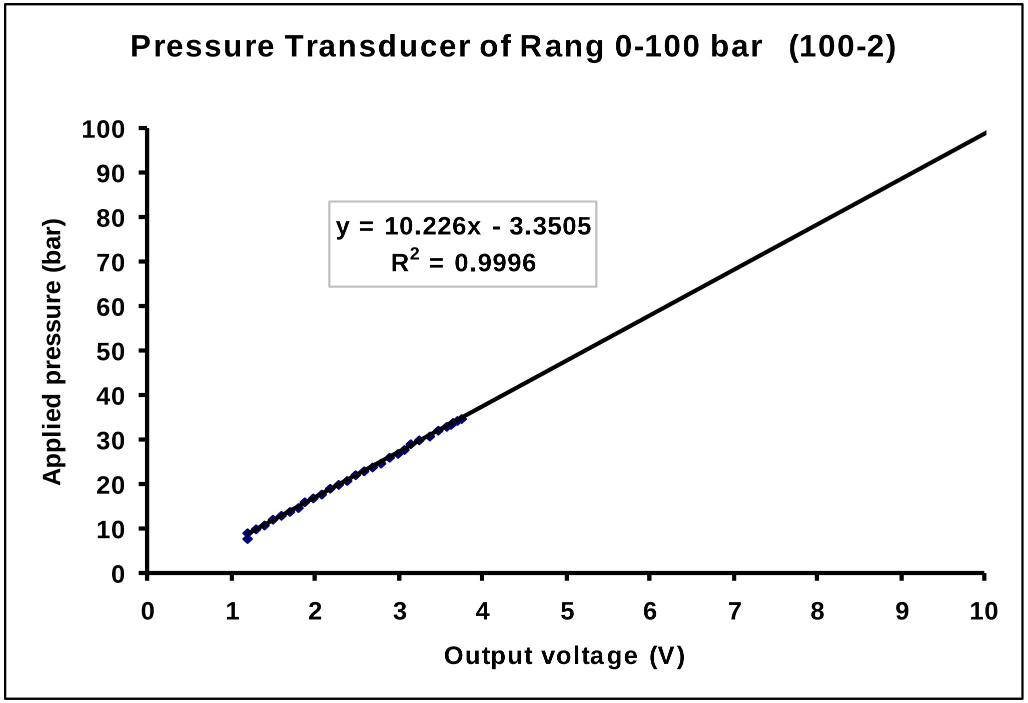
Make : Keller, Swiss

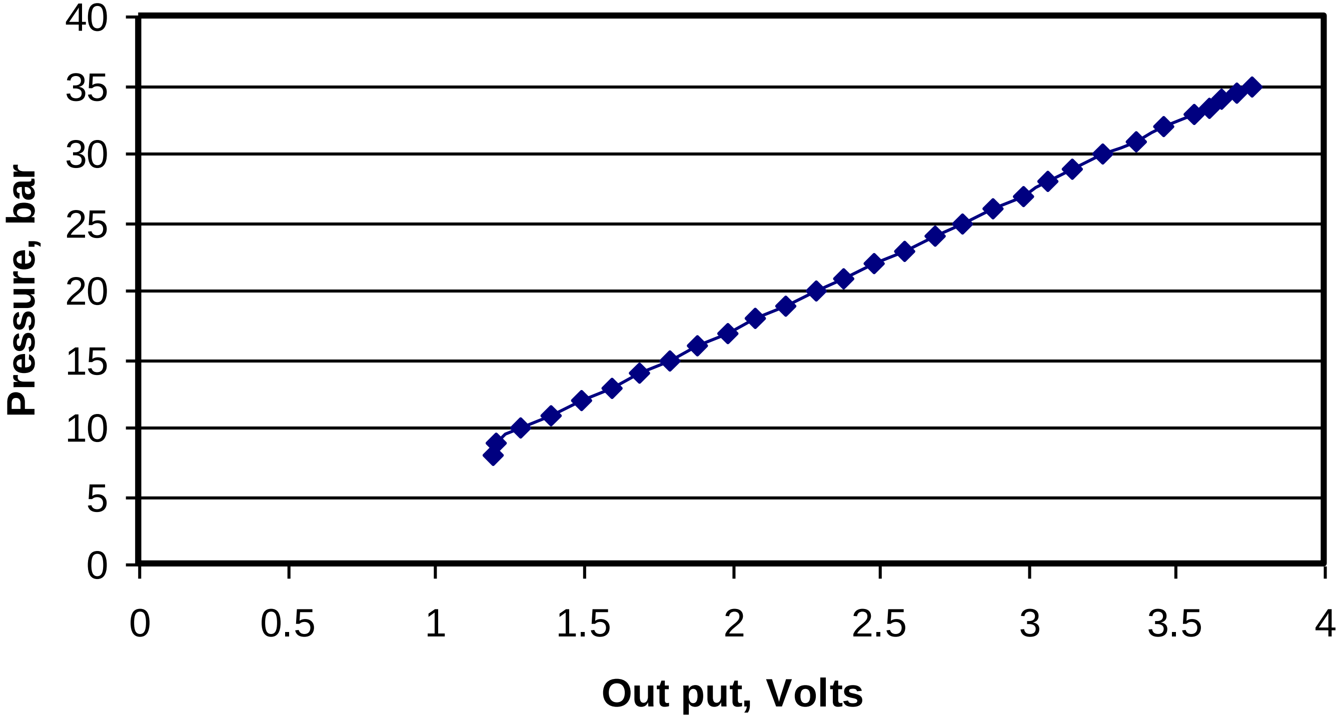
Model : 21 SC

Range 0 - 200 bar



mA	Atual value	Measu. value
4	0	-0.395
8	50	50.821
12	100	102.037
16	150	153.25
20	200	204.469





Threshold Error between (0-10 bar)

Measurement of High Pressure (above 700 bar)

Resistances of fine wires changes with the application of pressure.

$R = Ro(1+b\,\Delta p)$ Where Ro is the reference resistance

Δp is the gauge pressure

b calibration coefficient

Fine wire of Manganin (84 % Cu, 12% Mn, 4% Ni)

