5. Pressure and Sound Sensors

- Pressure is not a fundamental quantity, but derived from force and area, which in turn derived from mass, length, and time.
- 1 Pa = 1 N/m^2 1 bar = 10^5 Pa 1 atm = 101325 Pa (Phys, Hg)
- 1 atm = 98066.5 Pa (Techn, H_2O) 1 Torr = 1 mm Hg = 133.322 Pa 1 psi = 6,894.76 Pa
- ρ of Hg = 13550 Kg/m^3, 1 atm = 760 mm at 20°C
- ρ of H_2O = 1000 Kg/m^3, 1 atm = 10 m at 20°C

5.1 Basic Methods of Pressure Measurement

- Pressure usually can be transduced to force by allowing it to act on a known area, the basic methods of measuring force and pressure are essentially the same.
- Except for the near vacuum region where a variety of special methods are necessary.
- Most pressure measurement is based on comparison with known deadweights acting on known areas or on the deflection of elastic elements subjected to the unknown pressure.

5.2 Deadweight Gages and Manometers

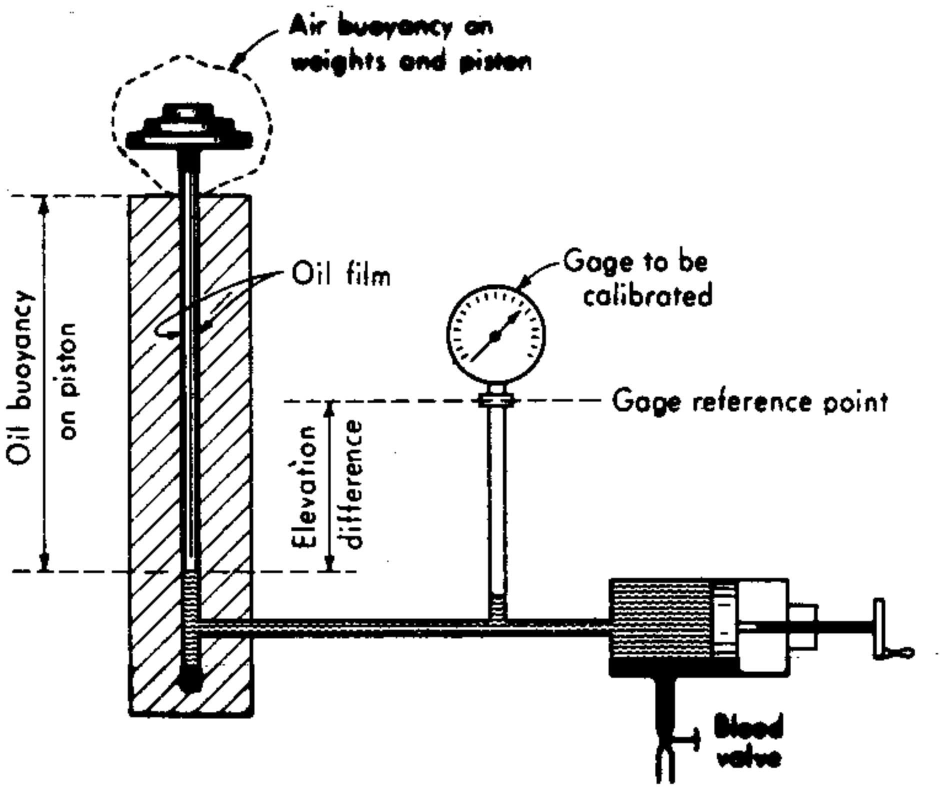


Figure 5.2-1 Deadweight Gage Calibrator

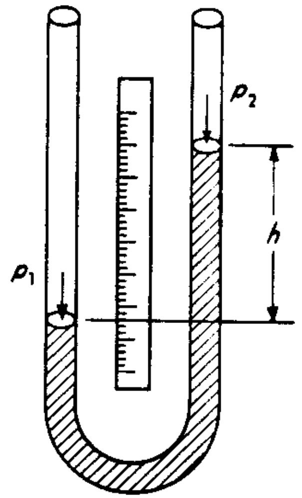


Figure 5.2-2 U-Tube Manometer

$$h = \frac{p_1 - p_2}{\rho g} \qquad (5.2\text{-}1)$$

where g = local gravity and ρ = mass density of manometer fluid.

- If p_2 is atmospheric pressure, then h is a direct measure of p_1 as a gage pressure.

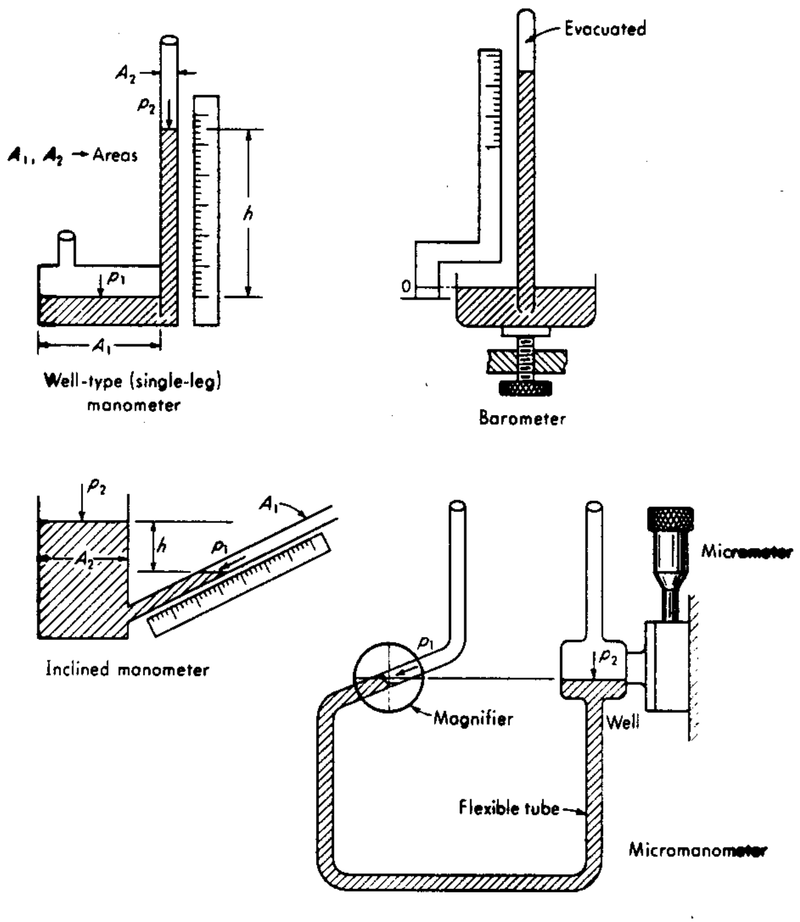


Figure 5.2-3 Various Forms of Manometers

- The well area is made very large compared with the tube; thus the zero level moves very little when pressure is applied.
- In barometer, one end is at zero absolute pressure, then h is an indication of absolute pressure.
- To increase sensitivity, the manometer may be tilted with respect to gravity, thus giving a greater motion of liquid along the tube for a given vertical-height change. $h = L\sin\theta$
- In micromanometer, the instrument is initially adjusted so that when $p_1 = p_2$, the meniscus in the inclined tube is located at a reference point given by a fixed hairline viewed through a magnifier. Application of the unknown pressure difference causes the meniscus to move off the hairline, but it can be restored to its initial position by raising or lowering the well with the micrometer. The difference in initial and final micrometer readings gives the height change h and thus the pressure.
- The sonar manometer employs a piezoelectric transducer at the bottom of each glass tube to launch ultrasonic pulses, which travel up through the mercury columns, are reflected at the meniscus, and return to the bottom to be received by the transducers. The pulse from the shorter column turns on a digital counter, while that from the longer one turns it off. Thus a digital reading is obtained that is proportional to the difference in column height and thus to pressure.

5.3 Elastic Transducers

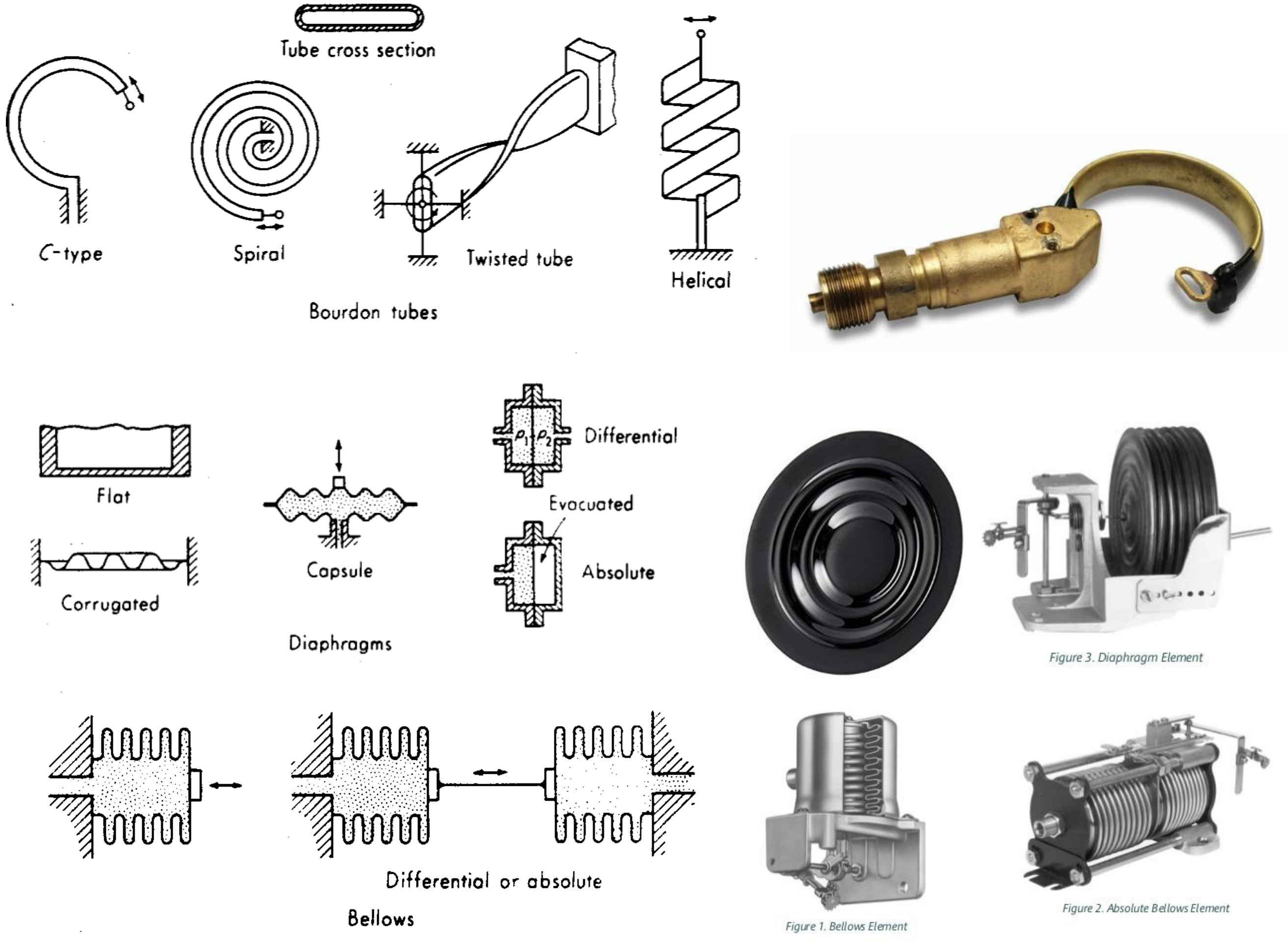


Figure 5.3-1 Elastic Pressure Transducers

- A pressure difference between the inside and outside of the **Bourdon tube**, with noncircular cross section, (higher pressure inside) causes the tube to attempt to attain a circular cross section. This results in distortions which lead to a curvilinear translation of the free end in the C type and spiral and helical types and a rotation in the twisted type, which motions are the output.
- Applied pressure causes displacement of the **diaphragm** and this movement is measured by a displacement transducer. In the case of differential pressure, the two pressures are applied to either side of the diaphragm and the displacement of the diaphragm corresponds to the pressure difference.
- The **bellow** is a device, which operates on a very similar principle to the diaphragm. Pressure changes within the bellow produce translational motion of the end of the bellow.
- The gross deflection of these elements may directly actuate a pointer/scale readout through suitable linkages or gears, or the motion may be transduced to an electrical signal by one means or another. Strain gages bonded directly to diaphragms or to diaphragm-actuated beams are widely used to measure local strains that are directly related to pressure.
- These devices are mostly made from stainless steel or brass. Copper is used in low pressure, 0-1000 Pa.

5.4 Force-Balance Transducers

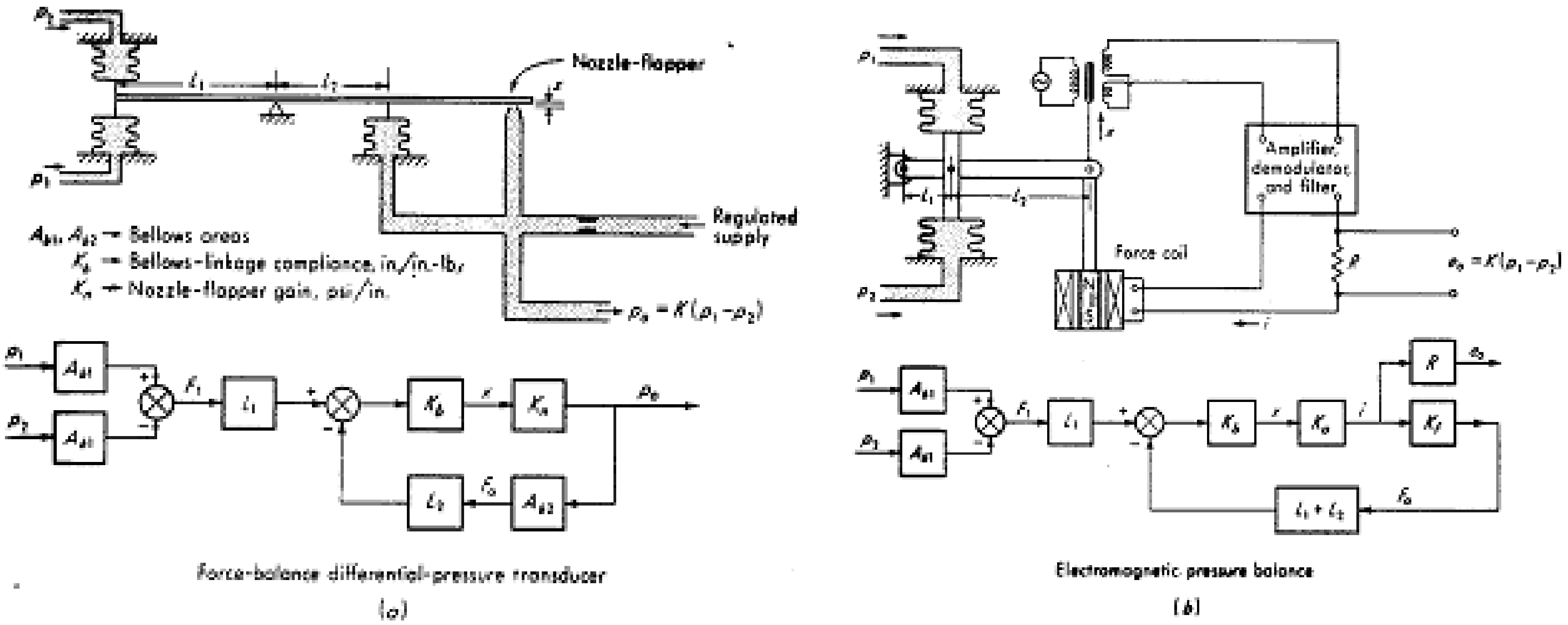


Figure 5.4-1 Null-Balance Pressure Sensors

5.5 Resonant-Wire Devices

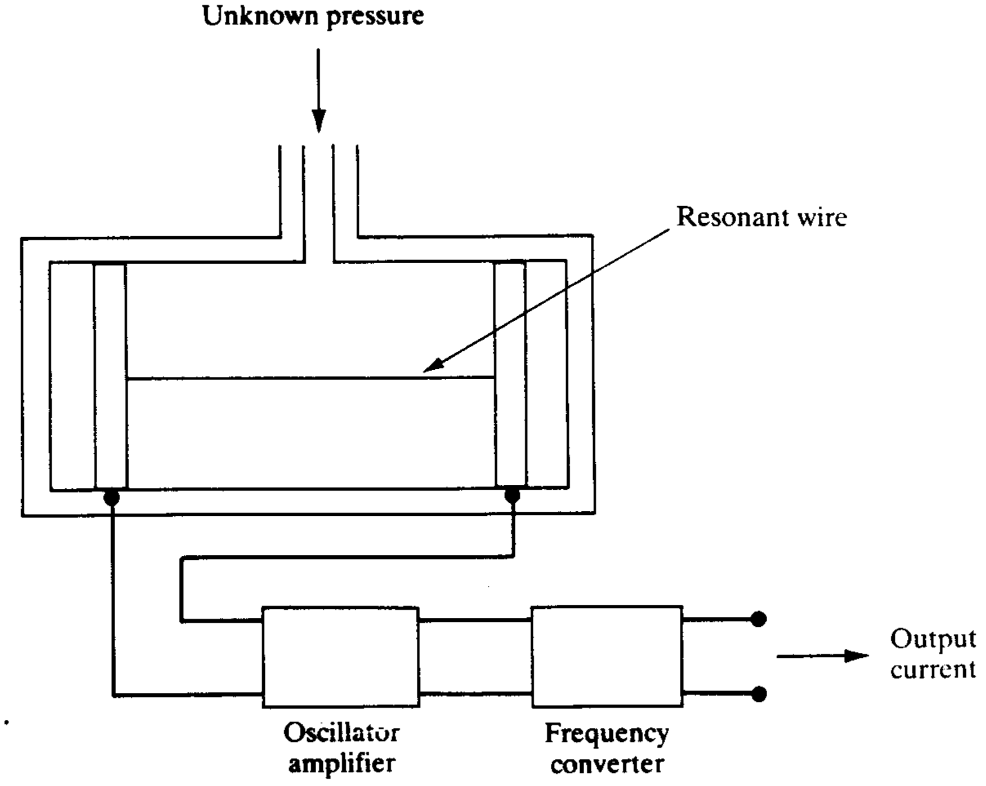


Figure 5.5-1 Resonant-Wire Device

5.6 High-Pressure Measurement

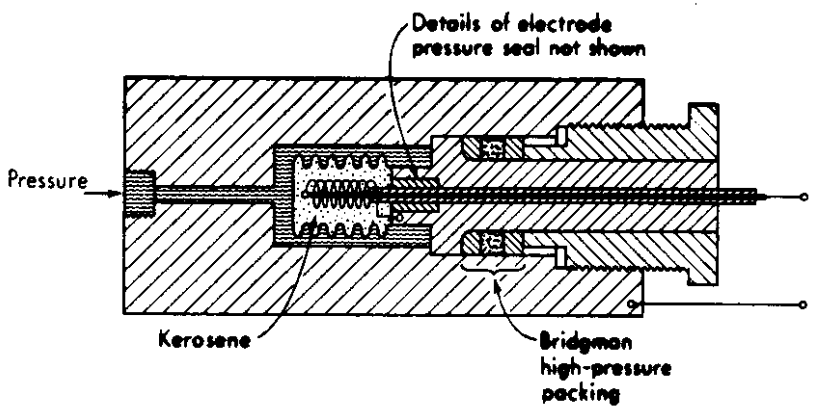


Figure 5.6-1 Very-High-Pressure-Transducer

- For high-pressures fluid, electrical gages based on the resistance change of Manganese or gold-chrome wire with hydrostatic pressure are generally utilized.
- The coil is enclosed in a flexible, kerosene-filled bellows, which transmits the measured pressure to the coil.
- The resistance change, which is linear with pressure, is sensed by conventional Wheatstone-bridge methods.