$b = 2.5 \times 10^{-11}\ pa^{-1}$

Bulk compression effect changes the resistance of the wire

High Accuracy about $\pm 0.1\%$

High response and effectively used up to about 100,000 bar

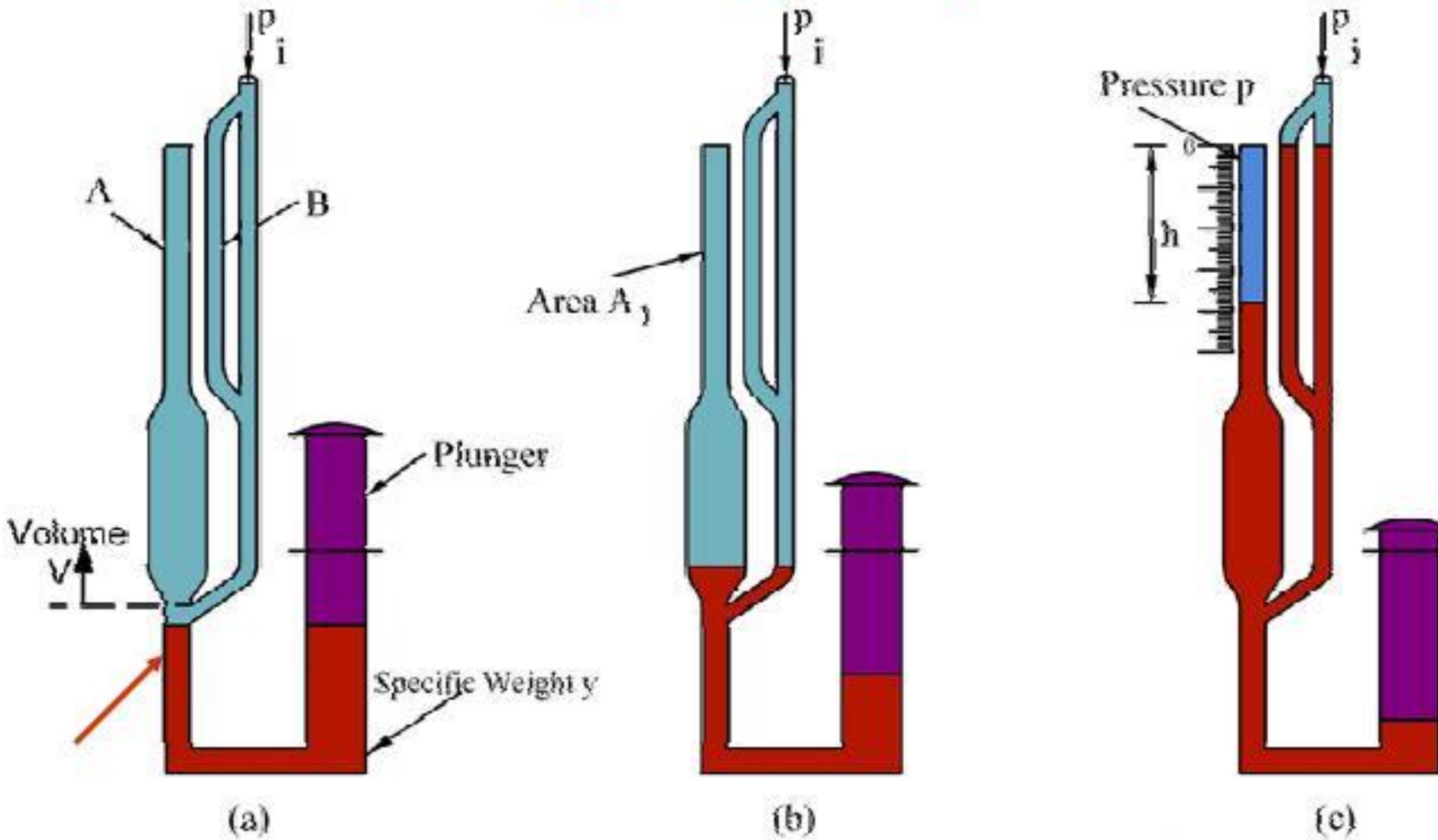
Low Pressure (Vacuum) Measurement

- Units of vacuum: torr, micrometer
- One torr is a pressure equivalent to 1 mm Hg
- One micrometer is 10^{-3} torr
- Manometers and bellows gauge to 0.1 torr, Bourdon gauges to 10 torr, diaphragm gauges to 10^{-3} torr

McLeod gauge

- Vacuum standard
  - useful above about 10^{-4} torr
- The principle of McLeod gauge is the compression of a sample of the low-pressure gas to a pressure sufficiently high to read with a simple manometer
- Boyle's law used

McLeod gauge operation



a. gas admitted

b. Port sealed, compression starts

c. Gas compressed, values read.

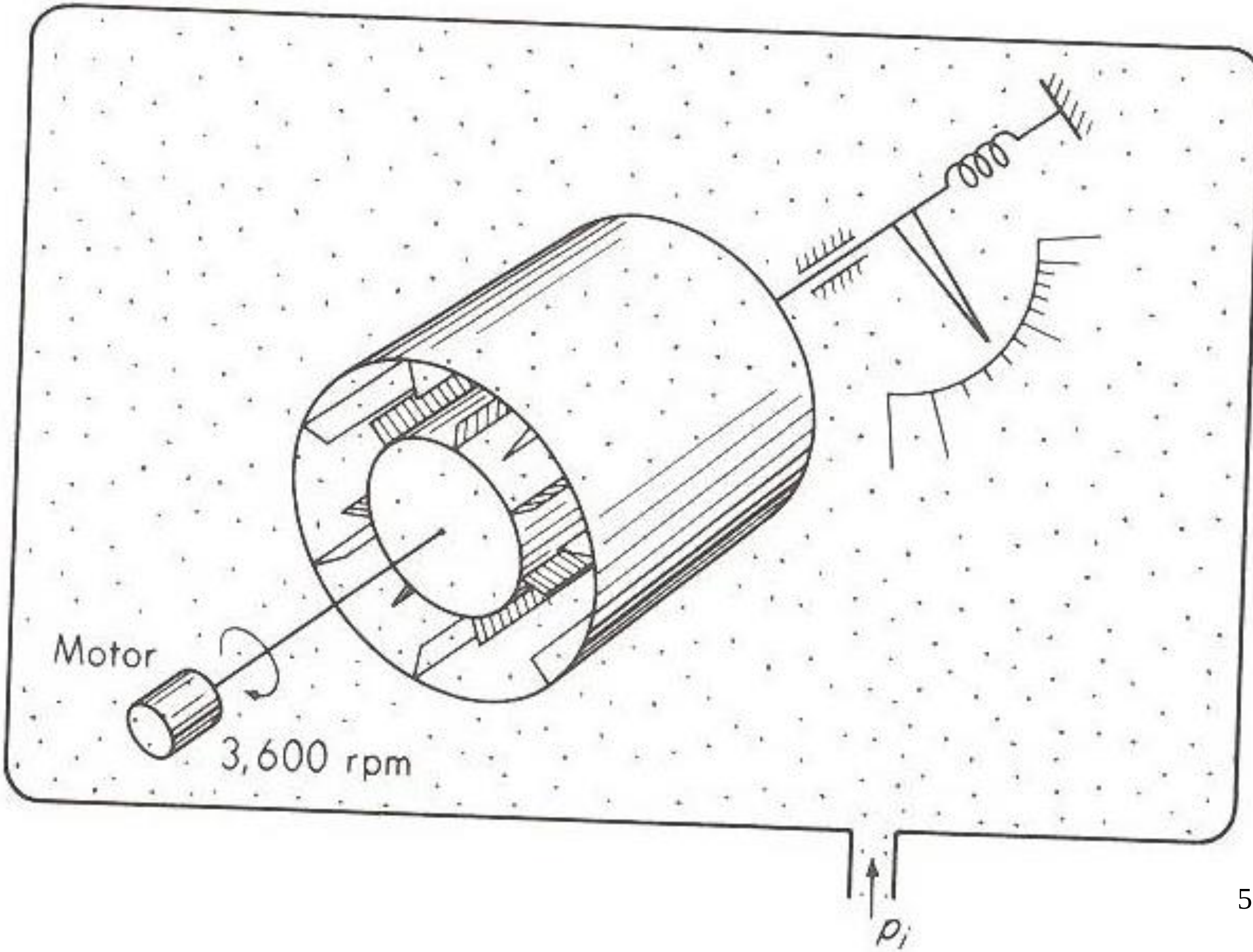
McLeod gauge operation

- Plunger withdrawn, mercury level is lowered admitting the gas at unknown pressure.
- Plunger is pushed. Mercury level goes up, sealing off a gas sample of known volume *V* in the bulb and capillary tube *A*.
- Further motion of the plunger causes compression of this sample. Mercury level noted.
- The unknown pressure is then calculated using Boyle's Law

Momentum gauge

- For pressures less than about 10^{-2} torr, viscosity of a gas directly proportional to the pressure
- Viscosity measured in terms of torque required to rotate a concentric cylinder within another
- For pressures greater than 1 torr, the viscosity is independent of pressure
- upto 10^{-7} torr

MOMENTUM GAUGE



PIRANI GAUGE

In this design, a sensor wire is heated electrically and the pressure of the gas is determined by measuring the current needed to keep the wire at a constant temperature.

The thermal conductivity of each gas is different, so the gauge has to be calibrated for the individual gas being measured. A Pirani gauge will not work to detect pressures above 1.0 torr, because, above these pressures, the thermal conductivity of the gases no longer changes with pressure.

The Pirani gauge is linear in the 10^{-2} to 10^{-4} torr range. Above these pressures, output is roughly logarithmic. Pirani gauges are inexpensive, convenient, and reasonably accurate. They are 2% accurate at the calibration point and 10% accurate over the operating range.