5.7 Low-Pressure (Vacuum) Measurement

5.7.1 McLeod Gage

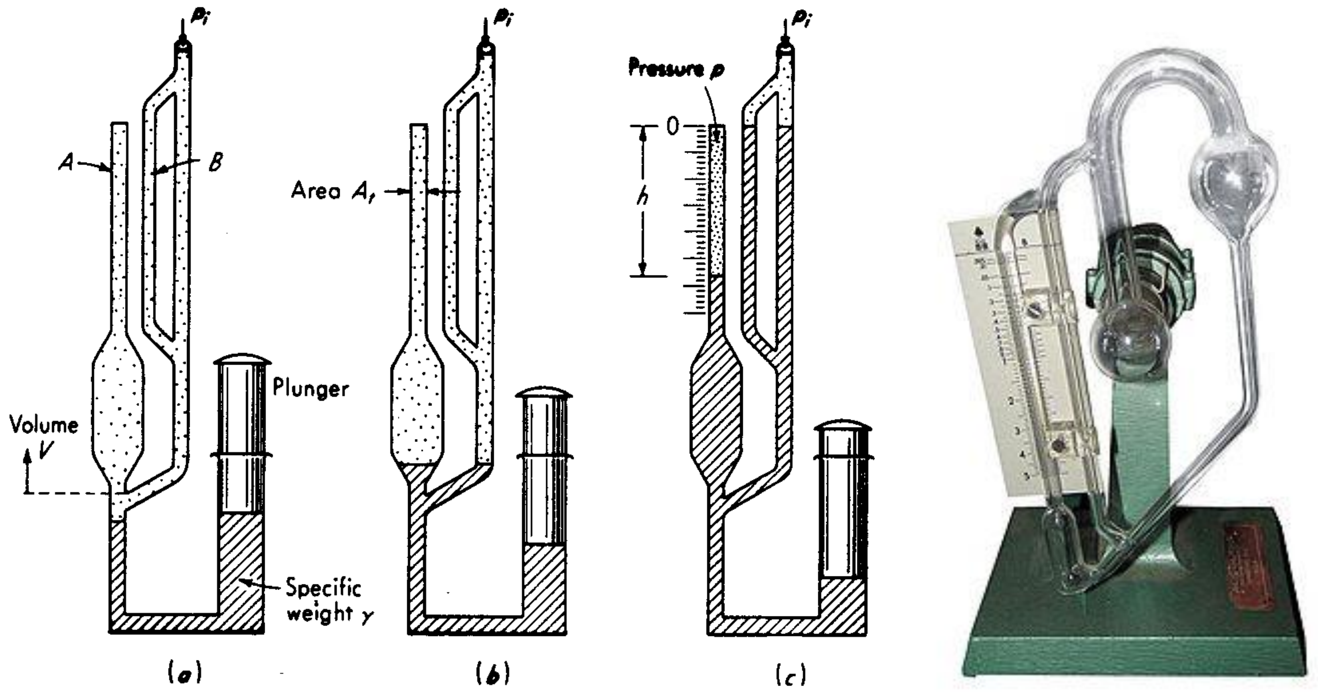


Figure 5.7.1-1 McLeod Gage

By using Boyle's law, $pV = nRT$, gas in a closed volume with constant temperature,

$$p_i V = p A_t h \tag{5.7.1-1}$$

$$p = p_i + \rho g h \tag{5.7.1-2}$$

ρ : the mass density of mercury.

$$p_i = \frac{A_t h^2 \rho g}{V - A_t h} \tag{5.7.1-3}$$

If the compressed volume, $A_t h$, is very much smaller than the original volume,

$$p_i \approx \frac{A_t h^2 \rho g}{V} \tag{5.7.1-4}$$

5.7.2 Knudsen Gage

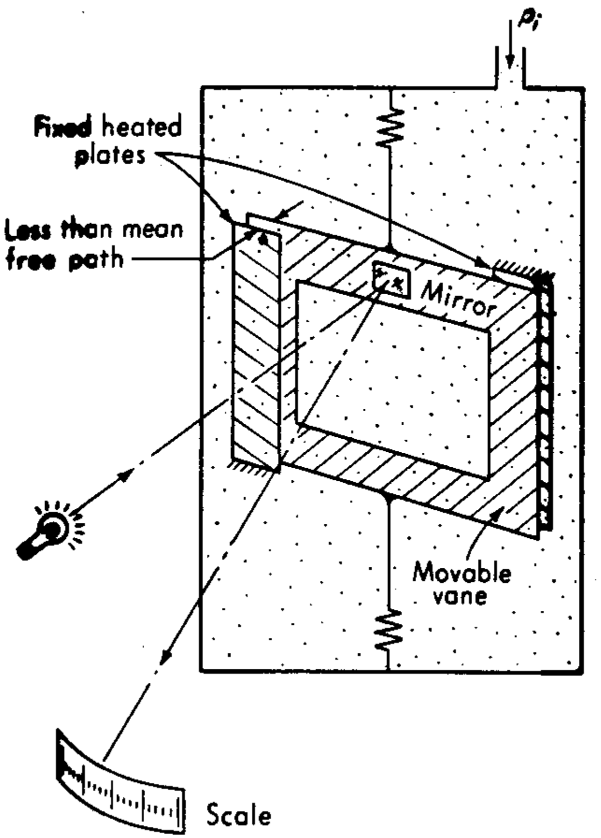


Figure 5.7.2-1 Knudsen Gage

- The unknown pressure p_i is admitted to a chamber containing fixed plates heated to absolute temperature T_f, and a spring-restrained movable vane with temperature T_v.
- The spacing between the fixed and movable plates must be less than the mean free path of the gas.
- The kinetic theory of gases shows that gas molecules rebound from the heated plates with greater momentum than from the cooler movable vane, thus giving a net force on the movable vane which is measured by the deflection of the spring suspension.

$$p_i = \frac{KF}{\sqrt{T_f / T_v - 1}} \tag{5.7.2-1}$$

where F : force and K : a constant.

5.7.3 Momentum-Transfer (Viscosity) Gages

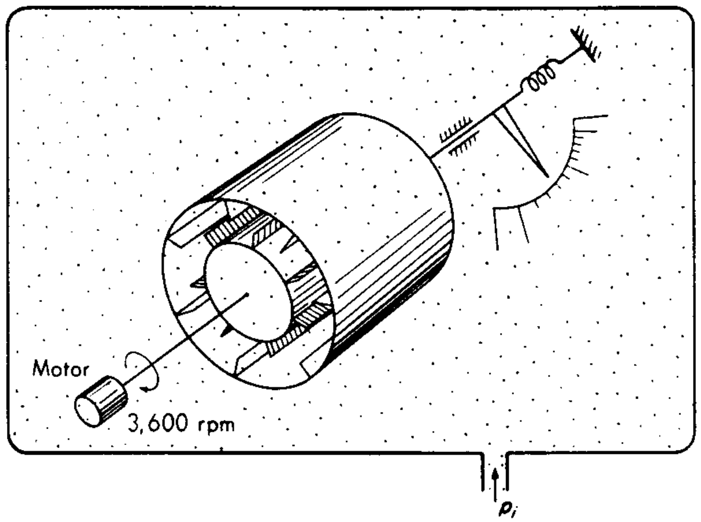


Figure 5.7.3-1 Momentum Gage

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

5.7.4 Thermal-Conductivity Gages

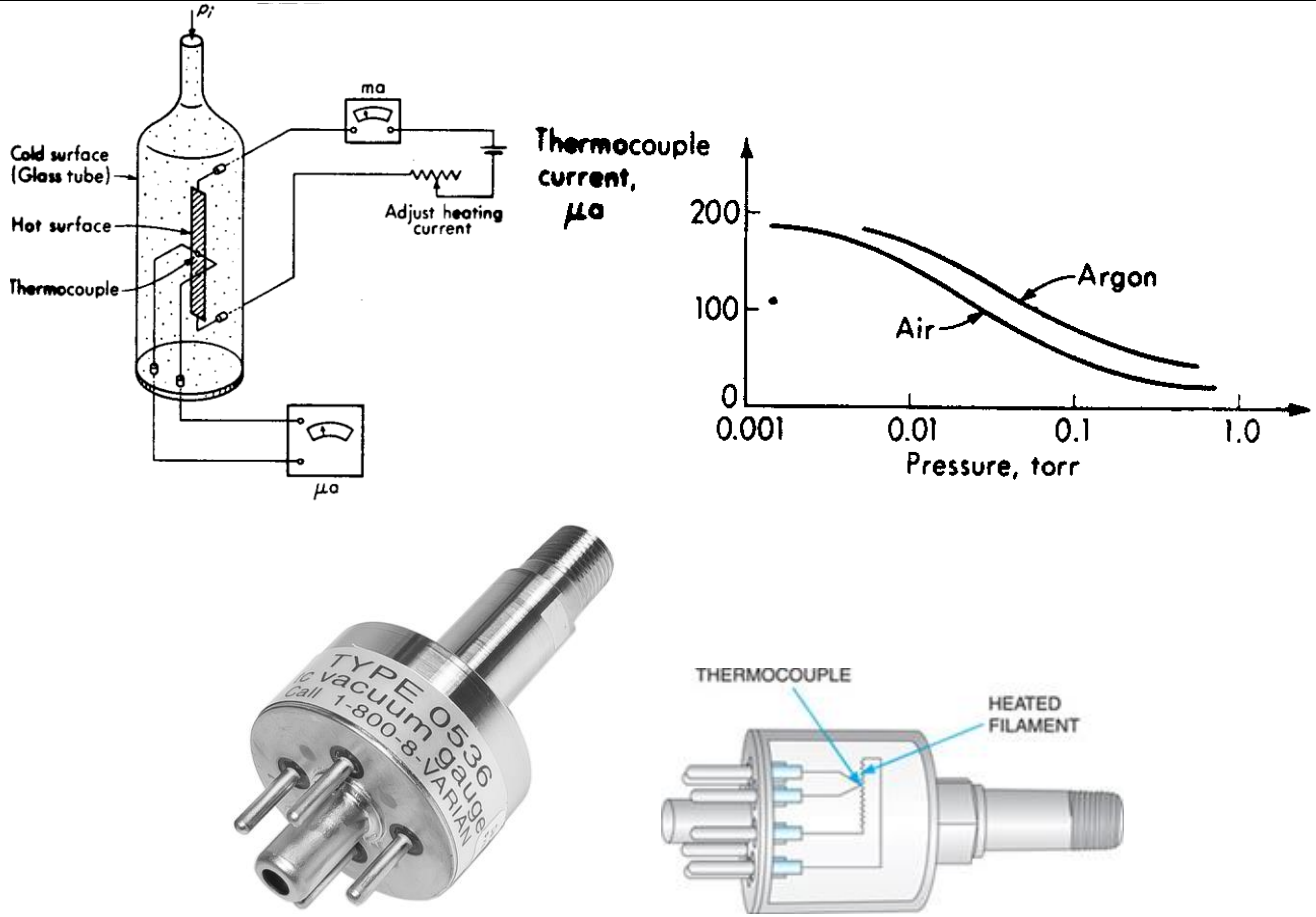


Figure 5.7.4-1 Thermocouple Gage

- When the pressure of a gas becomes low enough, approximately the range 10^{-2} to 1 torr, that the mean free path of molecules is large compared with the pertinent dimensions of the apparatus, the relation between pressure and thermal conductivity is linear.
- When the pressure is increased sufficiently, conductivity becomes independent of gas pressure.
- In a thermocouple vacuum gage, the hot surface is a thin metal strip whose temperature may be varied by changing the current passing through it.
- For a given heating current and gas, the temperature at the hot surface depends on pressure; this temperature is measured by a thermocouple welded to the hot surface. The cold surface here is the glass tube, which usually is near room temperature.

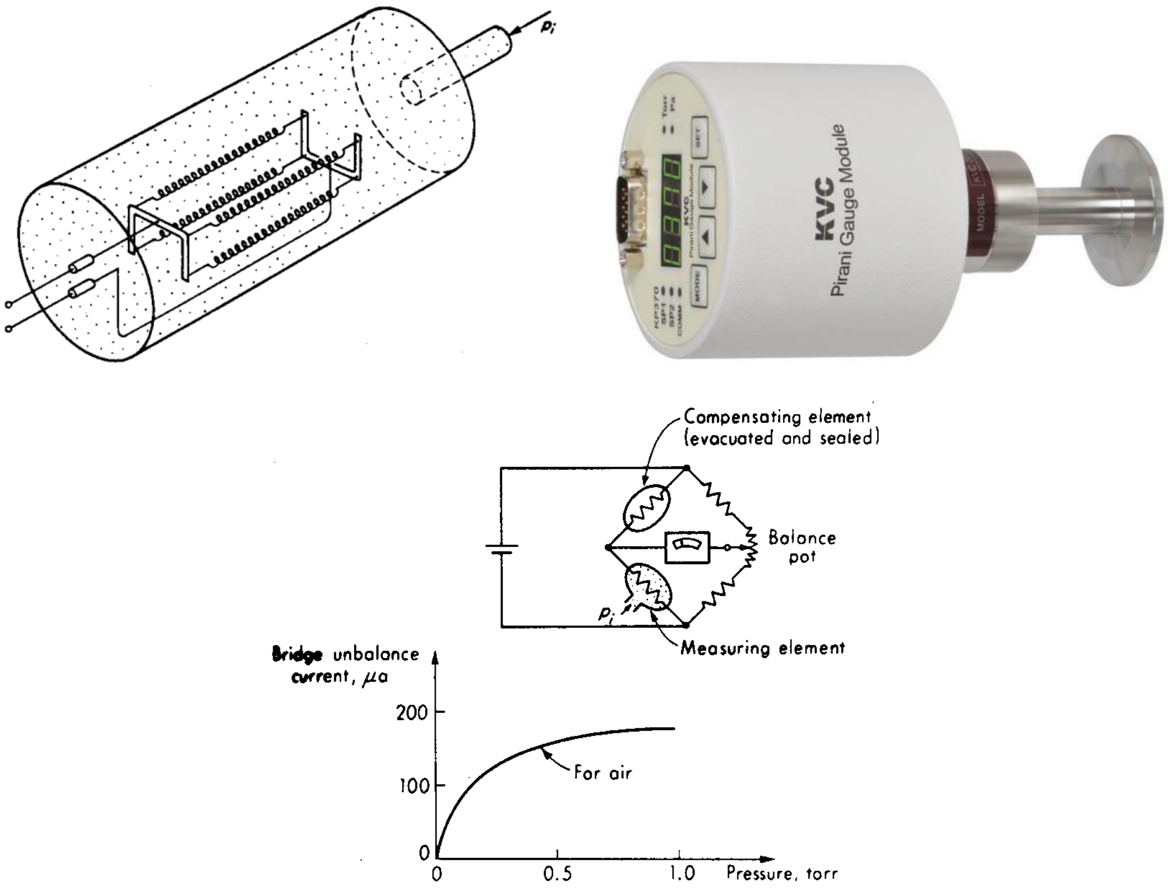
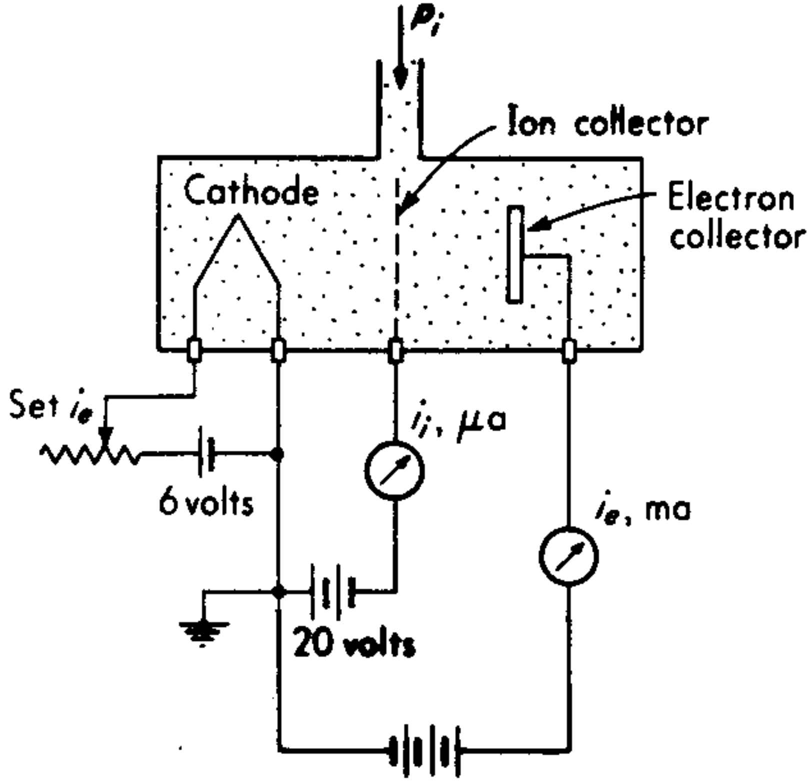


Figure 5.7.4-2 Pirani Gage

- In the resistance-thermometer (Pirani) gage, the resistance element is in the form of four coiled tungsten wires connected in parallel and supported inside a glass tube to which the gas is admitted. The cold surface is the glass tube.
- Two identical tubes generally are connected in a bridge circuit. One of the tubes is evacuated to a very low pressure and then sealed off while the other has the gas admitted to it.
- The evacuated tube acts as a compensator to reduce the effect of bridge-excitation-voltage changes and temperature changes on the output reading.
- Current flowing through the measuring element heats it to a temperature depending on the gas pressure. The electrical resistance of the element changes with temperature, and this resistance change causes a bridge unbalance. Generally, the bridge is used as a deflection rather than a null device.
- Thermistor vacuum gages operate on the same principle as the Pirani gage except that the resistance elements are temperature-sensitive semiconductor materials called thermistors, rather than metals such as tungsten or platinum.

5.7.5 Ionization Gages



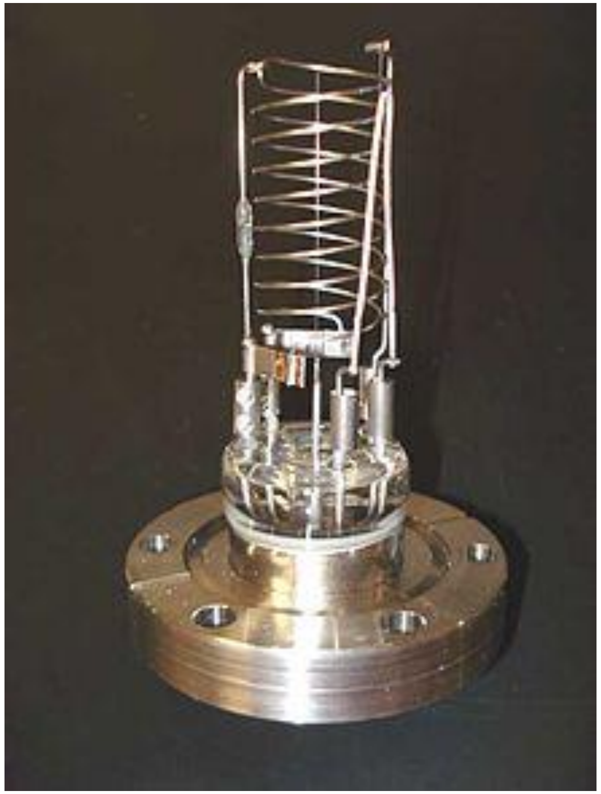


Figure 5.7.5-1 Ionization Gage

- In an ionization gage, a stream of electrons is emitted from a cathode. Some of these strike gas molecules and knock out secondary electrons, leaving the molecules as positive ions.
- For normal operation of the gage, the secondary electrons are a negligible part of the total electron current; thus, electron current i_e is the same whether measured at the emitting point (cathode) or the collecting point (anode).
- The number of positive ions formed is directly proportional to i_e and directly proportional to the gas pressure.
- If i_e is held fixed, the rate of production of positive ions (ion current) is a direct measure of the number of gas-molecules per unit volume and thus of the pressure.
- The positive ions are attracted to a negatively charged electrode, which collects them and carries the ion current.

The sensitivity, S, of an ionization gage is defined by

$$S = \frac{i_i}{p i_e} \qquad (5.7.5\text{-}1)$$

where i_i = ion current, gage output, i_e = electron current, and p = gas pressure, gage input.

- In a hot-cathode ionization gage, the emission of electrons is due to the heating of the cathode.
- Some disadvantages of hot-cathode gages are filament burnout if exposed to air while hot, decomposition of some gases by the hot filament, and contamination of the measured gas by gases forced out of the hot filament.
- The cold-cathode gage overcomes the problems associated with a high-temperature filament by the use of a cold cathode and a high accelerating potential (2,000 V).

5.8 Sound Measurement

The sound pressure level (SPL) is defined by

$$\text{SPL} = \text{sound pressure level} = 20\log\frac{p}{0.0002}\ \text{decibels (dB)} \tag{5.8-1}$$

where p = root-mean-square (rms) sound pressure, μbar.

- The value 0.0002 μbar is an accepted standard reference value of pressure. When p = 0.0002 μbar, the sound pressure level is 0 dB, the lowest pressure fluctuation normally discernible by human beings.

5.8.1 Sound-Level Meter

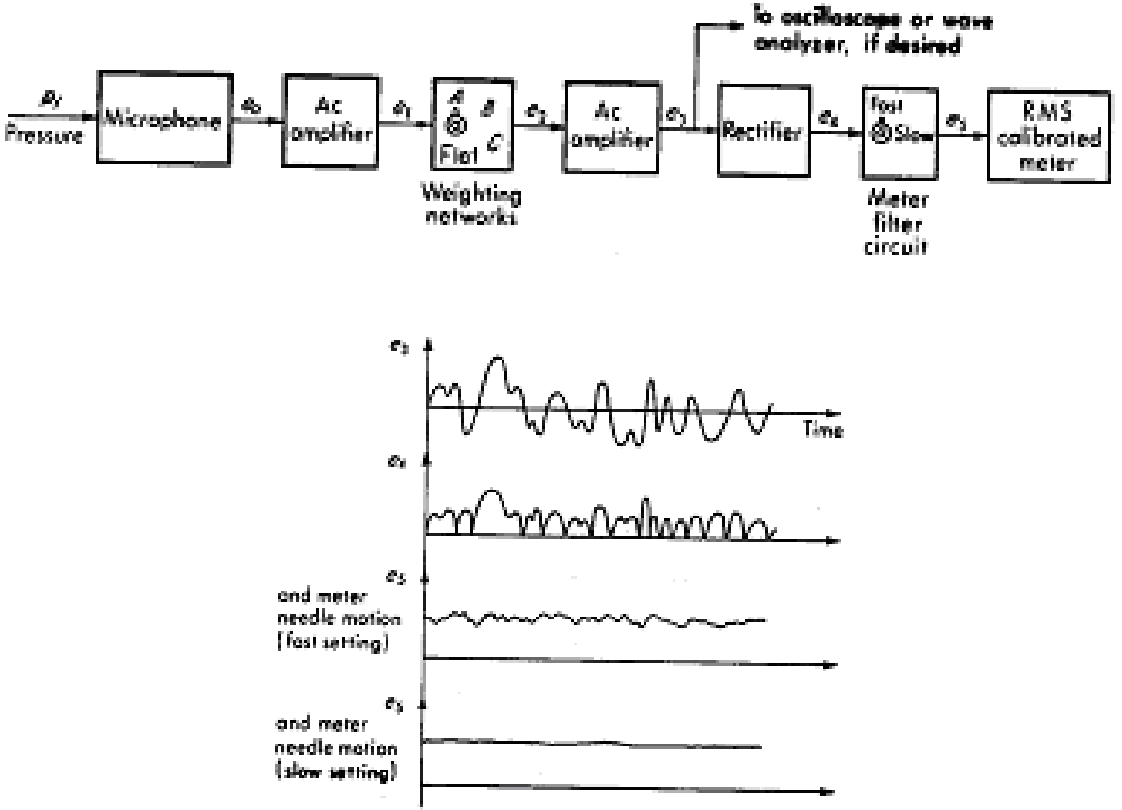
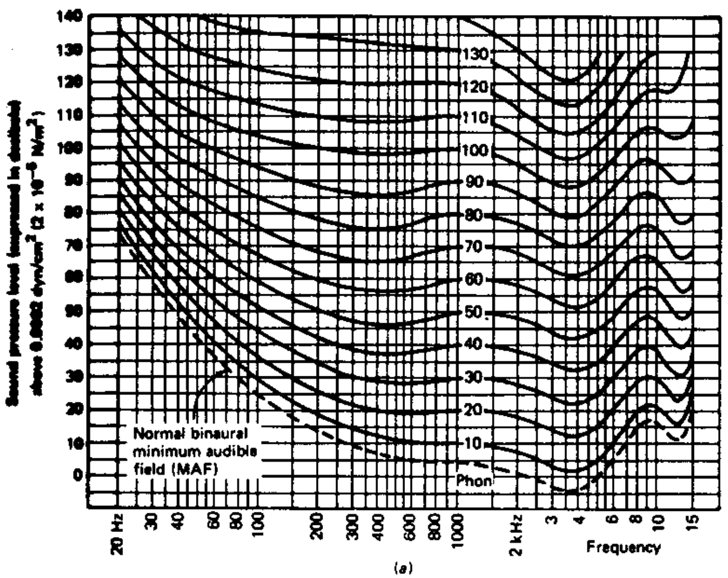


Figure 5.8.1-1 Sound-Level Meter

- The sound pressure p_i is transduced to a voltage by means of the microphone.
- Microphones generally employ a thin diaphragm to convert pressure to motion. The motion is then converted to voltage by some suitable transducer, usually a capacitance, piezoelectric, or moving-coil type.
- Microphones often have a slow leak (capillary tube), connecting the two sides of the diaphragm, to equalize the average pressure (atmospheric pressure) and prevent bursting of the diaphragm.
- An ac amplifier of high input impedance and gain is used at the output of the microphone.
- The weighting networks are electrical filters designed to approximate the human ear's response at three different loudness levels, so that instrument readings will reflect perceived loudness.
- Usually three filters; A (approximates 40-phon ear response), B (70-phon), and C (100-phon), are provided.
- Readings taken with a weighting network are called sound level rather than sound-pressure level.
- The output of the weighting network is further amplified, rectified and filtered.
- The filtering is accomplished by a simple low-pass RC filter or the low-pass meter dynamics. Some meters have a slow-fast response switch, which changes the filtering.
- The slow position gives a steady, easy-to-read needle position. If these short-term variations are of interest, they may be visually observed on the meter by switching it to fast response.
- Finally, a meter scale is calibrated to read rms values.



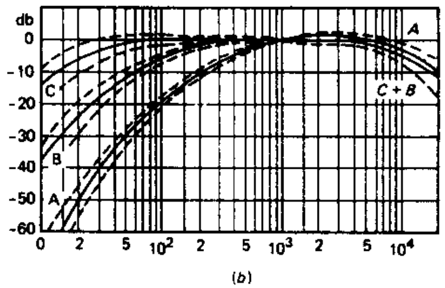


Figure 5.8.1-2 Response of Human Ear and Weighting Networks

5.8.2 Microphones

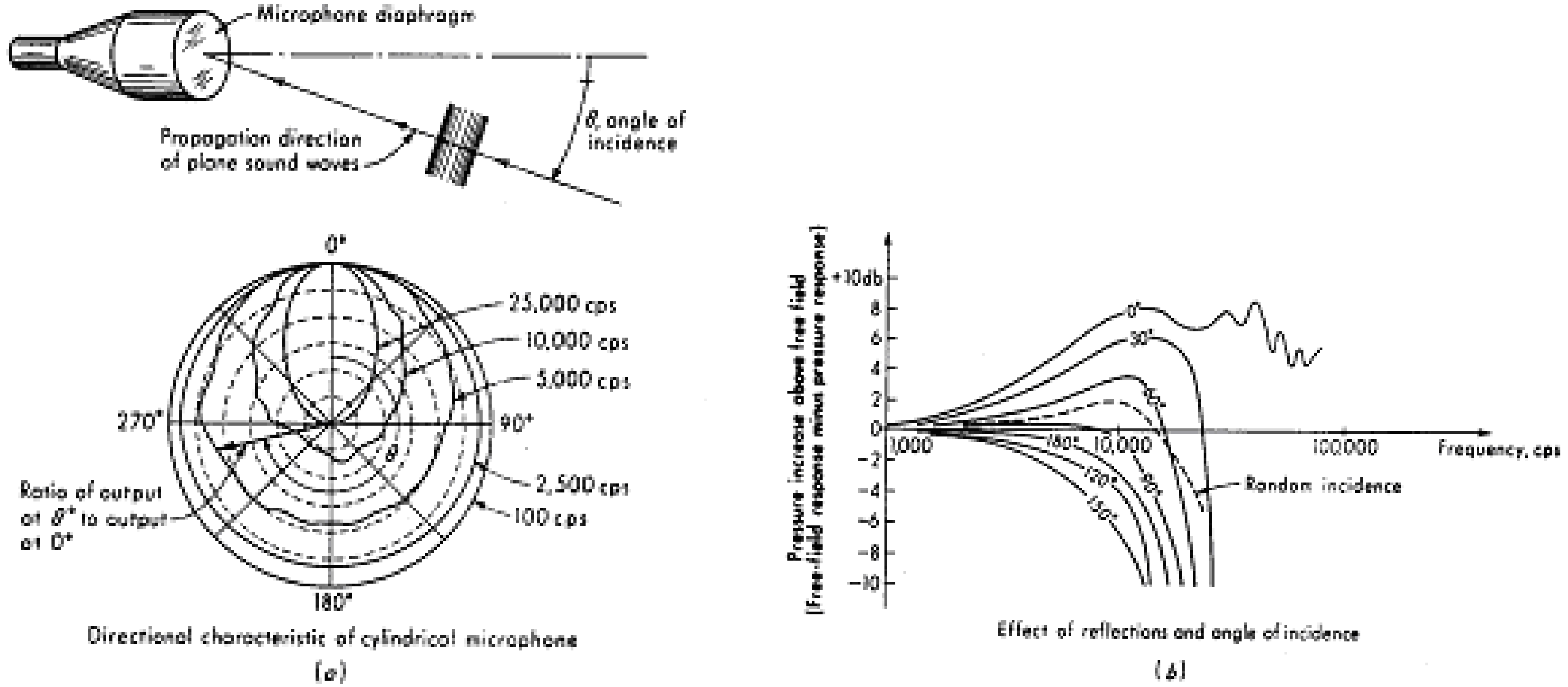


Figure 5.8.2-1 Microphone Response Characteristics

- The free-field response of the microphone is the relation between the microphone output voltage and the sound pressure that existed at the microphone location before the microphone was introduced into the sound field.
- The microphone distorts the pressure field because its acoustical impedance is radically different from that of the medium (air) in which it is immersed.
- When the wavelength of the sound wave is very large compared with the microphone dimensions (low frequencies), the effect of reflections is negligible for any angle of incidence between the diaphragm and the wave-propagation direction, and the free-field response is the same as the pressure response.
- At very high frequencies, where the wavelength is much smaller than the microphone dimensions, the microphone acts as an infinite wall and the pressure at the microphone surface (for waves propagating perpendicular to the diaphragm, 0° angle of incidence) is twice what it would be if the microphone were not there.
- For waves propagating parallel to the diaphragm, 90° incidence angle, the average pressure over the diaphragm surface is zero, giving no output voltage.
- Between the very low and very high frequencies, the effect of reflections is quite complicated and depends on sound wavelength (frequency), microphone size and shape, and angle of incidence.

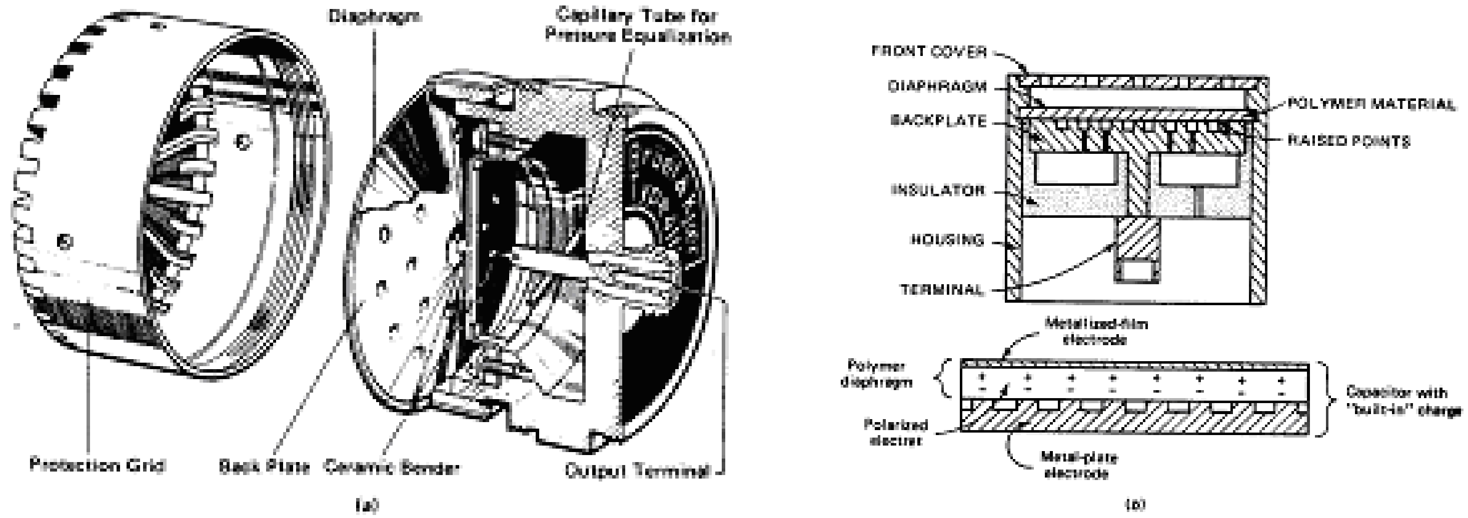


Figure 5.8.2-2 Piezoelectric and Electret Microphones

- Microphones used for engineering measurements are usually piezoelectric, capacitor, or electret types.
- The piezoelectric microphone uses PZT (lead zirconate titanate) as a bending beam coupled to the center of a conical diaphragm of thin metal foil.
- An electret type is related to the capacitor type; however, it requires no polarizing voltage since their charge is permanently built into the polymer film, which forms the diaphragm. Since the unsupported polymer film would sag and creep excessively, a backup plate with raised points is used.

5.8.3 Capacitor Microphone

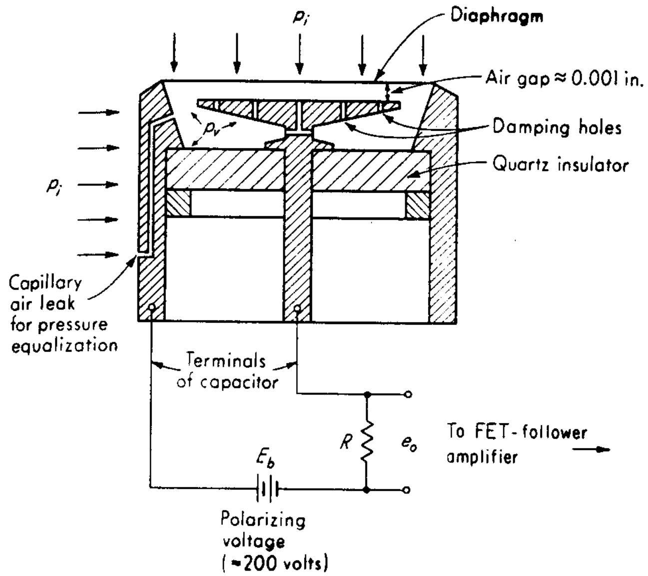


Figure 5.8.3-1 Capacitor Microphone

- The capacitor microphone is considered capable of the highest performance.
- The diaphragm is generally a very thin metal membrane, which is stretched by a suitable clamping arrangement.
- The diaphragm is deflected by the sound pressure and acts as the moving plate of a capacitance displacement transducer.

- The other plate of the capacitor is stationary and may contain properly designed damping holes.
- Motion of the diaphragm causes air flow through these holes with resulting fluid friction and energy dissipation. This damping effect is utilized to control the resonant peak of the diaphragm response.
- A capillary air leak is provided to give equalization of steady (atmospheric) pressure on both sides of the diaphragm to prevent diaphragm bursting.
- For varying (sound) pressures the capillary-volume system results in the varying component of pressure acting only on the outside of the diaphragm and thus causing the desired diaphragm deflection.
- The variable capacitor is connected into a simple series circuit with a high resistance R and polarized with a dc voltage E_b. This polarizing voltage acts as circuit excitation and determines the neutral (zero-pressure) diaphragm position because of the electrostatic attraction force between the capacitor plates.
- For a constant diaphragm deflection, no current flows through R and no output voltage e_o exists; thus there is no response to static pressure differences across the diaphragm.
- For dynamic pressure differences, a current will flow through R and an output voltage exists.
- The voltage e_o usually is applied to the input of a FET-follower amplifier, which always has a gain less than 1; thus the purpose of the amplifier is not to increase the voltage level. Rather, it has a high input impedance ($> 1\ G\Omega$) to prevent loading of the microphone, which has a high output impedance. Since the output impedance of the amplifier is low ($< 100\ \Omega$), its output signal may be coupled into long cables and low-impedance loads without loss of signal magnitude.

5.8.4 Acoustic Intensity

- While sound pressure is a scalar quantity, sound intensity or energy flux is a vector, which describes the amount and direction of time-averaged flow of acoustic power per unit area at a given position.

$$I_r = \lim_{T\to\infty} \frac{1}{T}\int_0^T p(t)v_r(t)dt \qquad (5.8.4\text{-}1)$$

where I_r = acoustic intensity, $p(t)$ = pressure at selected position, T = averaging time, and $v_r(t)$ = particle velocity in selected direction r, at selected position.

- Measurement of p with conventional microphones is straightforward but measurement of v_r is indirect using an approximation based on fluid-mechanics theory.

From the linearized momentum (Euler) equation with zero mean flow,

$$\rho\frac{\partial v_r}{\partial t} + \frac{\partial p}{\partial r} = 0 \qquad (5.8.4\text{-}2)$$

where ρ = fluid mass density.

Approximating the partial derivative as $\Delta p/\Delta r$ leads to

$$v_r = \frac{1}{\rho\Delta r}\int_0^t (p_2 - p_1)dt \qquad (5.8.4\text{-}3)$$

where p_1 and p_2 are pressures measured by two microphones located along the direction vector r at r_1 and r_2 ($r_2 > r_1$).

Further approximating p as $(p_1 + p_2)/2$ gives

$$I_r \approx \frac{1}{2\rho\Delta r}\frac{1}{T}\int_0^T \left(\frac{p_1 + p_2}{2}\right)(p_2 - p_1)dt \qquad (5.8.4\text{-}4)$$

where T is a suitably long averaging time.

6. Fluid Flow Sensors

6.1 Local Flow Velocity, Magnitude, and Direction

6.1.1 Flow Visualization

- Two basic principles of flow visualization:
    - The introduction of tracer particles
    - The detection of flow-related changes in fluid optical properties
- In liquids, colored dyes and gas bubbles are common tracers.
- A line of hydrogen bubbles can be formed in water by applying a short electric pulse to a straight wire immersed in the flow. Photography with steady illumination shows the bubbles as short streaks whose length can be measured to obtain velocity data, while stroboscopic light gives a series of dots whose spacing gives similar information.
- For gas flows, smoke, helium-filled soap bubbles, or gas molecules made luminous by an ionizing electric spark have served as tracers.

- Shadowgraph, schlieren, and interferometer techniques employ the variation in refractive index of the flowing gas with density.
- In shadowgraph and schlieren methods, light and dark patterns related to flow conditions are produced by the bending of light rays as they pass through a region of varying density.
- For interferometer, the light/dark patterns are formed by interference effects resulting from phase shifts between a reference beam and the measuring beam. For no flow, a regular grid of light/dark fringes is present. When flow occurs, this grid is distorted and numerical values of density can be calculated from the fringe displacements.

6.1.2 Velocity Magnitude from Pitot-Static Tube

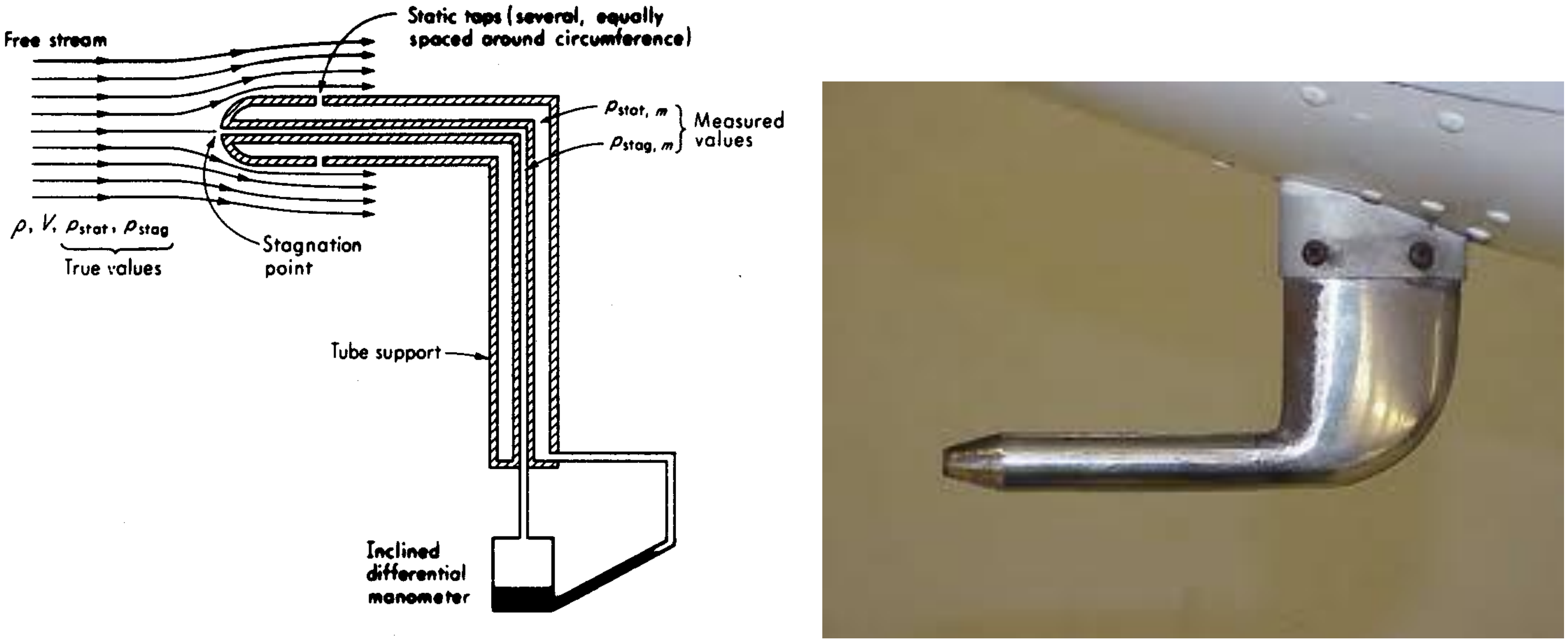


Figure 6.1.2-1 Pitot-Static Tube

- A pitot-static tube must be properly aligned with the direction of fluid.
- In an incompressible frictionless fluid, the Bernoulli equation, $\frac{p}{\rho}+\frac{V^2}{2}+gh=\text{constant}$, is applied.

$$\frac{p_{stat}}{\rho}+\frac{V_{stat}^2}{2}=\frac{p_{stag}}{\rho}+\frac{V_{stag}^2}{2} \tag{6.1.2-1}$$

where p_{stat} = static pressure of free stream, p_{stag} = pressure at stagnation point, V_{stat} = flow velocity of free stream, V_{stag} = flow velocity at stagnation point = 0, and ρ = fluid mass density.

The velocity of free stream,

$$V_{stat}=\sqrt{\frac{2(p_{stag}-p_{stat})}{\rho}} \tag{6.1.2-2}$$

In subsonic flow (Mach number N_M < 1) of compressible fluid, the velocity,

$$V_{stat}=\sqrt{\frac{2k}{k-1}\frac{p_{stat}}{\rho_{stat}}\left[\left(\frac{p_{stag}}{\rho_{stag}}\right)^{(k-1)/k}-1\right]} \tag{6.1.2-3}$$

where $k=\frac{\text{specific heat at constant pressure}}{\text{specific heat at constant volume}}=\frac{C_p}{C_v}$.