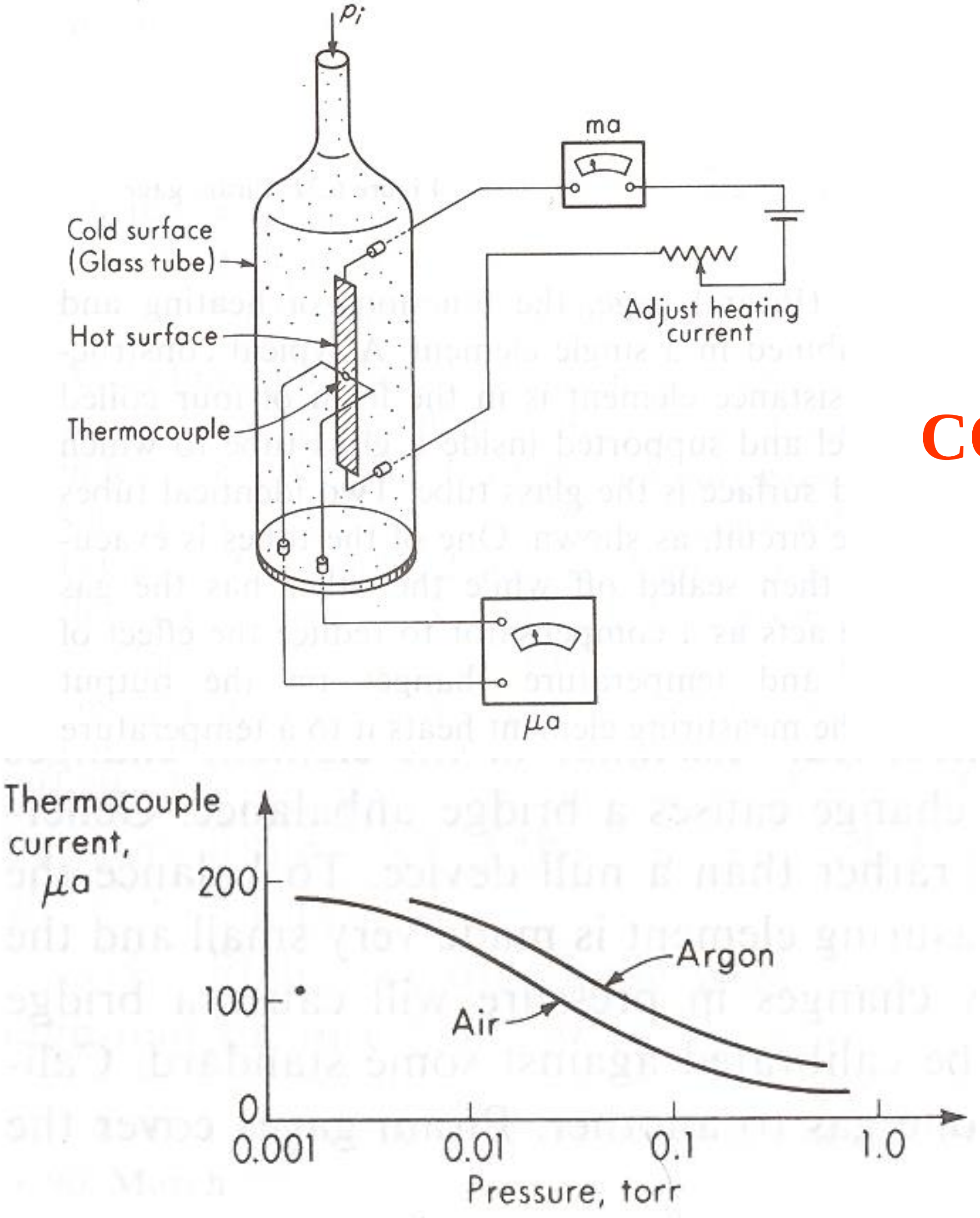
PIRANI GAUGE

THERMOCOUPLE/ THERMAL CONDUCTIVITY GAUGES

- **The thermocouple gauge relates the temperature of a filament in the process gas to its vacuum pressure. The filament is heated by a constant current of 20-200 mA dc, and the thermocouple generates an output of about 20 mV dc. The heater wire temperature increases as pressure is reduced.**

- **Typical thermocouple gauges measure 1 millitorr to 2 torr. This range can be increased by use of a gauge controller with a digital/analog converter and digital processing.**