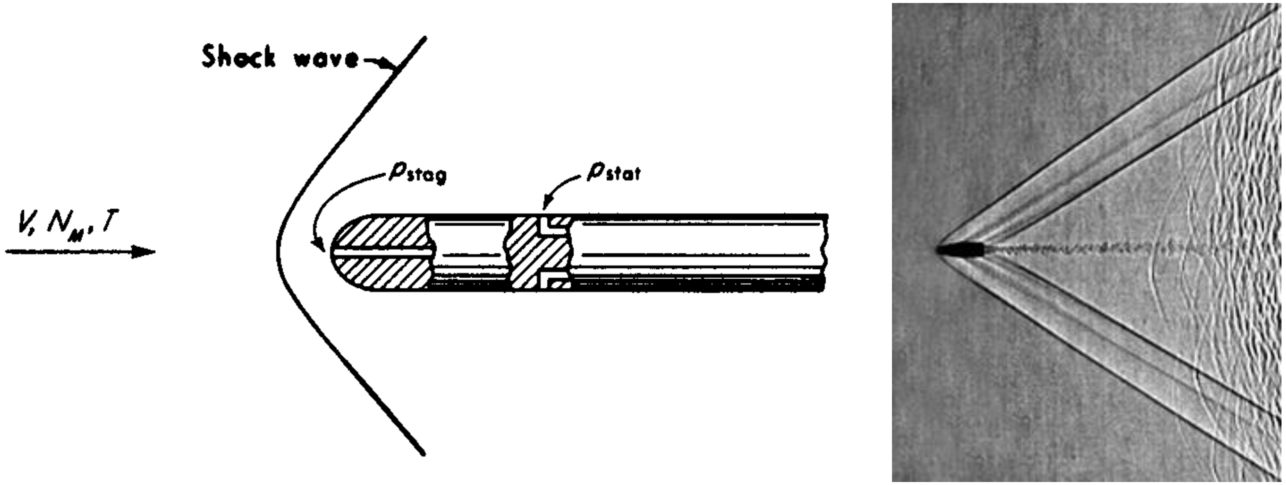


Figure 6.1.2-2 Nonuniform-Velocity Profile and Supersonic Probe

- For supersonic flow ($N_M > 1$), a compression shock wave forms ahead of the pitot tube.
- Between this shock wave and the tube end, the velocity is subsonic.
- This subsonic velocity is then reduced to zero at the tube stagnation point.

$$\frac{p_{stag}}{p_{stat}} = N_M^2 \left(\frac{k+1}{2}\right)^{k/(k-1)} \left[\frac{2kN_M - k + 1}{N_M^2 (k+1)}\right]^{1-1/(k-1)} \tag{6.1.2-4}$$

6.1.3 Velocity Direction from Yaw Tube, Pivoted Vane, and Servoed Sphere

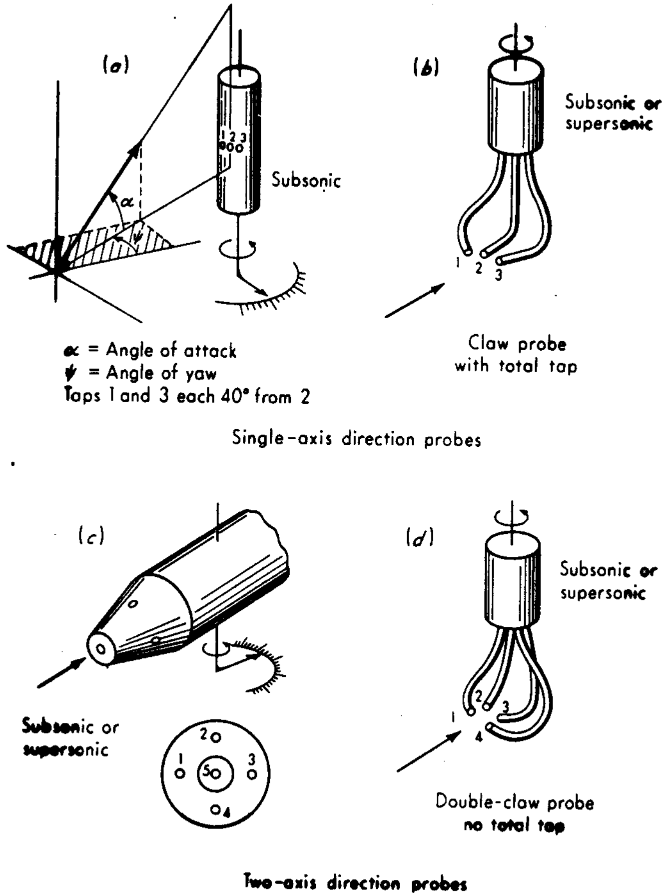


Figure 6.1.3-1 Flow-Direction Probes (a) Yaw Tube (b) Claw Tube (c) and (d) Two-Axis Probes

- Yaw tubes and claw tubes are employed to determine the direction of local flow.
- Taps 1 and 3 are connected to a differential-pressure instrument that reads zero when the tube is aligned with the flow.
- A central tap 2 is often included to read the stagnation pressure after alignment is attained.
- The two-axis probes are designed to allow rotation about each axis.
- Probe operation consists of rotation about the probe axis to balance taps 1 and 3.
- Then pressures 2 and 4 are each measured, and calibration charts give the angle of attack.
- Tap 5 does not read stagnation pressure directly; this can be obtained from calibration charts.
- Any of these probes may be made automatically self-aligning by using the pressure difference p_1-p_3 as the error signal in a servo-system, which rotates the probe until a null is achieved.

6.1.4 Dynamic Wind-Vector Indicator

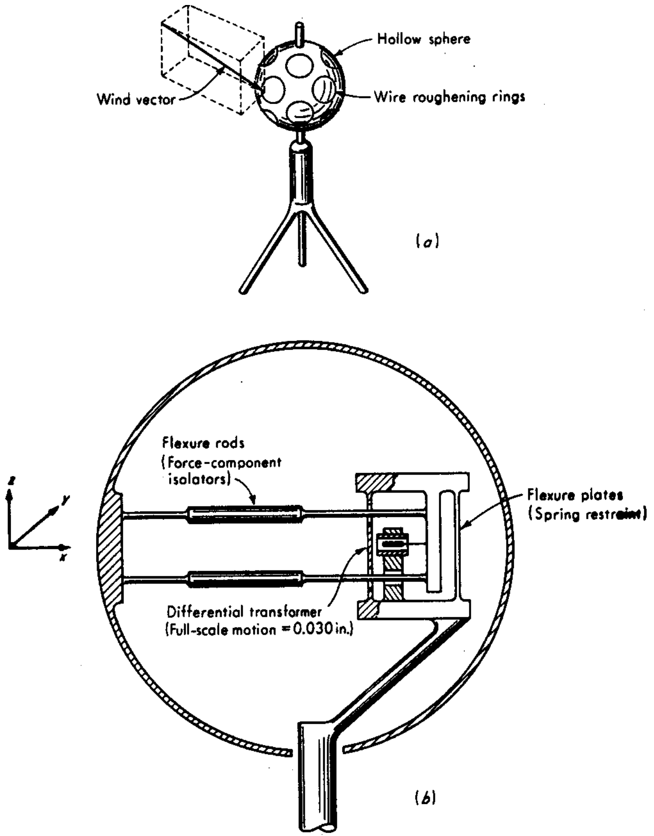


Figure 6.1.4-1 Wind-Vector Indicator

- Wind-vector indicator measures the magnitude and direction of flow velocity in terms of the drag force, F_d ,exerted on a hollow sphere.

$$F_d = C_d \frac{A\rho V^2}{2} \tag{6.1.4-1}$$

where C_d = drag coefficient of body, A = projected area of body, ρ = density, and V = flow velocity.

- Measurement of the x, y, and z components of F_d completely defines the magnitude and direction of V.
- The drag coefficient of a laminar flow, $N < 2$, is dependent on the Reynolds number, N.

$$N = \frac{Q_v d\rho}{\mu} \tag{6.1.4-2}$$

where Q_v = flow velocity, d = pipe diameter, ρ = density, and μ = viscosity.

- The drag coefficient of a turbulent flow, $N > 4$, is constant over the entire design range of V for a given transducer.
- Wire roughening rings are attached to the sphere surface of wind-vector indicator to ensure turbulence.
- The drag coefficient of the roughened sphere is constant over the entire design range of V for a given transducer.
- The separation of the total drag force into three rectangular components is accomplished by mounting the sphere on a force-resolving flexure assembly.
- The force components are applied to flexure-plate springs to produce proportional motions which are then measured by suitable displacement transducers.
- Sensors of this type have been used for both wind and ocean current measurement.

6.1.5 Hot-Wire and Hot-Film Anemometers

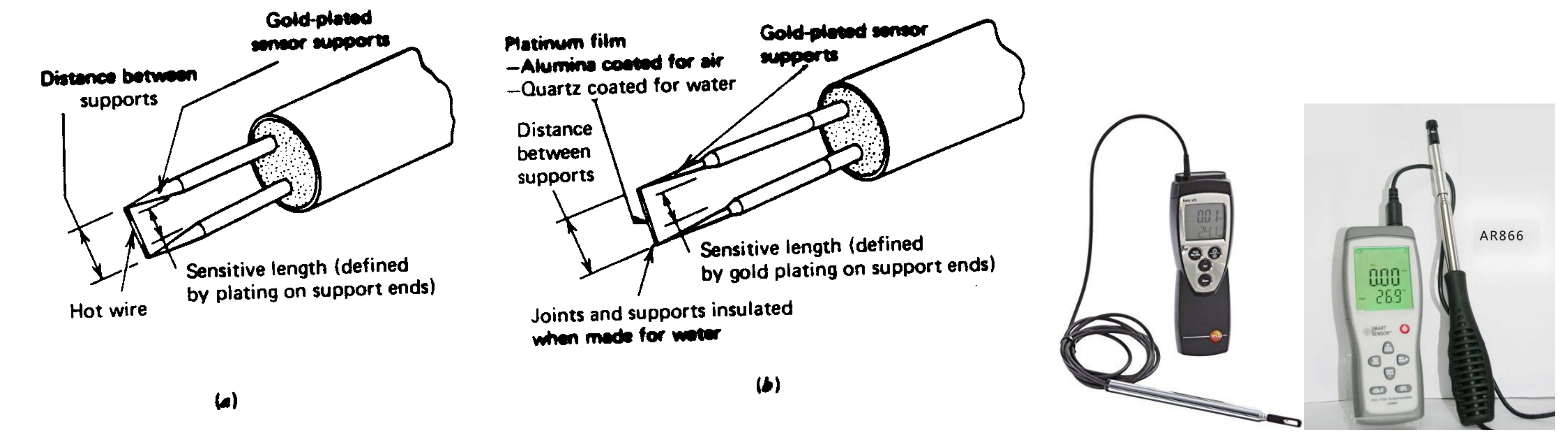


Figure 6.1.5-1 Typical Sensing Elements of Hot-Wire and Hot-Film (a) Hot-Wire Sensor (b) Hot-Film Sensor

- Hot-wire and hot-film anemometers are devices that can be used to measure either velocity or velocity fluctuations (at frequencies up to 500 kHz) at a point in a fluid (liquid or gas) flow.
- Hot-wire sensors are fabricated from platinum, platinum-coated tungsten, or a platinum-iridium alloy.
- Since the wire sensor is extremely fragile, hot-wire anemometers are usually used only for clean air or gas applications.

- Hot-film sensors are extremely rugged; they can be used in both liquids and contaminated gas environments.
- In the hot-film sensor, the high-purity platinum film is bonded to a high-strength, fused-quartz rod. After the platinum film is bonded to the rod, the thin film is protected by using a thin coating of alumina if the sensor will be used in a gas, or a thin coating of quartz if the sensor will be used in a liquid.
- Hot-wire and hot-film anemometers measure velocity indirectly by relating power supplied to the sensor (rate of heat transfer from the sensor to the surrounding cooler fluid) to the velocity of the fluid in a direction normal to the sensor.

The heat transfer rate dQ/dt,

$$\frac{dQ}{dt} = (A + B\sqrt{\rho V})(T_a - T_f) = P = I_a^2 R_a \tag{6.1.5-1}$$

where A and B = calibration constants, ρ = the density of the fluid, V = free-stream velocity of the fluid, T_a = absolute temperature of the anemometer (hot wire or hot film), T_f = absolute temperature of the fluid, I_a = current passing through the wire (or film) sensor, and R_a = resistance of the wire (or foil) sensor.

- The quantity ($T_a - T_f$) is typically maintained at approximately 450°F in air and 80°F in water.
- Materials used for hot-wire and hot-film sensors exhibit a change in resistance with temperature change.

$$R_a = R_r[1 + \alpha(T_a - T_r)] \tag{6.1.5-2}$$

where R_r = resistance of the sensor at reference temperature T_r and α =temperature coefficient of resistance of the wire or foil.

6.1.5.1 Constant-Current Anemometer Circuit

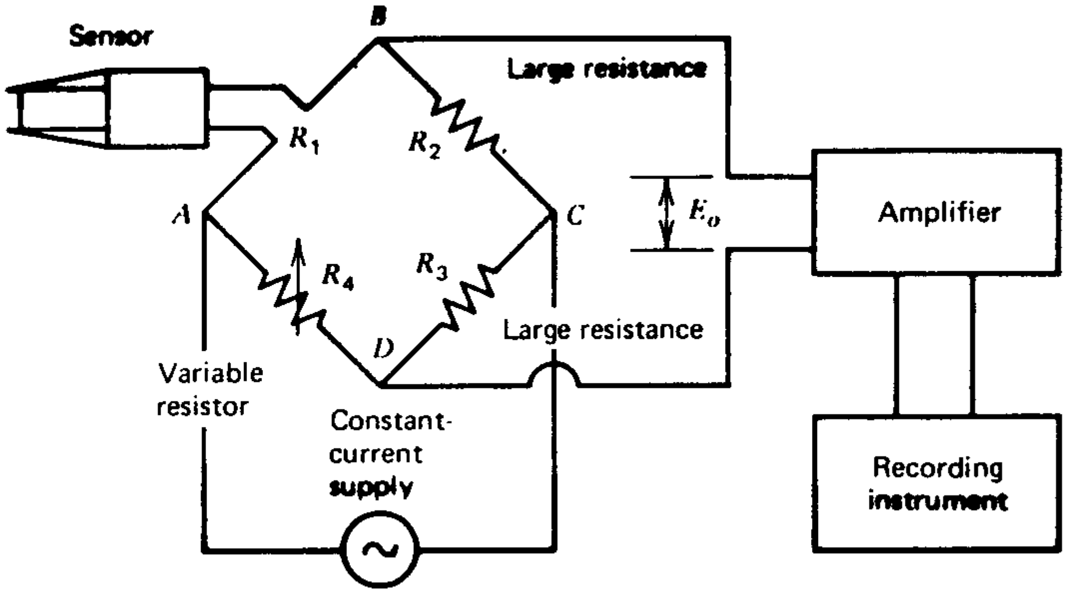


Figure 6.1.5.1-1 Constant-Current Anemometer Circuit

- In this bridge arrangement, resistance R_2 is much larger than sensor resistance R_a; therefore, current I_a is for all practical purposes independent of changes in sensor resistance R_a.
- Variable resistor R_4 is used to balance the bridge under conditions of zero velocity.
- Any flow past the sensor cools the hot wire (or film), decreases its resistance, and thereby unbalances the bridge.

- The unbalancing of the bridge produces an output voltage E_o, which is related to the fluid velocity V.
- The output voltage E_o from the bridge is small; therefore, amplification is needed before it can be used to drive most voltage measuring instruments.
- Two outstanding features of a constant-current anemometer system are its low noise level and its excellent sensitivity.
- The range of frequencies for a typical anemometer is from 1 to 120,000 Hz.
- The constant-current anemometer is very sensitive to small changes in velocity at low velocities; therefore, it is an excellent instrument for low-velocity measurements.
- The constant-current anemometer system has two disadvantages.
    - The frequency response of the constant-current anemometer is separated into two bands: the uncompensated low-frequency band and the compensated high-frequency band.
    - The compensated output is distorted when small high-frequency fluctuations are measured in the presence of large-amplitude, low-frequency oscillations.

6.1.5.2 Constant-Temperature Anemometer Circuits

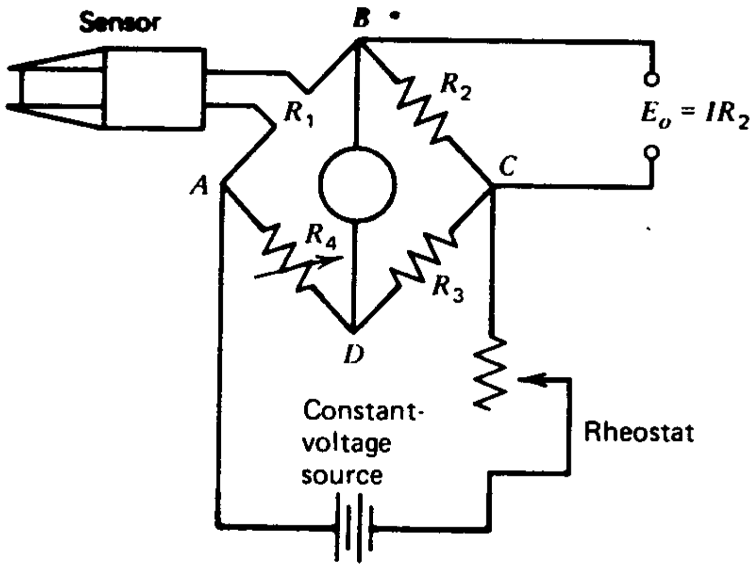


Figure 6.1.5.2-1 Constant-Temperature Anemometer Circuit

- The hot-wire (or film) sensor is used as the active element in a Wheatstone bridge that is balanced under no-flow conditions by using variable resistor R_4.
- As flow past the sensor cools the hot wire (or film), sensor resistance R_a decreases and the bridge becomes unbalanced. The unbalance is sensed with a galvanometer placed across points B and D of the bridge.

- The balance condition can be restored by adjusting the rheostat to increase the input voltage E_i to the bridge.
- The increase in bridge voltage increases the current flowing through the sensor and increases both sensor temperature T_a and sensor resistance R_a back to their no-flow values.

Under conditions of constant sensor temperature and resistance,

$$V = C_0\left[\left(\frac{I}{I_0}\right)^2 - 1\right]^2 \tag{6.1.5.2-1}$$

where C_0 = a calibration constant for the particular hot-wire (or film) probe, I_0 = current at zero velocity that gives the desired sensor temperature, and I = sensor current at velocity V.

- The current I or I_0 passing through the sensor is easily measured by recording the voltage drop across resistance R_2 in the Wheatstone bridge.
- Since the sensor current is proportional to the input voltage E_i for this constant resistance bridge, input voltage, also, can be used as a measure of sensor current.
- An important feature of this constant-temperature anemometer system is the provision for linearized output that makes possible accurate measurements of large-amplitude, low-frequency velocity fluctuations.

- Problems when hot-wire or hut-film sensors are used in liquids.
    - Liquids often carry dirt particles, lint, or organic matter. These materials can quickly coat the hot wire or film and cause significant reductions in heat transfer.
    - The presence of a current-carrying wire in a conducting medium can cause electrolysis of metals, shunting of the hot wire, and spurious changes in sensitivity.
    - The presence of the hot wire can cause formation of bubbles that significantly reduce the heat transfer. Bubbles can arise from entrained air or gas in the liquid, from electrolysis, or from boiling of the liquid.
- Successful use of anemometers in liquids usually require low wire temperatures, coatings on the hot wires, lower operating voltages, degasification of the liquid, and application of other bubble-removal techniques.

6.1.6 Hot-Film Shock-Tube Velocity Sensors

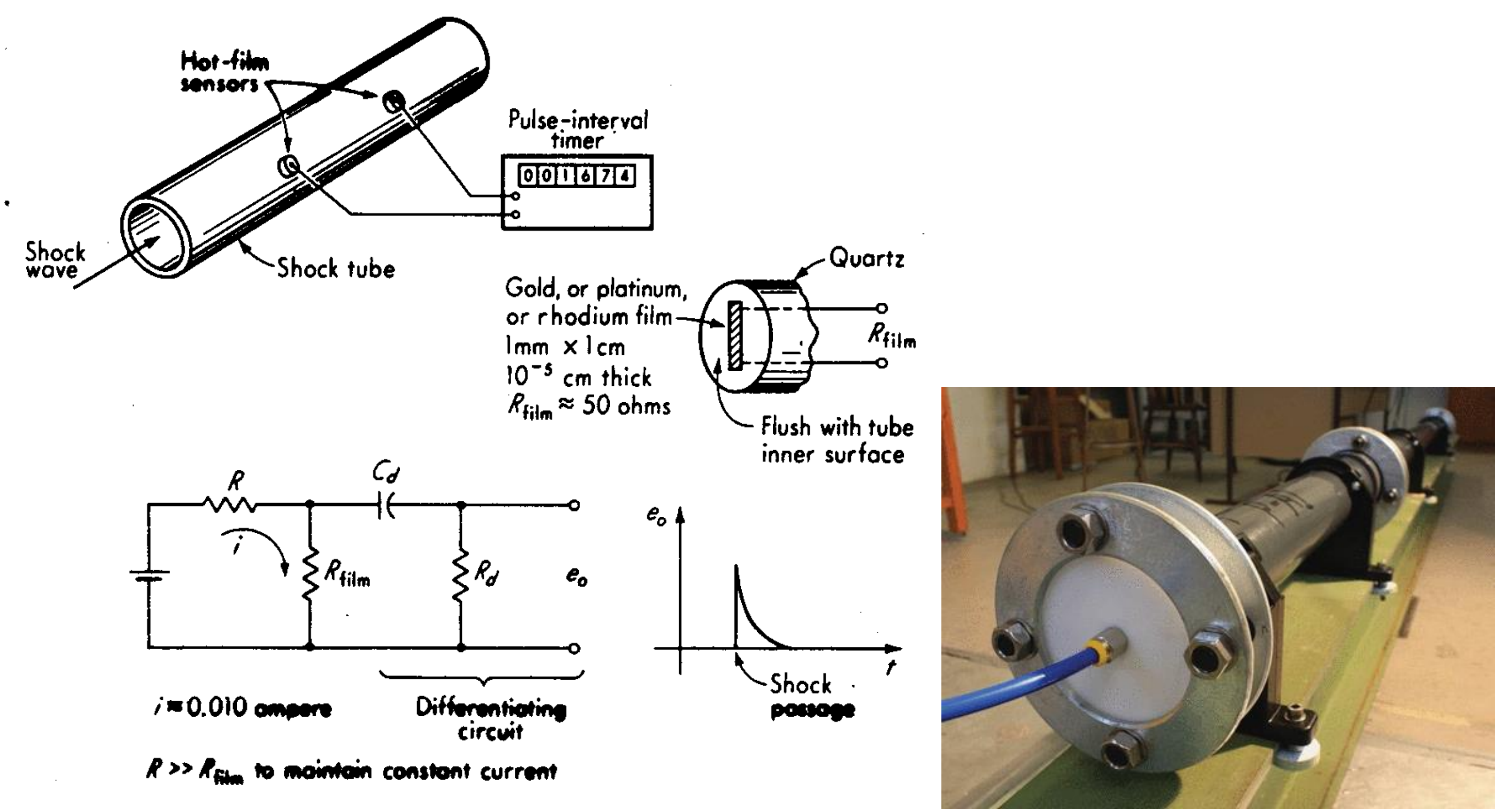
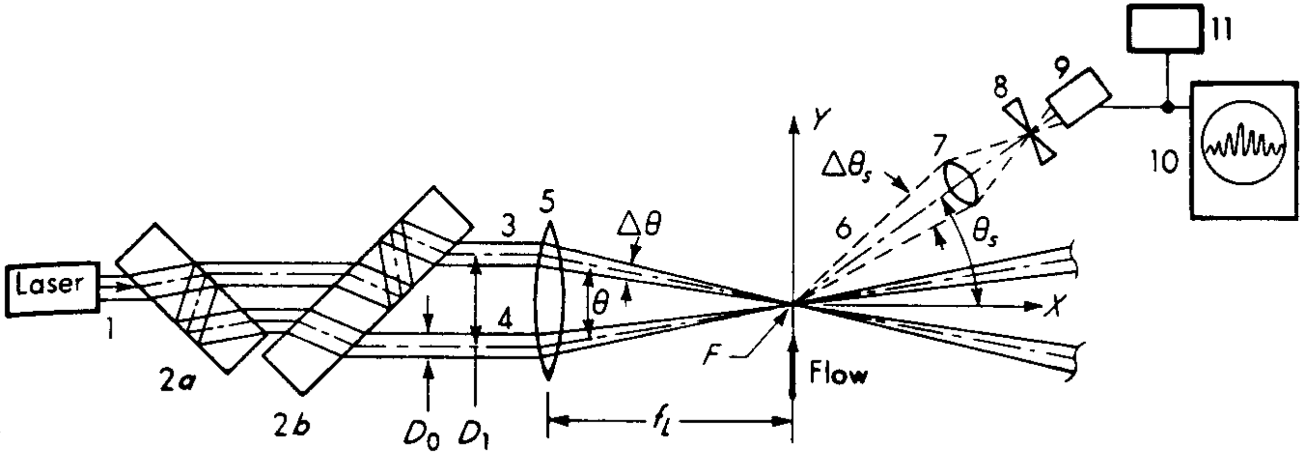


Figure 6.1.6-1 Thin-Film Velocity Sensor

- In shock-tube, hot-film temperature sensors are in wide use.
- The passage of the shock wave past a particular section of the tube make a step change in gas temperature.
- By locating thin resistance films flush with the inside of the tube, the instant of wavefront passage may be detected as a temperature (and therefore resistance) change.
- If two such film sensors are mounted a known distance apart, the average wave velocity may be computed from the time interval between the two sensor responses.
- The films are operated at constant current, and a differentiating circuit is employed to sharpen the pulses for greater timing accuracy.

6.1.7 Laser Doppler Velocimeter



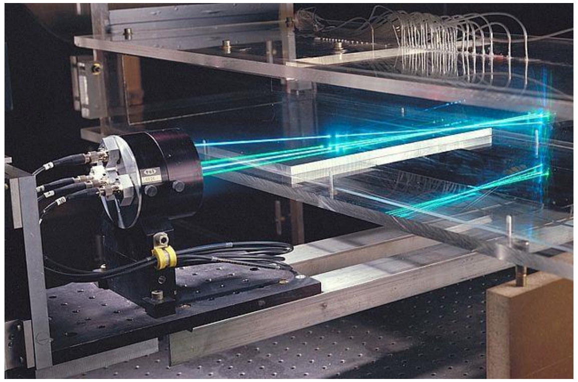


Figure 6.1.7-1 Layout of Laser Doppler Velocimeter

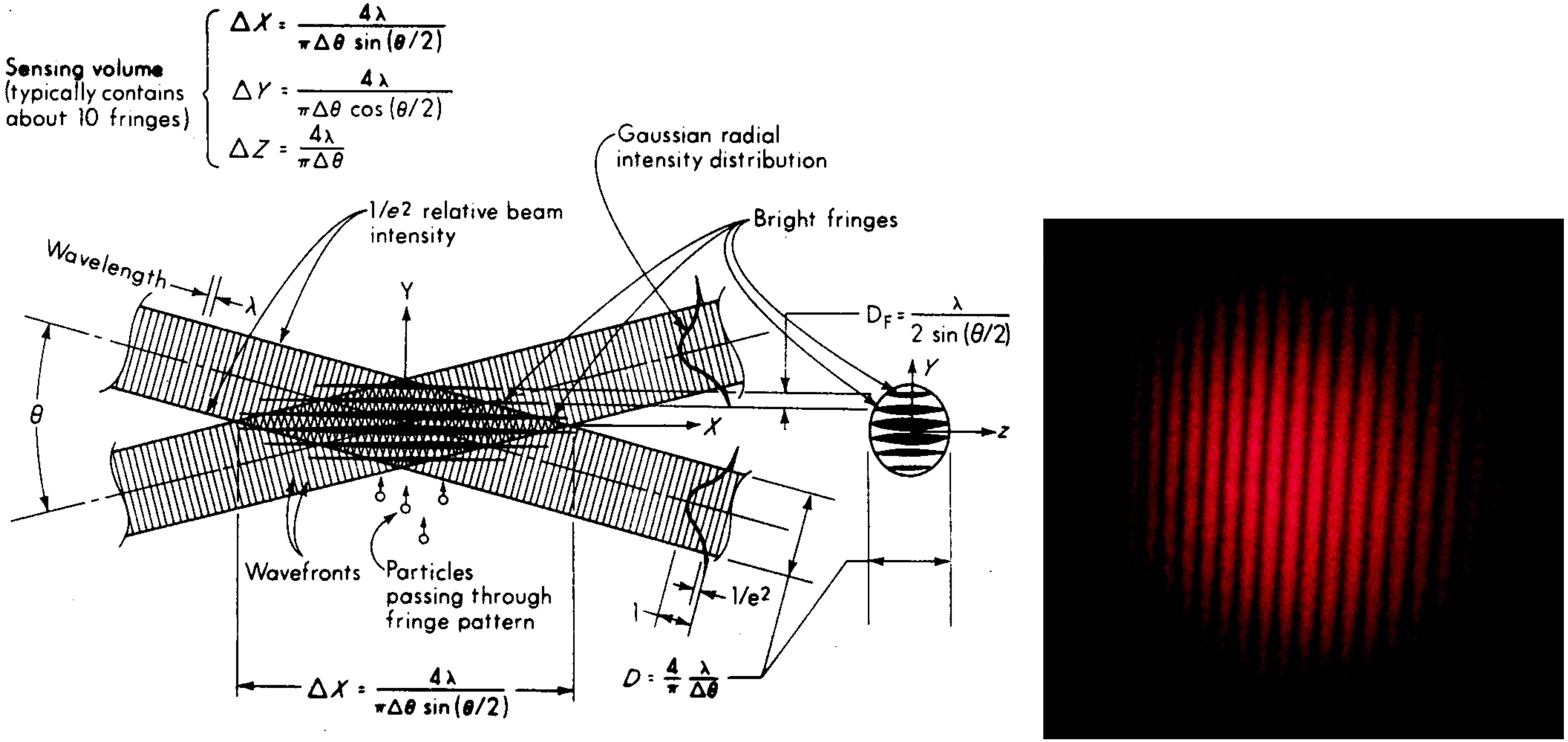


Figure 6.1.7-2 Interference Fringes in Sensing Volume

- Main advantages of Laser doppler velocimeter
    - Measurement of velocity is direct rather than by inference from pressure (pitot tube) or heat-transfer coefficient (hot-wire).
    - No physical object need be inserted into the flow; thus flow is undisturbed by measurement.
    - Sensing volume can be very small (a cube 0.2 mm on a side is not unusual).
    - Very-high-frequency response (to megahertz range) is possible.
- Disadvantages
    - The need for transparent flow channels
    - The necessity for tracer particles in the fluid
    - The cost and complexity of the apparatus
- The operating principle
    - Focusing laser beams at the point where velocity is to be measured
    - Sensing with a photodetector the light scattered by tiny particles carried along with the fluid as it passes through the laser focal point
- The velocity of the particles (assumed to be identical to the fluid velocity) causes a doppler shift of the scattered light's frequency and produces a photodetector signal directly related to velocity.

- Actually, artificial tracer particles are not always necessary; the microscopic particles normally present in liquids may suffice; however, gas flows often need to be seeded.

For many gas flows, which models the particle as a spherical body of radius *r* and density ρ immersed in a fluid of viscosity μ, by using Stokes' law for the viscous force,

$$\frac{4}{3}\pi r^3 \rho \frac{dv_p}{dt} = 6\pi\mu r(v_f - v_p) \qquad (6.1.7\text{-}1)$$

Time constant $\tau = 2\rho r^2/(9\mu)$ relating particle velocity v_p to fluid velocity v_f.

The frequency *f* of the electric signals, produced by a particle moving across the dark and light fringe pattern with a velocity component *V* normal to the fringes,

$$f = \frac{2V\sin(\theta/2)}{\lambda} \qquad (6.1.7\text{-}2)$$

- The velocimeter measures the velocity component perpendicular to the fringe pattern.
- To measure the other component of a two-dimensional velocity vector, the fringe pattern must be rotated 90°.

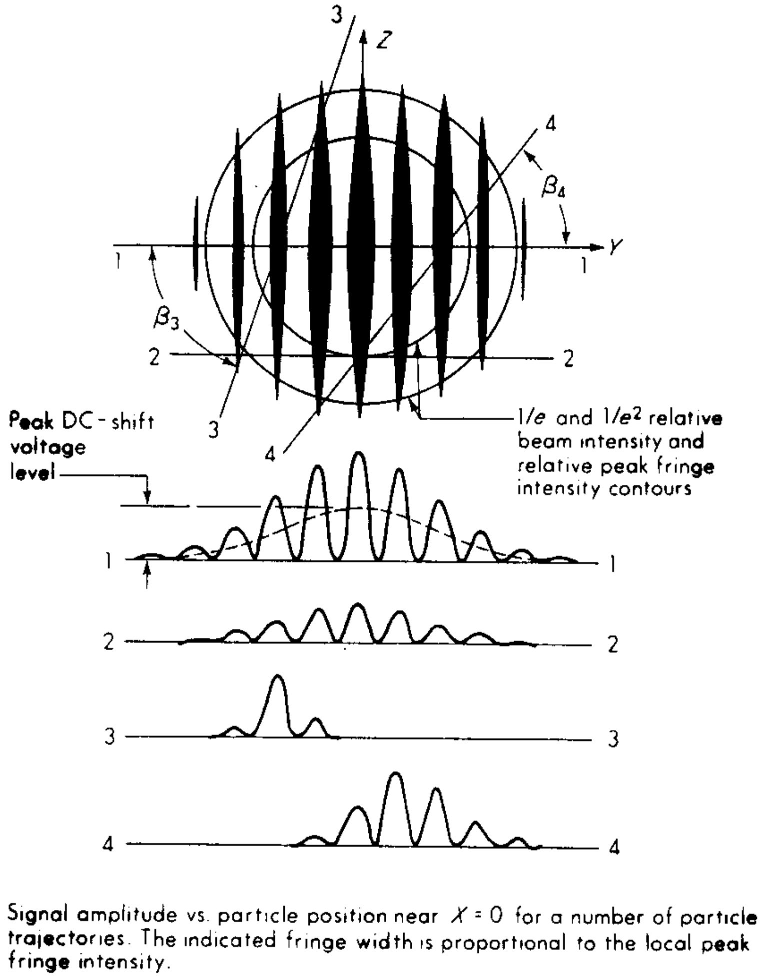


Figure 6.1.7-2 Electronic Signals from Velocimeter and Comparison of Processors

6.2 Gross Volume Flow Rate

6.2.1 Flow Rates in Closed Systems by Pressure-Variation Measurements

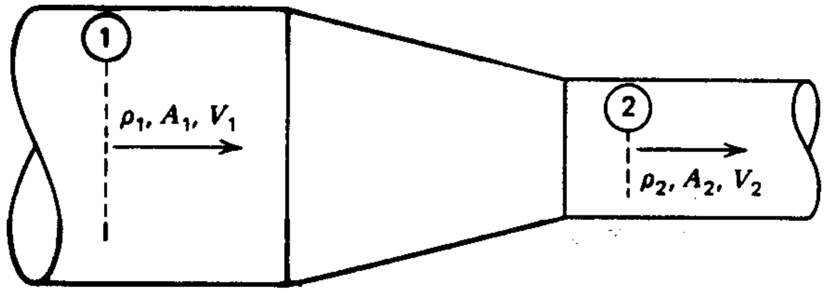


Figure 6.2.1-1 Illustration of Conservation of Mass at Two Locations in a Closed System

- The operation is based on the fact that a change in geometry of the stream tube causes a corresponding change in velocity and pressure of the fluid within the tube.

The Bernoulli equation for an ideal incompressible fluid ($\rho_1 = \rho_2$),

$$\frac{p_1}{\rho} + \frac{V_1^2}{2} + gz_1 = \frac{p_2}{\rho} + \frac{V_2^2}{2} + gz_2 \tag{6.2.1-1}$$

By using the continuity equation (conservation of mass),

$$Q = A_1V_1 = A_2V_2 \tag{6.2.1-2}$$

The ideal volume flow rate Q_i (for an ideal frictionless fluid),

$$Q = A_2 V_2 = \frac{A_2}{\sqrt{1-(A_2/A_1)^2}}\sqrt{2\left(\frac{p_1}{\rho}+gz_1-\frac{p_2}{\rho}-gz_2\right)} \qquad (6.2.1\text{-}3)$$

- For real fluid flow, the flow rate will be less due to friction in the flow between the two pressure measuring points.
- This energy loss is usually accounted for by introducing an experimentally determined coefficient C_V (coefficient of velocity).

Actual flow rate Q_a,

$$Q_a = \frac{C_V A_2}{\sqrt{1-(A_2/A_1)^2}}\sqrt{2\left(\frac{p_1}{\rho}+gz_1-\frac{p_2}{\rho}-gz_2\right)} \qquad (6.2.1\text{-}4)$$

6.2.1.1 Venturi Meter

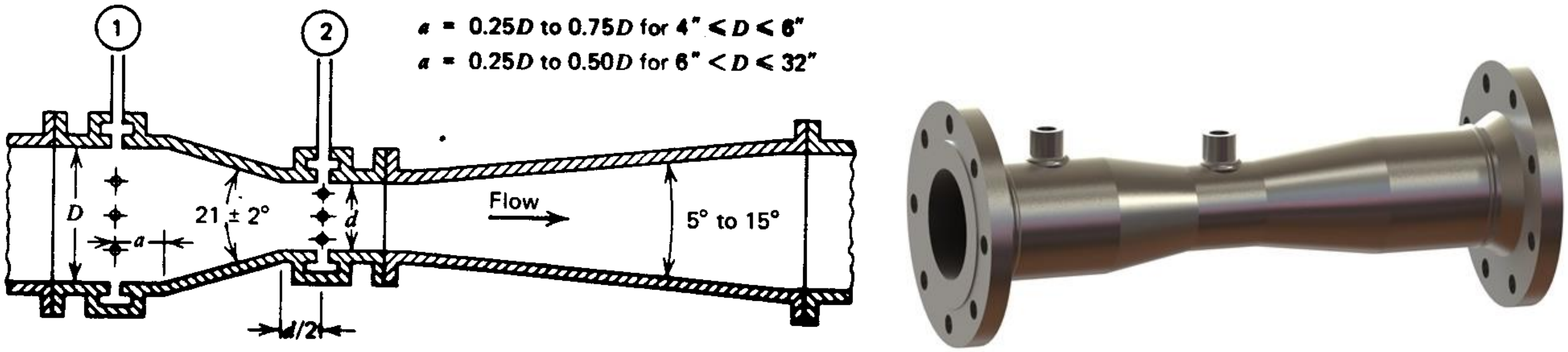


Figure 6.2.1.1-1 Recommended Proportions and Pressure Tap Locations for a Venturi Meter

- A typical venturi meter consists of a cylindrical inlet section, a smooth entrance cone (acceleration cone) having an angle of approximately 21 degrees, a short cylindrical throat section, and a diffuser cone (deceleration cone) having an angle between 5 and 15 degrees.
- Small diffuser angles tend to minimize head loss from pipe friction, flow separation, and increased turbulence.
- Installing the meter downstream from a section of straight and uniform pipe having a length of approximately 50 pipe diameters or installing straightening vanes at upstream of the venturi meter can reduce any rotational motion in the fluid.

6.2.1.2 Flow Nozzle

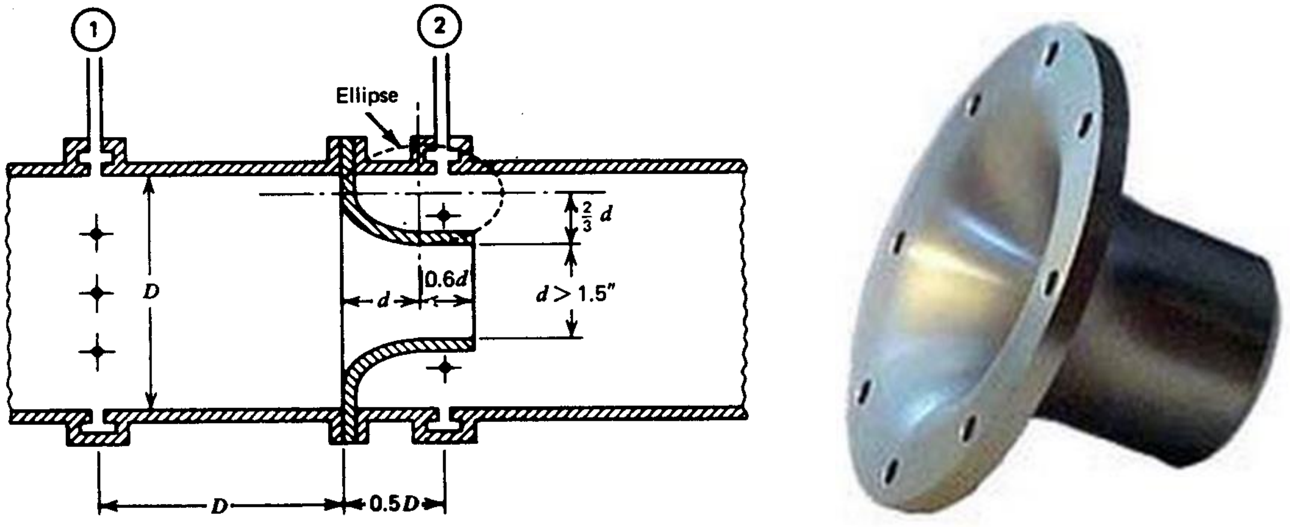


Figure 6.2.1.2-1 Recommended Geometry for an ASME Long-Radius Flow Nozzle

- A flow nozzle is essentially a venturi meter with the diffuser cone removed.
- Since the diffuser cone exists primarily to minimize head loss caused by the presence of the meter in the system, larger head losses will occur in flow nozzles than in venturi meters.
- The flow nozzle is preferred over the venturi meter in many applications because of its lower initial cost and because of the fact that it can be easily installed between two flanges in any piping system.

6.2.1.3 Orifice Meter

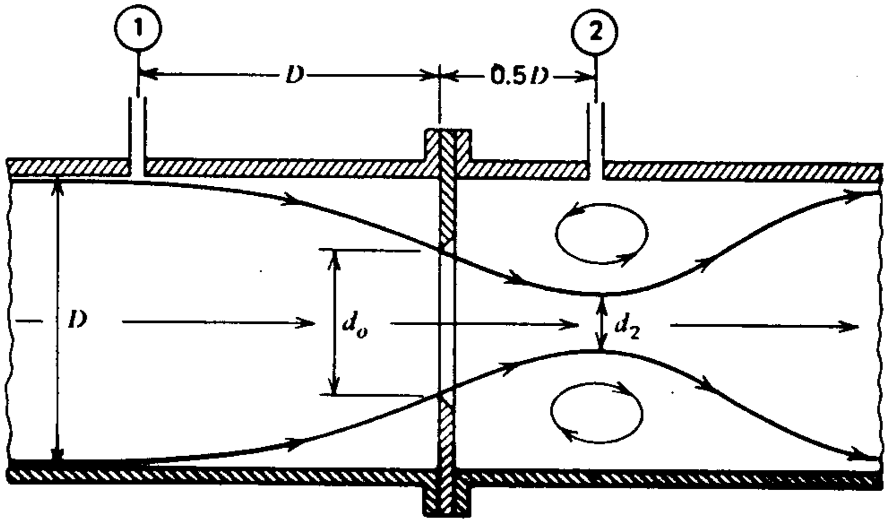


Figure 6.2.1.3-1 Flow through a Sharp-Edge Orifice Plate

- A restricted opening through which fluid flows is known as an orifice.
- An orifice meter consists of a plate with a sharp-edged circular hole, inserted between two flanges of a piping system for the purpose of establishing the flow rate from pressure-difference measurements across the orifice.
- The streamlines tend to converge a short distance downstream from the plane of the orifice; therefore. This minimum-flow area is known as the contracted area of the jet or the vena contracta.