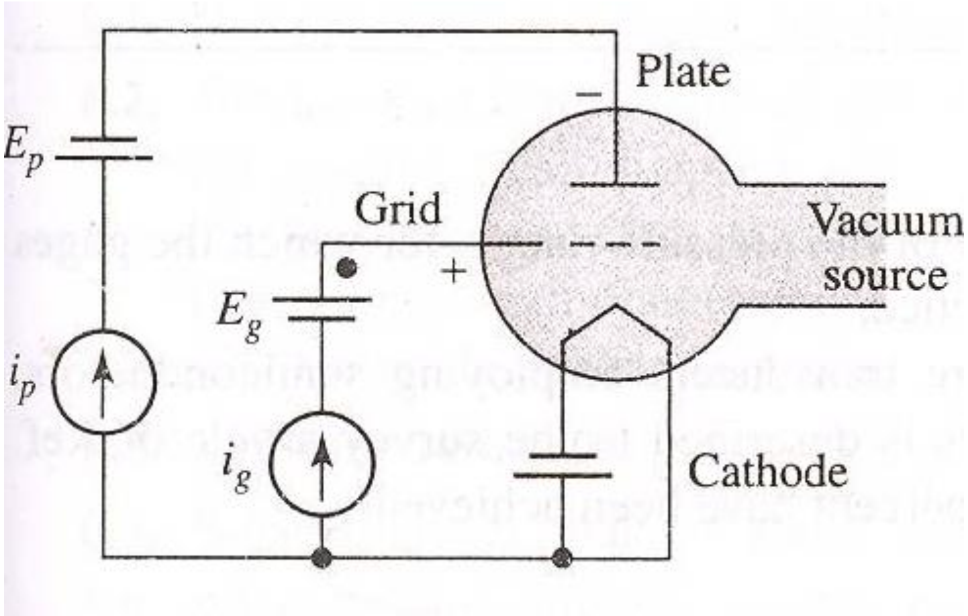
- **Using an industry standard thermocouple sensor, such a gauge controller can extend the range of a thermocouple sensor to cover from 10^{-3} to 1,000 torr, thereby giving it the same range as a convection-type Pirani gauge but at a lower price.**



THERMAL CONDUCTIVITY GAUGE

PENNING GAUGES / IONIZATION GAUGE

Range 10^{-10} to 1 torr

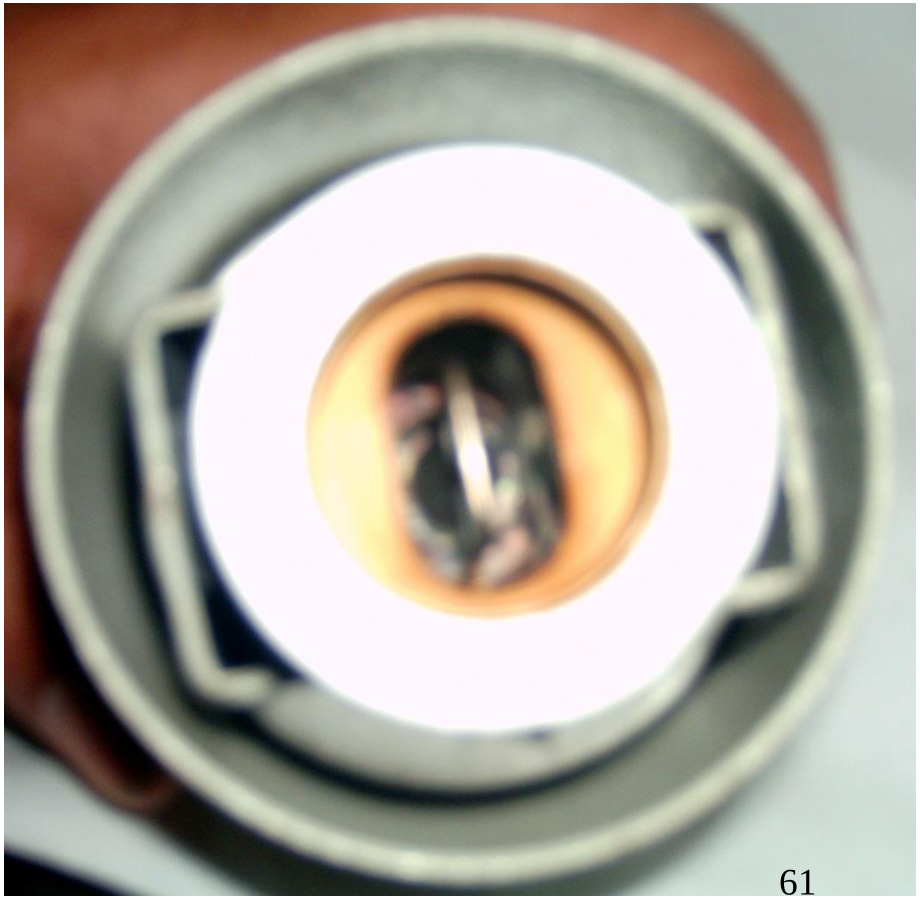


- **A heated cathode emits electrons, which are accelerated by the positively charged grid.**
- **As the electrons moves toward the grid, they ionize the gas molecules by collisions.**
- **A plate which is maintained negative potential collects the positively charged ions, producing the plate current i_p**
- **The electrons and negative ions are collected by the grid, producing the grid current i_g.**
- **Hence, the pressure of the gas** $P = i_p/(S\ i_g)$; $S = 2.7\ kpa^{-1}$ for N_2

PENNING GAUGES / IONIZATION GAUGE

They measure vacuum by making use of the current carried by ions formed in the gas by the impact of electrons.