The area at the vena contracta,

$$A_2 = C_C A_0 \tag{6.2.1.3-1}$$

where A_0 : the area of the hole in the orifice plate, C_C : a contraction coefficient.

The flow rate through the orifice,

$$Q_a = \frac{C_V C_C A_0}{\sqrt{1-(C_C A_0 / A_1)^2}} \sqrt{2\left(\frac{p_1}{\rho} + gz_1 - \frac{p_2}{\rho} - gz_2\right)} = CA_0 \sqrt{2\left(\frac{p_1}{\rho} + gz_1 - \frac{p_2}{\rho} - gz_2\right)} \tag{6.2.1.3-2}$$

where the orifice coefficient $C = C_V C_C / \sqrt{1-(C_C A_0 / A_1)^2}$.

6.2.1-4 Elbow Meter

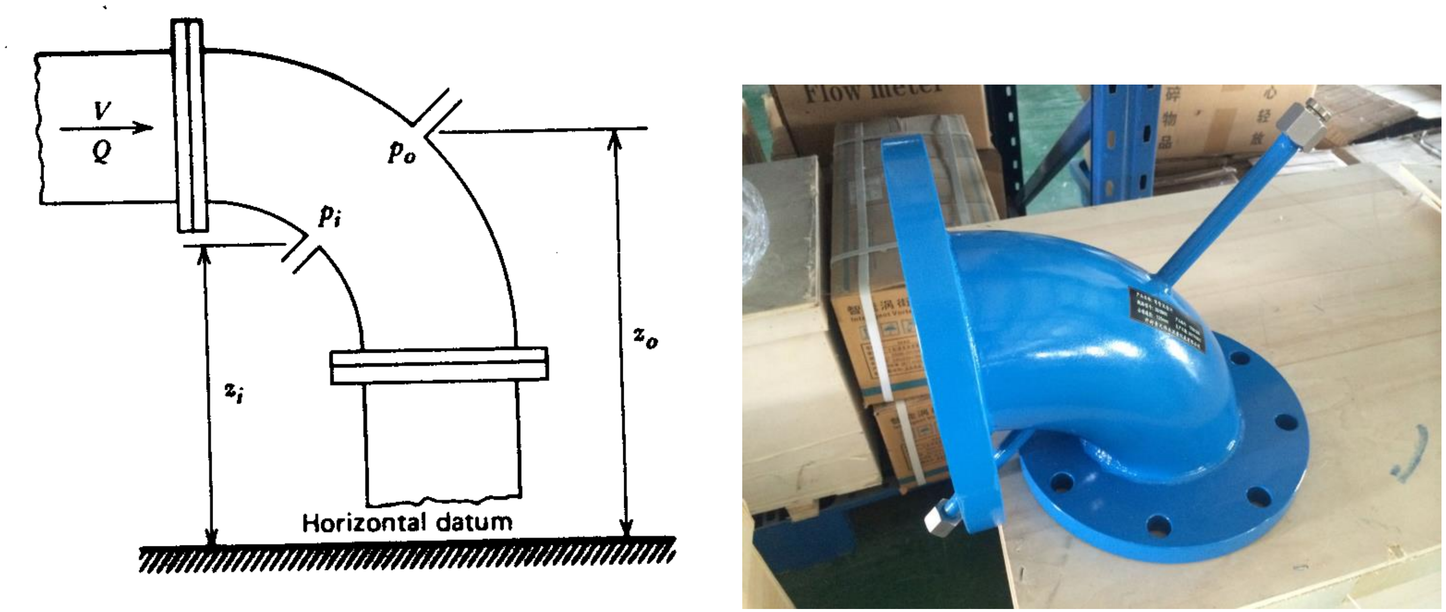


Figure 6.2.1.4-1 Principle of Operation of an Elbow Meter

- The venturi meter, flow nozzle, and orifice meter make the energy losses in the system.
- Elbow meter does not introduce additional losses in the system, since it can simply replace an existing elbow in the system that is being used to change the direction of flow.

$$C_k \frac{V^2}{2} = \frac{p_0}{\rho} + z_0 g - \frac{p_i}{\rho} - z_i g \qquad (6.2.1.4\text{-}1)$$

where C_k: a coefficient that depends upon the size and shape of the elbow.

The volume flow rate Q,

$$Q = AV = \frac{A}{\sqrt{C_k}} \sqrt{2\left(\frac{p_0}{\rho} + gz_0 - \frac{p_i}{\rho} - gz_i\right)} = CA\sqrt{2\left(\frac{p_0}{\rho} + gz_0 - \frac{p_i}{\rho} - gz_i\right)} \qquad (6.2.1.4\text{-}2)$$

where $C = 1/\sqrt{C_k}$: the elbow meter coefficient.

- The elbow meter requires a minimum of 10 to 30 pipe diameters of unobstructed upstream flow (to reduce large-scale turbulence and swirl) for satisfactory operation and accurate flow measurements; otherwise, flow straighteners must be used to stabilize the flow prior to entry into the flow metering device.

6.2.2 Averaging Pitot Tubes

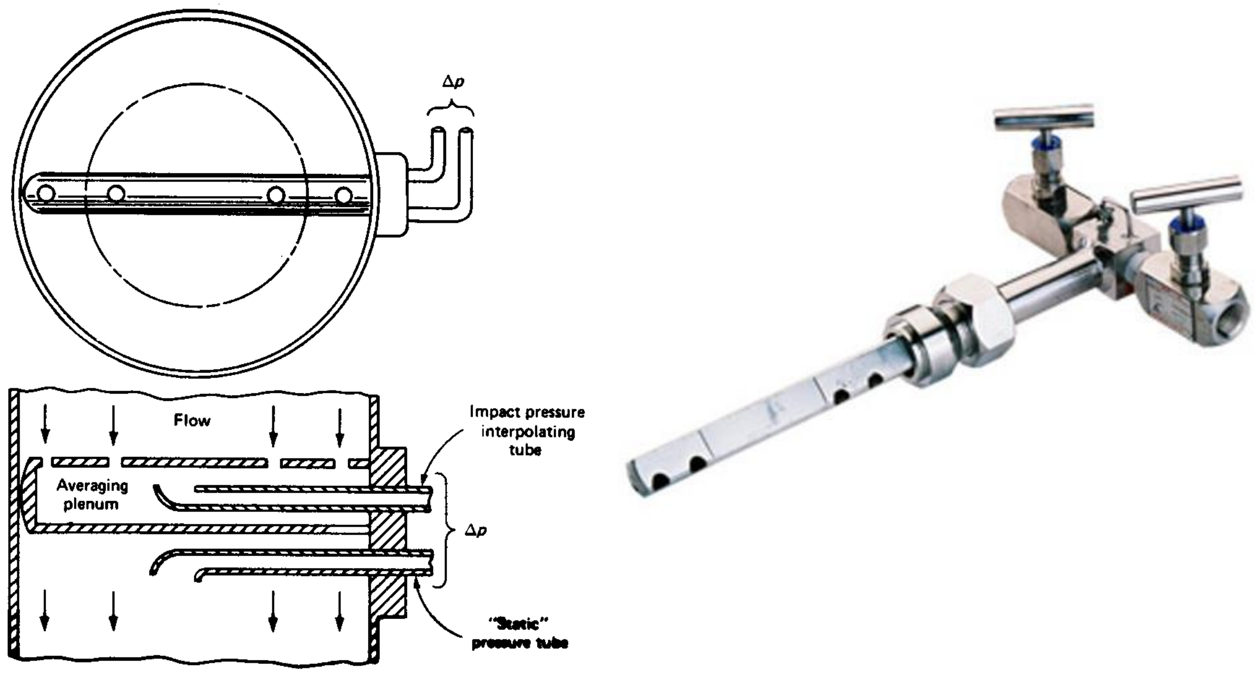


Figure 6.2.2-1 Averaging Pitot Tube

- Averaging pitot tube measure fluid flow by using a fixed probe with several spatially dispersed sensing ports, whose readings are averaged in a plenum to produce a single impact pressure and a single static pressure.

6.2.3 Drag-Force Velocity Transducers

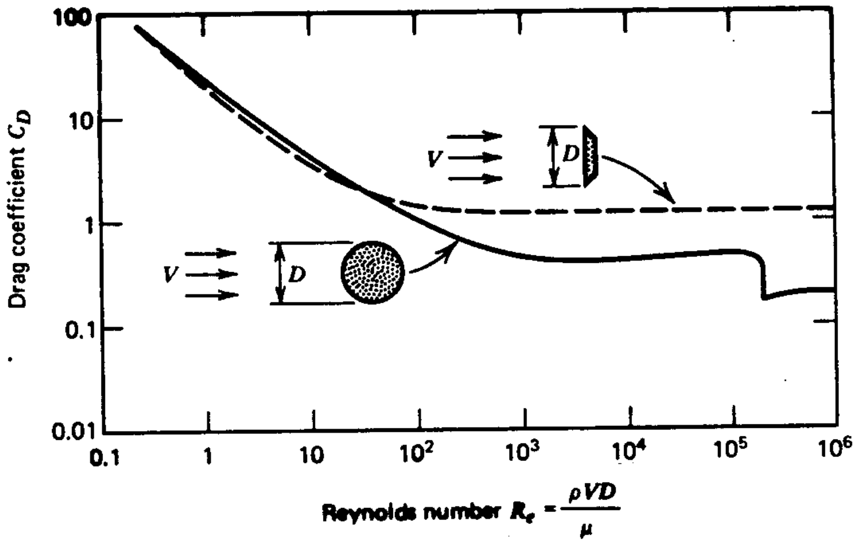


Figure 6.2.3-1 Drag Coefficients for a Sphere and a Circular Disk as a Function of Reynolds Number

- Drag-force velocity transducers operate on the principle that the drag force F_D on a body in a uniform flow is related to the fluid velocity V, the fluid density ρ, and frontal area A of the body normal to the flow direction.

$$F_D = C_D \frac{\rho V^2 A}{2} \quad (6.2.3\text{-}1)$$

where C_D : a nondimensional parameter known as the drag coefficient.

6.2.3.1 Rotameter

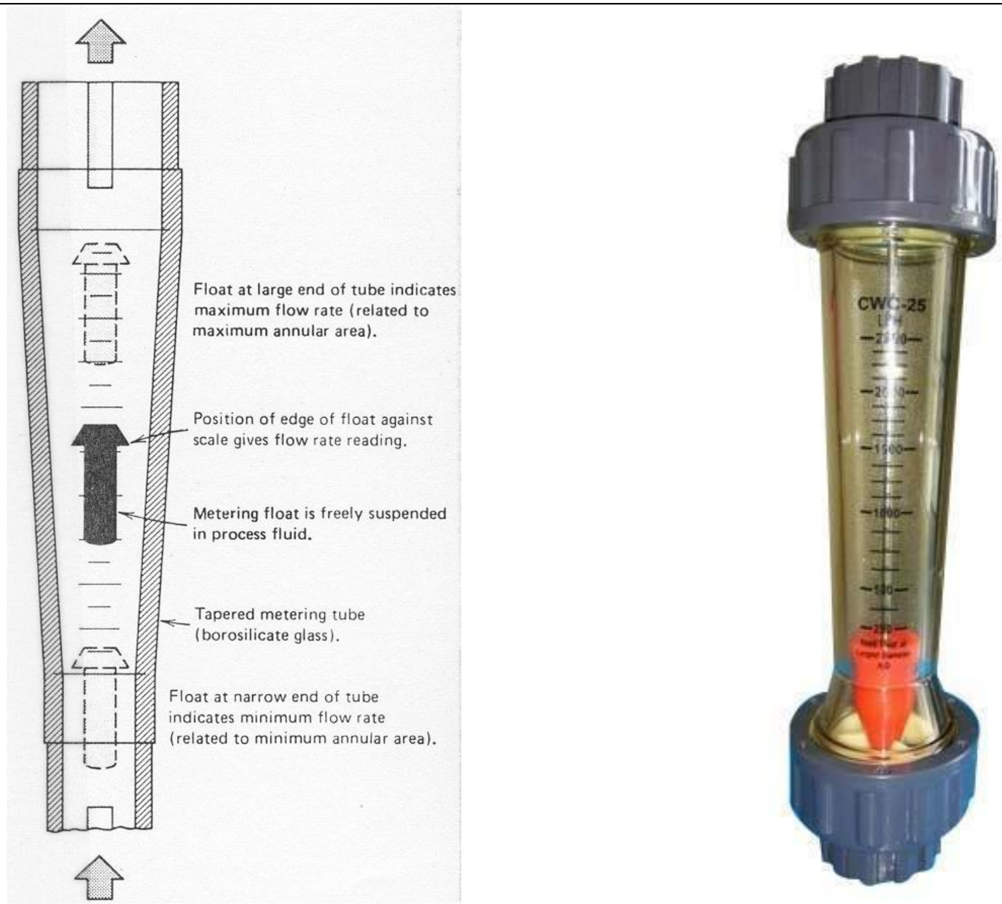


Figure 6.2.3.1-1 Rotameter (a) Principle of Operation (b) Glass-Tube Rotameter

- The rotameter is a common flow measurement device whose operation is based on drag principles.
- The rotameter consists of a tapered tube and a solid float (bob) that is free to move vertically in the tube.
- At any flow rate within the range of the meter, fluid entering the bottom of the tube raises the float (thereby increasing the area between the float and the tube) until the drag and buoyancy forces are balanced by the weight of the float.

$$C_D \frac{\rho_f V^2 A_b}{2} + \rho_f V_b g = \rho_b V_b g \qquad (6.2.3.1\text{-}1)$$

where A_b: the frontal area of the float, V_b: the volume of the float, ρ_b: the density of the float, and V: the mean velocity of the fluid in the annular space between the float and the tube.

- The first term in the equation is the drag force on the float, the second term is the buoyancy force on the float, and the third term is the weight of the float.

The annular area A,

$$A = \frac{\pi}{4}[(D + ay)^2 - d^2] \approx \frac{\pi}{2} Day \qquad (6.2.3.1\text{-}2)$$

where a : a constant that describes the taper of the tube.

6.2.4 Turbine Meters

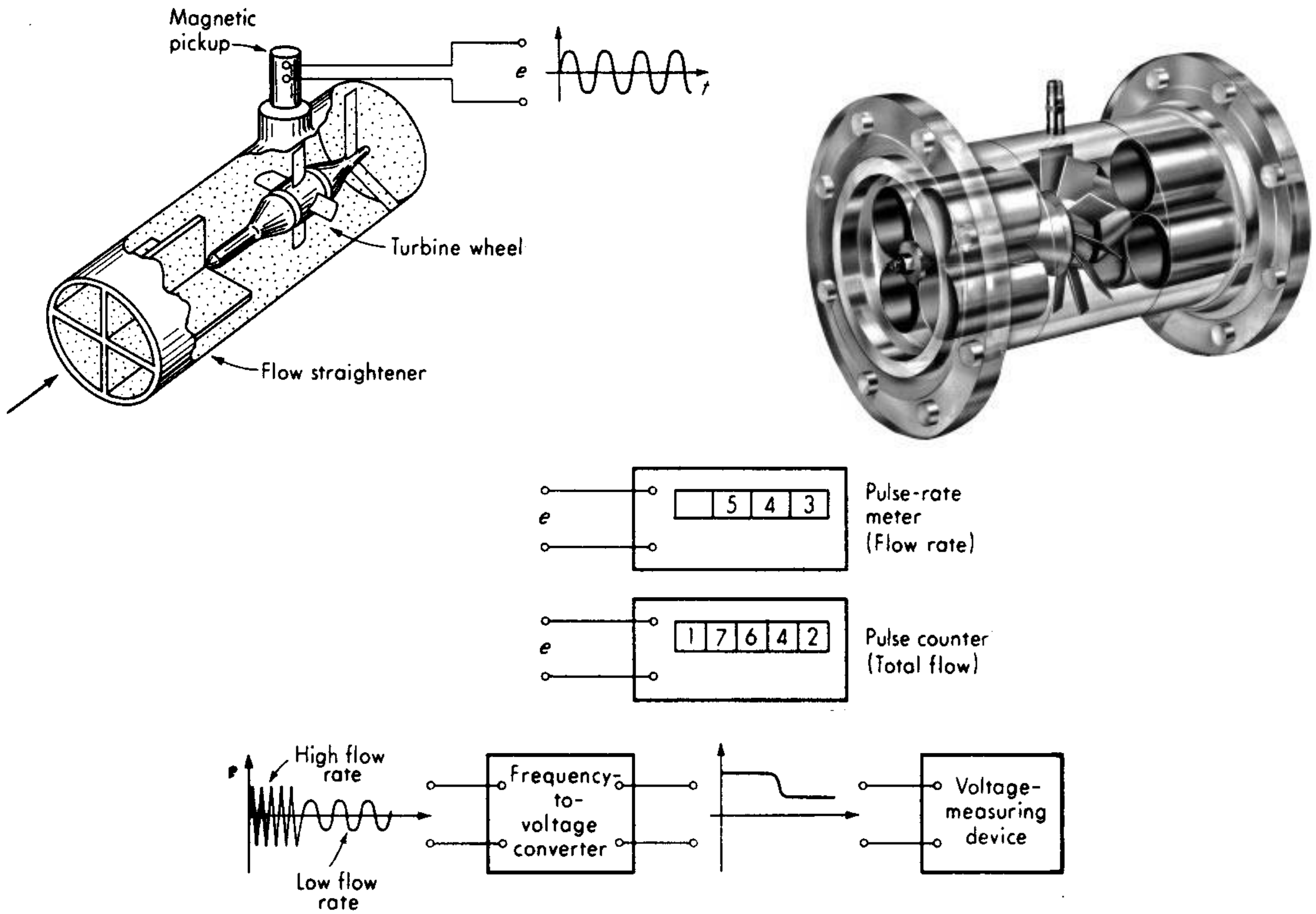


Figure 6.2.4-1 Turbine Flowmeter

- If a turbine wheel is placed in a pipe containing a flowing fluid, its rotary speed depends on the flow rate of the fluid.
- By reducing bearing friction and keeping other losses to a minimum, one can design a turbine whose speed varies linearly with flow rate; thus, a speed measurement allows a flow-rate measurement.
- The speed can be measured by counting the rate at which turbine blades pass a given point, using a magnetic proximity pickup to produce voltage pulses.
- By feeding these pulses to an electronic pulse-rate meter, one can measure flow rate; by accumulating the total number of pulses during a timed interval, the total flow is obtained.
- If an analog voltage signal is desired, the pulses can be fed to a frequency-to-voltage converter.

6.2.5 Positive-Displacement Meters

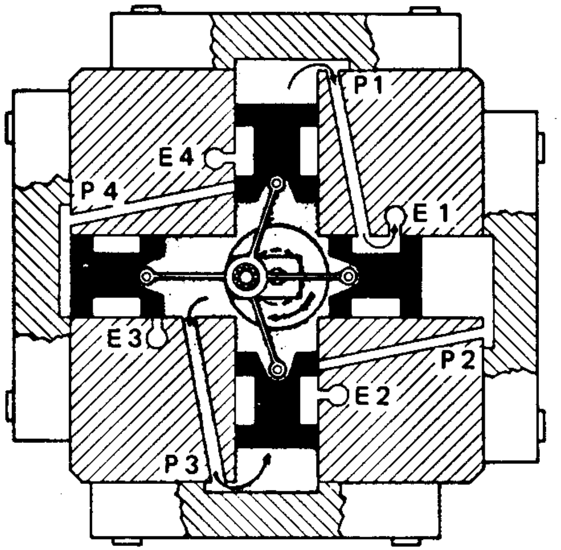


Figure 6.2.5-1 Piston-Type Positive-Displacment Flowmeter

- These meters are actually positive-displacement fluid motors in which friction and inertia have been reduced to a minimum.
- A self-porting four-piston is designed with fluid entering at $P3$ and leaving at $E1$, causing a clockwise shaft rotation which sequentially brings pairs ($P4$-$E2$, $P1$-$E3$, $P2$-$E4$, $P3$-$E1$) of inlet/outlet ports into operation through the three-way valve action of each piston.

- To eliminate friction-producing fluid seals, the meter shaft is coupled to the speed sensor magnetically through a nonmagnetic wall.
- Digital (pulse-rate) output is also available that uses photo-optic techniques or rotary differential-transformer methods.
- An advantage of positive-displacement meter is their insensitivity to distorted inlet/outlet flow profiles; thus flow straighteners and/or long runs of straight pipe upstream/downstream of the meter usually are not required.