Range 10^{-10} to 1 torr



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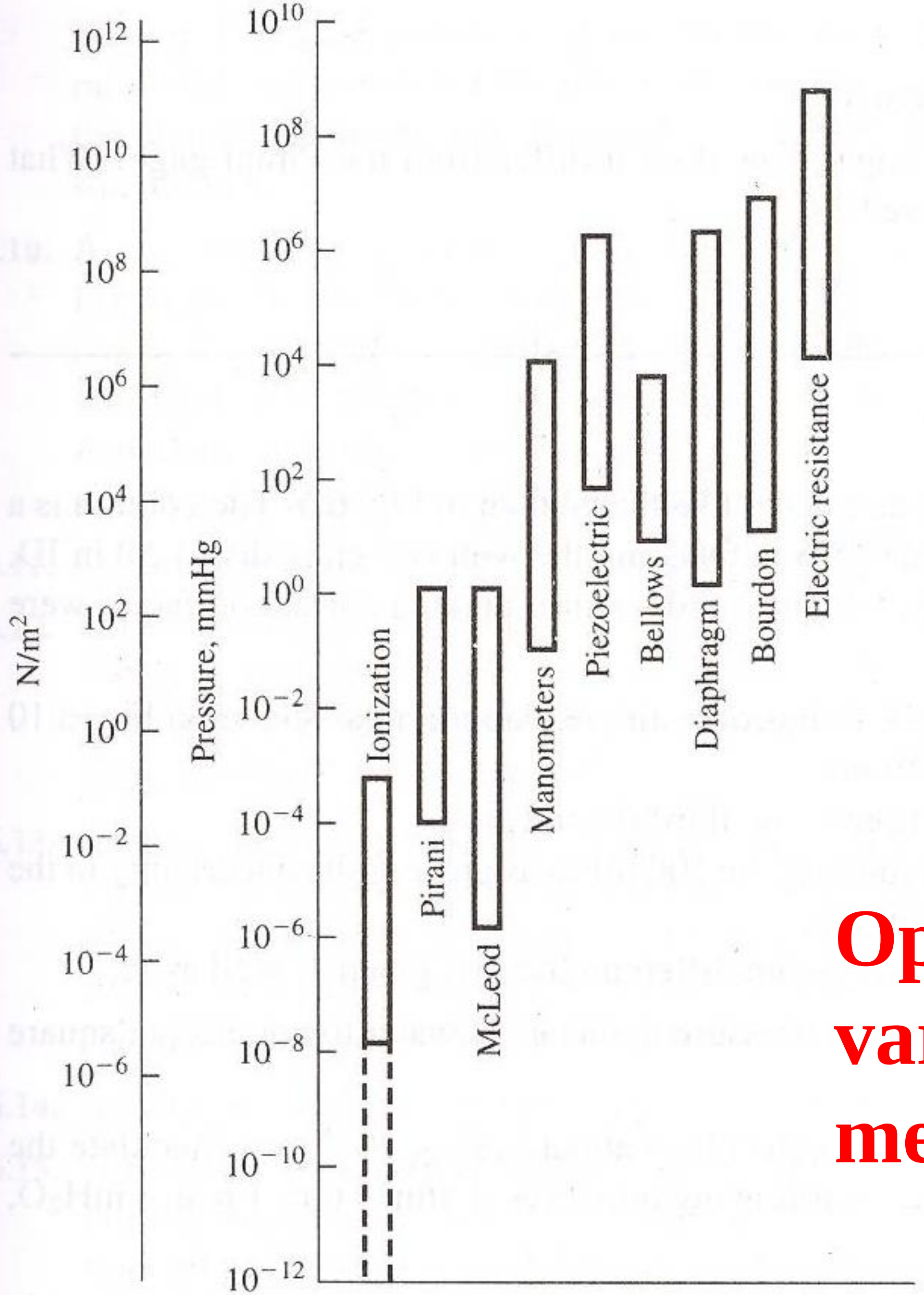

Operating ranges of various pressure measuring instruments