6.2.6 Electromagnetic Flowmeters

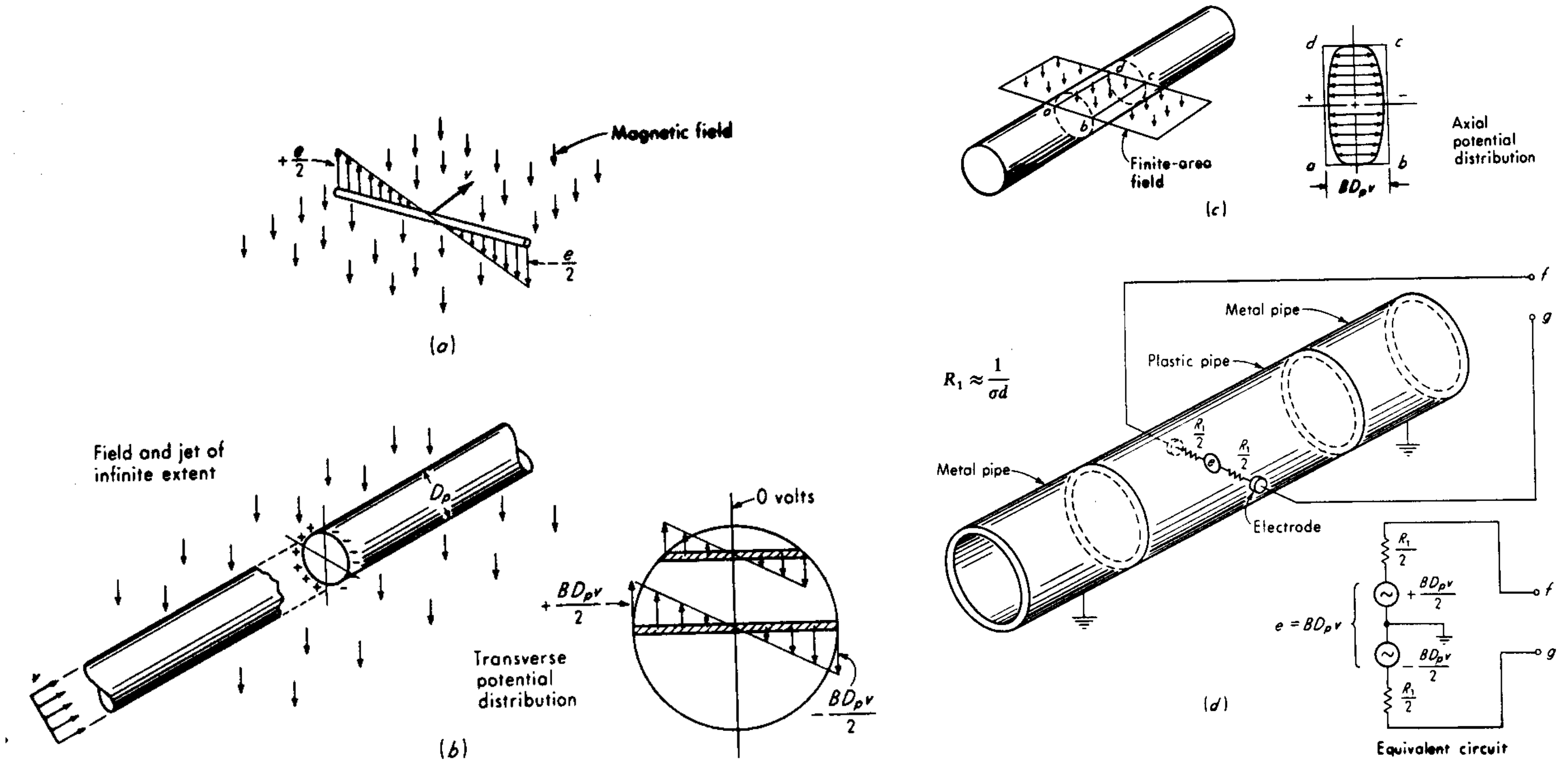


Figure 6.2.6-1 Electromagnetic Flowmeter

Figure 6.2.6-2 Electromagnetic Flowmeter

- The electromagnetic flowmeter is an application of the principle of induction.

The induced voltage,

$$e = Blv \tag{6.2.6-1}$$

where *B*: field flux density, *l*: conductor length, and *v*: conductor velocity.

- The induced voltage will cause a current *i* to flow through the moving conductor, which has a resistance *R*, causing an *iR* drop, so that the terminal voltage of the moving conductor becomes *e* - *iR*.

- The maximum voltage difference is found across the ends of a horizontal diameter and is BD_pv in magnitude.
- In a practical situation, the magnetic field is of limited extent, thus no voltage is induced in that part of the jet outside the field. Since these parts of the fluid are, however, still conductive paths, they tend partially to short-circuit the voltages induced in the section exposed to the field; thus the voltage is reduced from the value BD_pv.
- If the field is sufficiently long, this effect will be slight at the center of the field length. A length of 3 diameters usually is sufficient.
- The pipe must be nonmagnetic to allow the field to penetrate the fluid and usually is nonconductive (plastic, for instance).
- This nonconductive pipe has two electrodes placed at the points of maximum potential difference.
- These electrodes then supply a signal voltage to external indicating or recording apparatus.
- Because it is impractical to make the entire piping installation nonconductive, a short length (the flowmeter itself) of nonconductive pipe must be coupled into an ordinary metal-pipe installation.
- Since the fluid itself is conductive, this means that there is a conductive path between the electrodes. This path is split into two equal parts $R_1/2$ and containing the signal source $e = BD_pv$.
- The magnitude of this source resistance determines the loading effect of any external circuit connected to the electrodes.
- The magnetic field used in such a flowmeter could be either constant or alternating.

- Advantages of ac systems at 50 or 60 Hz
    - reducing polarization effects at the electrodes,
    - no causing of flow-profile distortion from magnetohydrodynamic effects
    - using high-pass filtering to eliminate slow, spurious voltage drifts resulting from thermocouple and galvanic actions
    - allowing use of high-gain ac amplifiers whose drift was less than that of dc types of comparable gain.
- Disadvantage
    - The powerful ac field coils induced spurious ac signals into the measurement circuit.
- To cancel this error, the flow must be periodically stopped to get a pipe-full, zero-velocity condition and then balance control is adjusted to get a zero output reading.
- In the dc meter, a dc field is switched in a square-wave between the working value and zero, at about 3 to 6 Hz.
- When the field is zero, by storing non-zero output error and subtracting it from the total instrument output obtained when the field is next applied, an automatic zero feature, which corrects for zero errors several times a second, can be implemented.
    - Advantage includes power savings of up to 75 percent and simpler wiring practices.
    - A disadvantage in some applications is the slower response time of about 7 s. (60-Hz systems have about 2s).

- Pure dc types is employed in metering liquid metals, such as mercury.
    - There is no polarization problem exists.
    - An insulating pipe liner is not needed, since the conductivity of the liquid metal is very good relative to that of an ordinary metal (stainless-steel) pipe.
    - No special electrodes are necessary, the output voltage being tapped off the metal pipe itself at the points of maximum potential difference.
- Small, inexpensive pure dc meters using a permanent magnet field and special sintered silver-silver chloride electrodes, which greatly ease the classical electrode instability problems of dc meters, recently have appeared.
- Because of the permanent-magnet field and dc operation, the electronics can be very simple, giving a fast-response instrument of modest stability and accuracy useful in various research applications.
- Some general features of electromagnetic flowmeters include the lack of any flow obstruction; ability to measure reverse flows; insensitivity to viscosity, density, and flow disturbances as long as the velocity profile is symmetrical; wide linear range; and rapid response to flow changes (instantaneous for a pure dc system; limited by the field frequency in an ac or switched dc system).

6.2.7 Ultrasonic Flowmeters

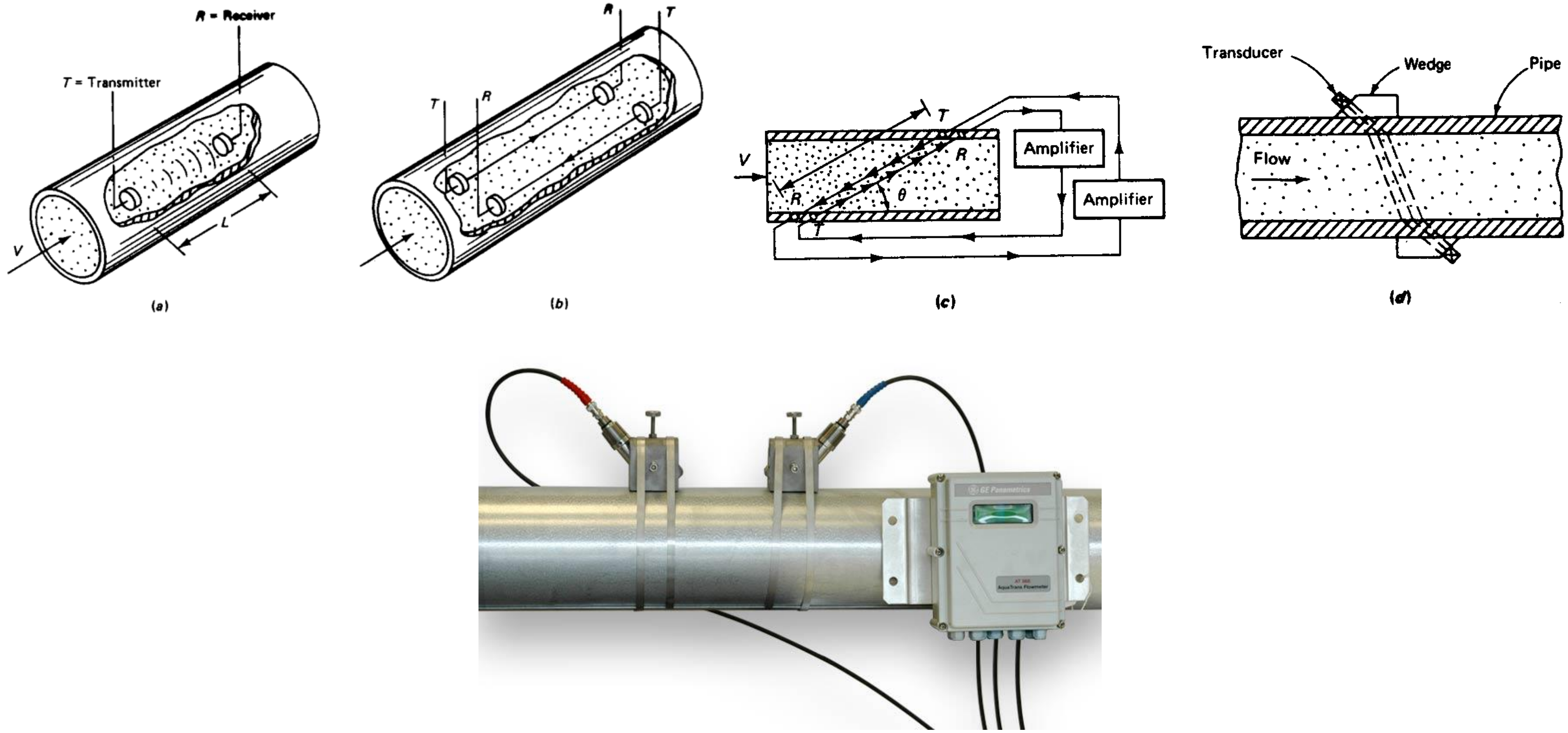


Figure 6.2.7-1 Ultrasonic Flowmeters

- The term ultrasonic refers the pressure disturbances which usually are short bursts of sine waves whose frequency is above the range audible to human hearing, about 20,000 Hz. A typical frequency might be 10 MHz.
- A common approach is to utilize piezoelectric crystal transducers for both transmitters and receivers.
- In a transmitter, electrical energy in the form of a short burst of high-frequency voltage is applied to a crystal, causing it to vibrate. If the crystal is in contact with the fluid, the vibration will be communicated to the fluid and propagated through it.
- The receiver crystal is exposed to these pressure fluctuations and responds by vibrating. The vibratory motion produces an electrical signal in proportion, according to the usual action of piezoelectric displacement transducers.
- For a crystal to be an efficient transmitter of acoustic energy, its diameter D must be large compared with the wavelength λ of the oscillation.
- The conical beam projected from a circular crystal has a half-angle a given by sin $\alpha = 1.2\lambda/D$; thus the desired small angles also require a small λ/D ratio.

With zero flow velocity the transit time t_0 of pulses from the transmitter to the receiver,

$$t_0 = \frac{L}{c} \tag{6.2.7-1}$$

where L : distance between transmitter and receiver and c : acoustic velocity in fluid.

If the fluid is moving at a velocity *V*, the transit time *t*,

$$t = \frac{L}{c+V} = L\left(\frac{1}{c} - \frac{V}{c^2} + \frac{V^2}{c^3} - \cdots\right) \approx \frac{L}{c}\left(1 - \frac{V}{c}\right) \quad (6.2.7\text{-}2)$$

(From the series $a + ab + ab^2 + \cdots = \frac{a}{1-b}$), $\Delta t = t_0 - t$,

$$\Delta t = \frac{LV}{c^2} \quad (6.2.7\text{-}3)$$

If t_1 is the transit time with the flow and t_2 is the transit time against the flow,

$$\Delta t = t_2 - t_1 = \frac{L}{c-V} - \frac{L}{c+V} = \frac{2VL}{c^2 - V^2} \approx \frac{2VL}{c^2} \quad (6.2.7\text{-}4)$$

- This Δt is twice as large as before and also is a time increment that physically exists and may be measured directly. However, the dependence on c^2 is still a drawback.
- Two self-excited oscillating systems can be created by using the received pulses to trigger the transmitted pulses in a feedback arrangement.
- The pulse repetition frequency in the forward propagating loop is $1/t_1$ while that in the backward loop is $1/t_2$. The frequency difference is $\Delta f = 1/t_1 - 1/t_2$.

$$\Delta f = \frac{c + V\cos\theta}{L} - \frac{c - V\cos\theta}{L} = \frac{2V\cos\theta}{L} \quad (6.2.7\text{-}5)$$

- Now it is independent of c and thus not subject to errors due to changes in c.
- Two methods of reading out the frequency difference Δf are common: the sing-around and the up-down counter.
- In the sing-around method, the two signals of different frequency are multiplied, giving an output with sum and difference frequencies. Filtering then extracts the difference frequency.
- The up-down counter scheme accumulates the two frequencies separately for 5 to 20 s. and then subtracts them, giving an averaging effect, which may reduce spurious noise problems.
- To cut costs and reduce errors due to path-length changes caused, most flowmeters of now use two transducers, rather than the four. This is achieved by timesharing the single pair of transducers so it is used alternately for upstream and downstream propagation. High-speed electronic switching makes this possible, and since there is now only one value of L, there is no bias error ($\Delta f \neq 0$ when $V = 0$) and independence of c is retained.
- In the clamp-on type of ultrasonic meter, the transducers are outside the pipe, which eliminates the fouling problems and gives an extremely convenient installation devoid of transducer/fluid compatibility problems.
- Generally, the existing pipe can be employed, and the transducers are attached by mechanical clamping or adhesive bonds, leaving the pipe intact and obstruction-free.
- Clamp-on meters exhibit their own problem areas, such as acoustic short circuiting (receiving transducer feels both liquid-path and pipe-path signals) and changes in beam path due to clamp slippage, temperature expansion, etc. However, these can often be overcome by proper design or use of compensation methods.

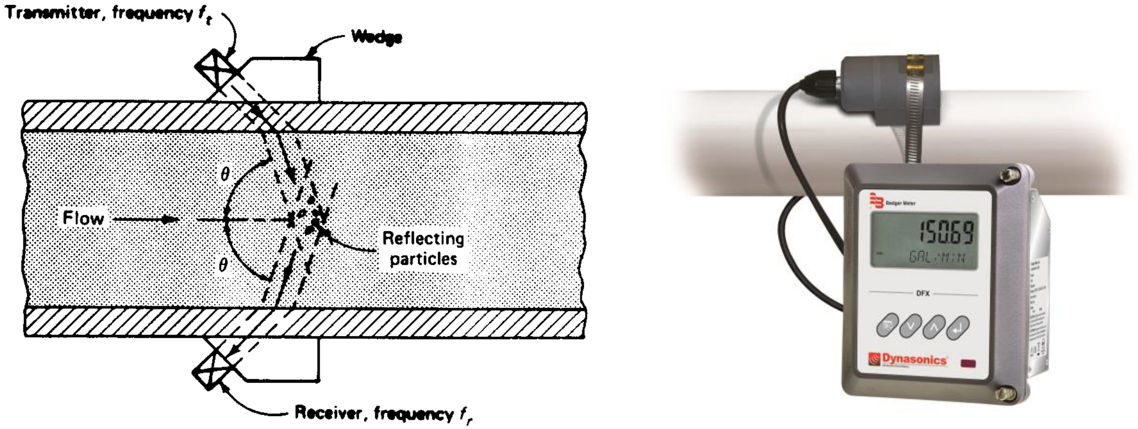


Figure 6.2.7-2 Clamp-On Doppler Ultrasonic Flowmeter

- By using the doppler principle, whereas the transit time meters require relatively clean fluid to minimize signal attenuation and dispersion, doppler meters will not work at all unless sufficient reflecting particles and/or air bubbles are present.
- Doppler meters usually employ a clamp-on configuration.
- The transmitter propagates a continuous-wave (CW) ultrasonic (0.5 to 10 MHz) signal into the fluid, whereupon particles (assumed to be moving at velocity *V*) reflect some of the energy to the receiver.

$$\Delta f = f_t - f_r = \frac{2 f_t \cos\theta}{c} V \qquad (6.2.7\text{-}6)$$

6.2.8 Vortex-Shedding Flowmeters

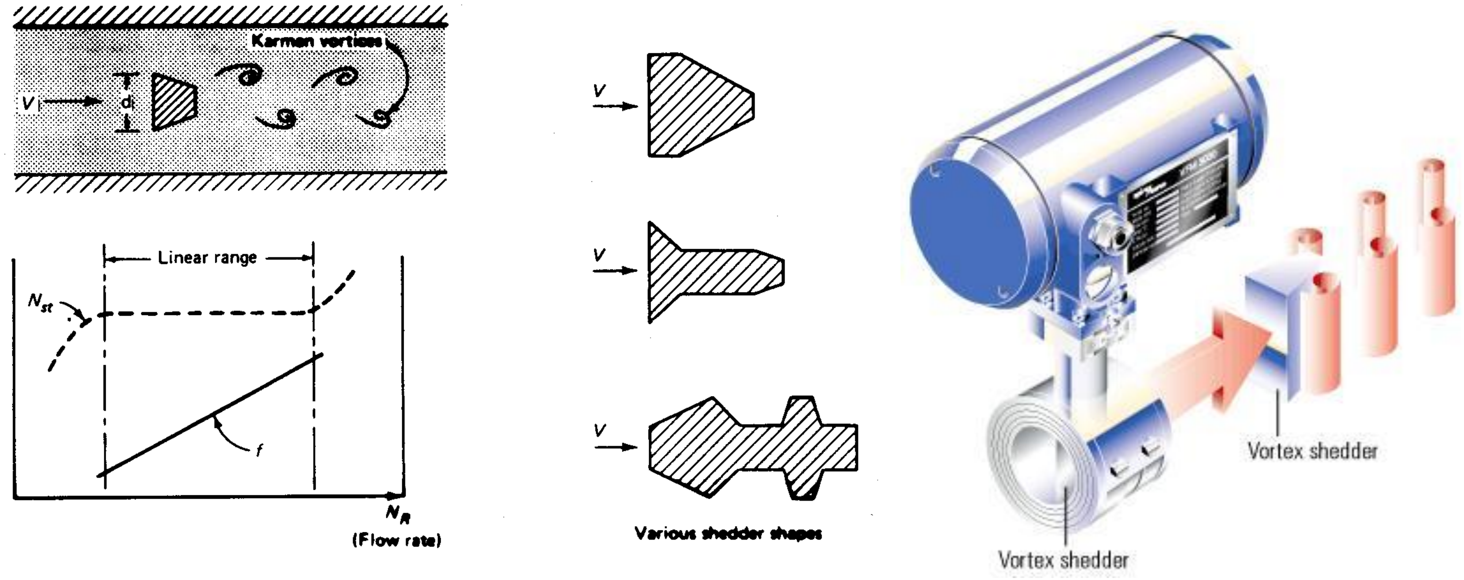


Figure 6.2.8-1 Vortex-Shedding Flowmeter Principles

- The phenomenon of vortex shedding (Karman vortex street) downstream of an immersed solid body of blunt shape when a steady flow impinges upstream is well known in fluid mechanics and is the basis of the vortex-shedding flowmeter.

- When the pipe Reynolds number N_R exceeds about 10,000, vortex shedding is reliable.

The shedding frequency *f*,

$$f = \frac{N_{st}V}{d} \tag{6.2.8-1}$$

where V : fluid velocity, d =: characteristic dimension of shedding body, and N_{st} : Strouhal number, an experimentally determined number, nearly constant in the useful flowmetering range.

- By proper design of the shedding body shape, N_{st} can be kept nearly constant over a wide range of N_R (and thus flow rate), making *f* proportional to *V*.
- The vortices cause alternating forces or local pressures on the shedder whose frequency can be measured by
    - Piezoelectric and strain-gage methods can be employed to detect these.
    - Hot-film thermal anemometer sensors buried in the shedder can detect the periodic flow-velocity fluctuations.
    - The interruption of ultrasonic beams by the passing vortices can be used to count them.
    - Vortex-induced differential pressures will cause oscillation of a small caged ball whose motion can be detected with a magnetic proximity pickup.

6.3 Gross Mass Flow Rate

6.3.1 Volume Flowmeter Plus Density Measurement

$$\rho V g - m g = F_b$$

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

$$\rho \propto \Delta p$$

acoustic impedance $\propto \rho c$ (sound speed)

radiation $\propto \rho$

$$P = \rho R T$$

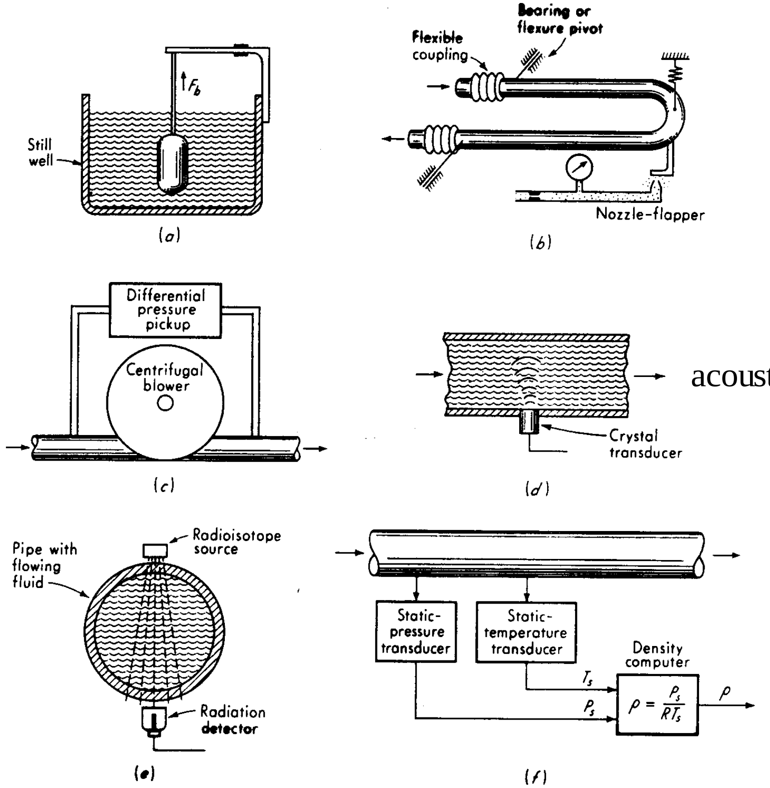


Figure 6.3.1-1 Fluid-Density Measurement

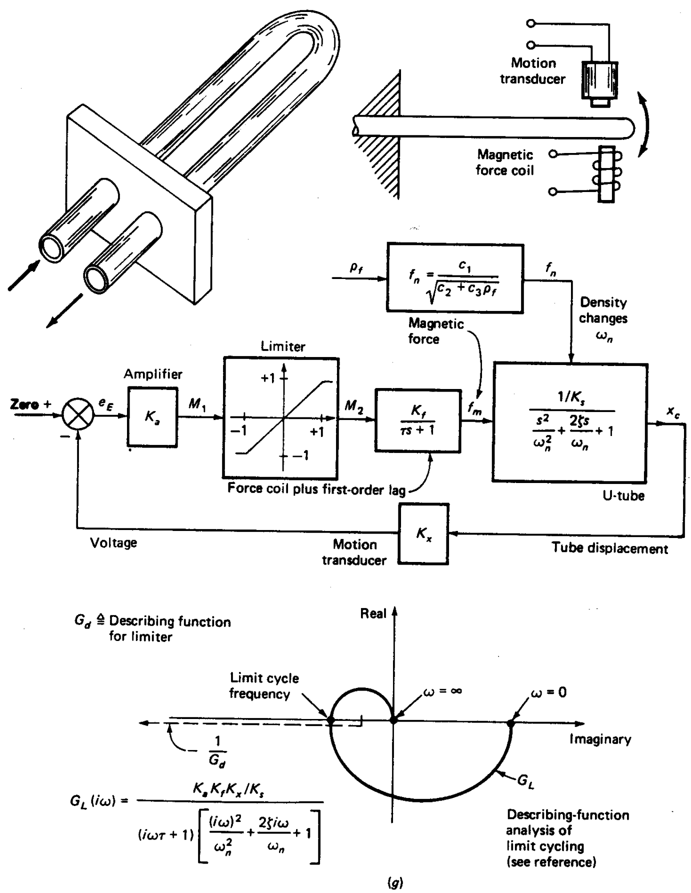


Figure 6.3.1-2 Densitometer

- Densitometers based on the effect of density on the natural frequency of a vibrating system are available for both liquids and gases.

Natural frequency f_n,

$$f_n = \frac{0.5605\sqrt{EI}}{\sqrt{\pi}L^2}\sqrt{\frac{1}{\rho_f R_i^2 + \rho_t (R_o^2 - R_i^2)}} \tag{6.3.1-1}$$

where L : tube length, I : tube-area moment of inertia (bending), ρ_f : liquid density, ρ_t : tube-material mass density, and R_i, R_o : tube inside and outside radii.

- An intentionally unstable, amplitude-limited feedback system maintains continuous oscillation at a limit-cycling frequency. This frequency is very close to the tube's density-dependent natural frequency and tracks it as the natural frequency changes with density.

6.3.2 Direct Mass Flowmeters

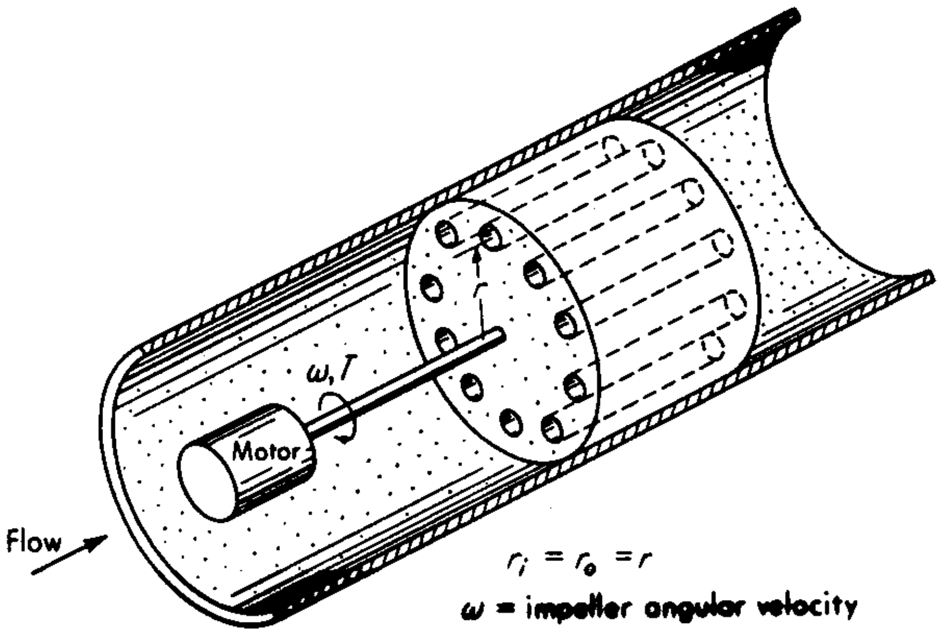


Figure 6.3.2-1 Angular-Momentum Element

- A principle widely employed in aircraft fuel-flow measurement depends on the moment-of-momentum law of turbomachines.

For one-dimensional, incompressible, lossless flow through a turbine or an impeller wheel, the torque *T* exerted by an impeller wheel on the fluid (minus sign) or on a turbine wheel by the fluid (plus sign),

$$T = G(V_{ti} r_i - V_{to} r_o) \tag{6.3.2-1}$$

where G : mass flow rate through wheel, V_{ti} : tangential velocity at inlet, V_{to} : tangential velocity at outlet, r_i : radius at inlet, r_o : radius at outlet, and T =torque.

If the incoming flow has no rotational component ($V_{ti} = 0$); and if the axial length of the impeller is enough to make ($V_{to} = r\omega$, the driving torque necessary on the impeller,

$$T = r^2 \omega G \tag{6.3.2-2}$$

- Since r and ω are constant, the torque T is a direct and linear measure of mass flow rate G.
- However, for $G = 0$, torque will not be zero, because of frictional effects; furthermore, viscosity changes also would cause this zero-flow torque to vary.
- A variation on this approach is to drive the impeller at constant torque (with some sort of slip clutch). Then, impeller speed is a measure of mass flow rate.

$$\omega = \frac{T / r^2}{G} \tag{6.3.2-3}$$

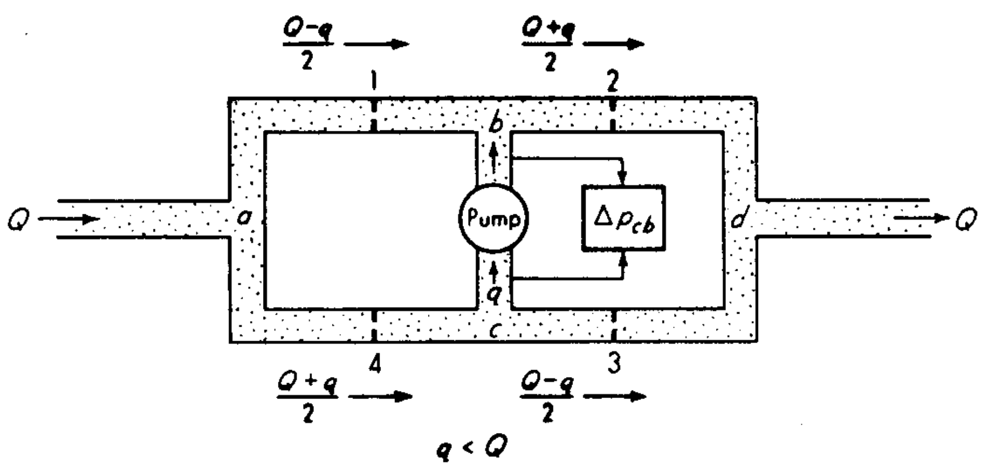


Figure 6.3.2-2 Bridge-Circuit Flowmeter

- For a given fluid, the pressure drop across an orifice is proportional to ρQ^2.
- In a bridge-circuit flowmeter, four identical orifices are connected into a bridge circuit. A positive-displacement pump of fixed displacement runs at constant speed and volume flow rate q. The pressure rise across this pump is Δp_{cb}.

The output signal Δp_{cb},

$$\Delta p_{cb} = K\rho\left(\frac{Q+q}{2}\right)^2 - K\rho\left(\frac{Q-q}{2}\right)^2 = Kq\rho Q = K_1 G \qquad (6.3.2\text{-}4)$$

- All orifice flow rates must be maintained at high enough Reynolds numbers that the discharge coefficients of all orifices are equal and do not vary when Q varies.

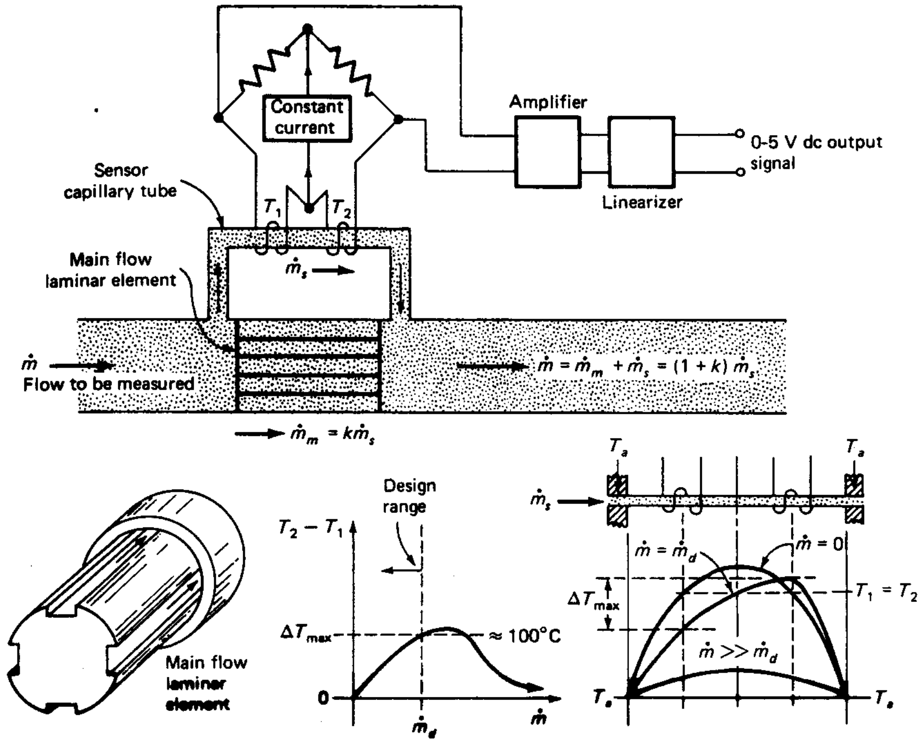


Figure 6.3.2-3 Mass Flowmeter Based on Thermal Principles

- In mass flowmeters, the sensor capillary tube has a length 50 to 100 times of its diameter, giving laminar flow for the entire measuring range.
- Two electric windings on the outer surface of the sensor tube act as both heaters and resistance-temperature detectors and provide a constant-heat input to the fluid at all flow rates.

- For zero flow rate ($\dot{m}_s = 0$) the system is thermally symmetric, giving the symmetric temperature profile, and making $\Delta T = T_1 - T_2$ equal to zero. The two windings are in adjacent legs of a bridge circuit, and bridge resistances are selected to give a balanced bridge (no output voltage) for the zero-flow condition.
- With a steady fluid mass flow rate $\dot{m}_s$ from left to right, the new temperature profile will be unsymmetric, with T_1 dropping a large amount but T_2 staying nearly constant.
- Temperature T_1 drops because the mass flow of hot fluid leaving this region carries energy away at a rate $\dot{m}_s c_p T_1$, a drop in T_1 is proportional to $\dot{m}_s$.
- Temperature T_2 changes little when flow occurs since the temperature difference of the coil with the flowing fluid is less.

7. Temperature Sensors

- Temperature, unlike other quantities such as length, time, or mass, is an abstract quantity that must be defined in terms of the behavior of materials as the temperature changes.
- Some examples of material behavior that have been used in the measurement of temperature include change in volume of a liquid, change in length of a bar, change in electrical resistance of a wire, change in pressure of a gas at constant volume, and change in color of a lamp filament.
- The International Practical Temperature Scale has been defined in terms of the behavior of a number of materials at thermodynamic fixed points. These six points correspond to an equilibrium state during a phase transformation of a particular material.

$$\frac{R}{4} = \frac{C}{5} = \frac{F-32}{9} = \frac{K-273}{5} \tag{7-1}$$

Material	Equilibrium State Phase Transformation	Temperature °C	°F
Oxygen	Liquid–vapor	− 182.962	− 297.33
Water[a]	Solid–liquid–vapor	0.01	32.02
Water	Liquid–vapor	100.00	212.00
Zinc	Solid–liquid	419.58	787.24
Silver	Solid–liquid	961.93	1763.47
Gold	Solid–liquid	1064.43	1947.97

[a] Triple point of water.

Table 7-1 Six Primary Points of the International Practical Temperature Scale

Material	Equilibrium State Phase Transformation	Temperature °C	Temperature °F
Hydrogen	Solid–liquid–vapor	−259.34	−434.81
Hydrogen	Liquid–vapor	−252.87	−423.17
Neon	Liquid–vapor	−218.789	−361.820
Water	Liquid–solid	0	32
Tin	Liquid–solid	231.9681	449.5426
Lead	Liquid–solid	327.502	621.504
Sulfur	Liquid–vapor	444.6	832.3
Antimony	Liquid–solid	630.74	1167.33
Aluminum	Liquid–solid	660.37	1220.67

Table 7-2 Other Secondary Points of the International Practical Temperature Scale

Temperature Range (°C)	Sensor	Fixed Point	Equation
−190 to 0	Platinum thermometer	Oxygen, ice, steam, sulfur	Reference equation
0 to 660	Platinum thermometer	Ice, steam, sulfur	Parabola
660 to 1063	10% rhodium platinum thermocouple	Antimony, silver, gold	Parabola
Above 1063	**Optical pyrometer**	—	**Planck's Law**

Table 7-3 Temperature Range, Sensors, and Interpolation Equations for the International Practical Temperature Scale

7.1 Resistance Thermometers

- Resistance thermometers consist of a sensor element that exhibits a change in resistance with any change in temperature, a signal conditioning circuit that converts the resistance change to an output voltage, and appropriate instrumentation to record and display the output voltage.
- Two different types of sensors are normally employed: resistance temperature detectors (RTDS) and thermistors.

7.1.1 Resistance Temperature Detectors (RTDS)

- A typical RTD consists of a wire coil for a sensor with a framework for support and a sheath for protection, a linearizing circuit, a Wheatstone bridge, and a voltage display instrument.
- The sensor is a resistive element that exhibits a resistance-temperature relationship.

$$R = R_0(1 + \gamma_1 T + \gamma_2 T^2 + \cdots + \gamma_n T^n) \qquad (7.1.1\text{-}1)$$

where γ_1, γ_2, …, γ_n : temperature coefficients of resistivity, and R_0 : the resistance of the sensor at a reference temperature T_0. The reference temperature is usually specified as $T_0 = 0°C$.

- The number of terms for any application depends upon the material used in the sensor, the range of temperature, and the accuracy required in the measurement.

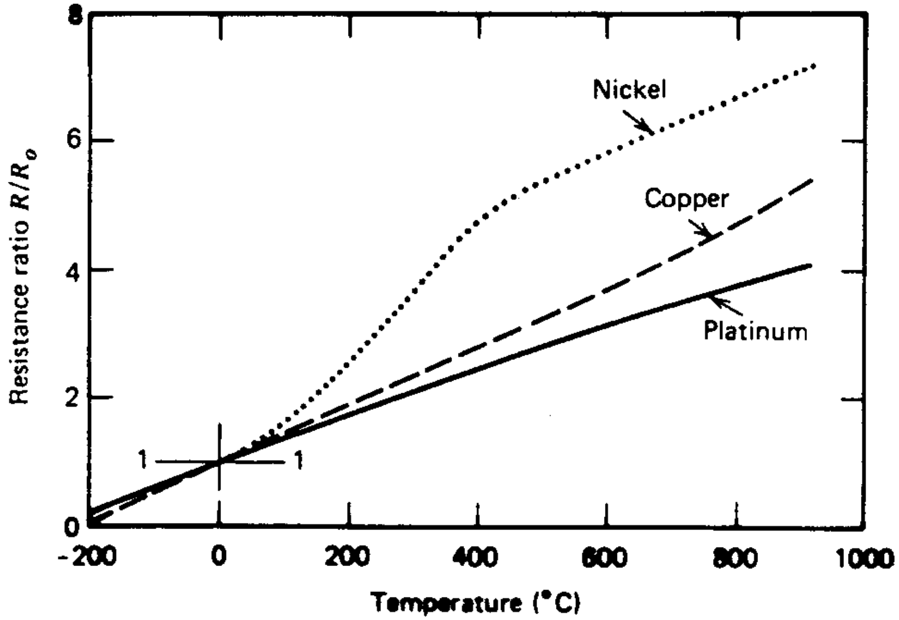


Figure 7.1.1-1 Resistance-Temperature Curves for Nickel, Copper, and Platinum

- For a limited range of temperature, the linear form is often used to relate resistance change to temperature change.

$$\frac{\Delta R}{R_0} = \gamma_1 (T - T_0) \qquad (7.1.1\text{-}2)$$

- When error due to the neglect of nonlinear terms becomes excessive. Either linearizing circuits can be used to compensate for the nonlinearities, or additional terms can be retained to relate the measured ΔR to the unknown temperature T.
- Retaining the temperature coefficients γ_1 and γ_2 yields the second-order relationship.

$$\frac{\Delta R}{R_0} = \gamma_1 (T - T_0) + \gamma_2 (T - T_0)^2 \tag{7.1.1-3}$$

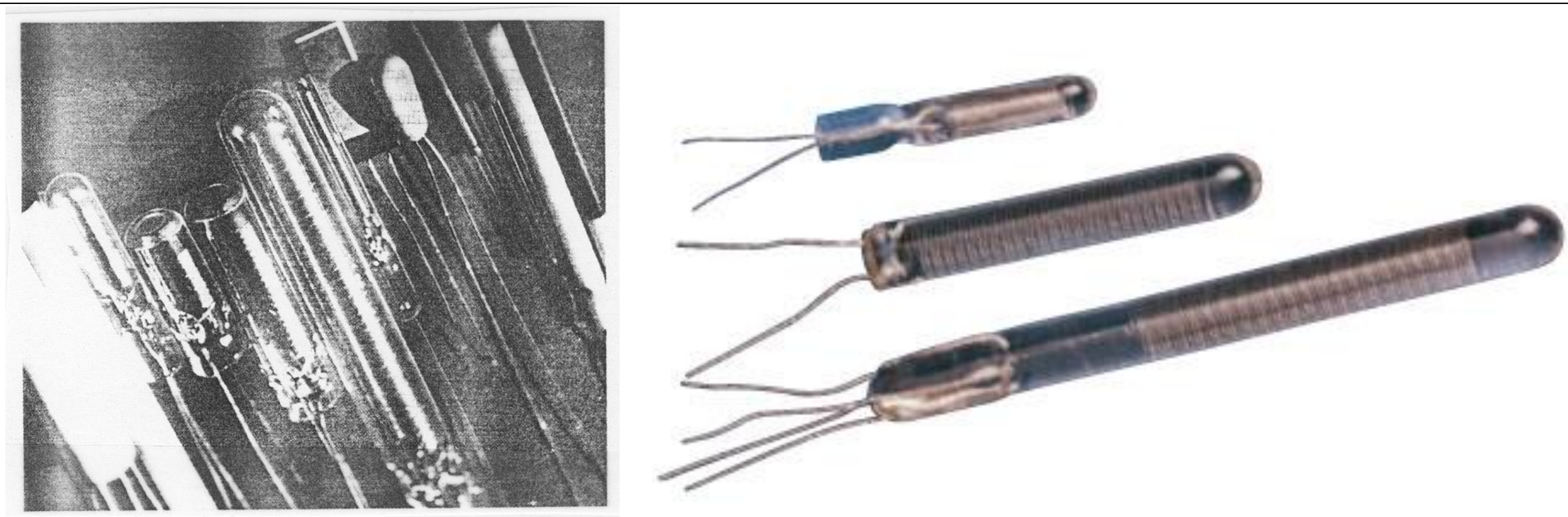


Figure 7.1.1-2 Selection of Resistance Temperature Detectors

- One widely used sensor consists of a high-purity platinum wire wound on a ceramic core. The element is stress relieved after winding, immobilized against strain, and artificially aged during fabrication to provide for long-term stability.
- The sensing element is usually protected by a sheath fabricated from stainless steel, glass, or a ceramic. Such sheaths are made pressure tight to protect the sensing element from the corrosive effects of both moisture and the process medium.
- Lead wires from the sensor exit from the sheath through a specially designed seal.
- Epoxy cements are used for the low- temperature range (< 260°C).
- Glass and ceramic cements are used for the high-temperature range (> 260°C).
- Since the temperature at the sheath exit is usually much lower than the process temperature being monitored, lead wires insulated with Teflon or impregnated fiberglass are often suitable for use with process temperatures as high as 750°C (1380°F).
- The immersion type transducers are inserted in the medium to measure fluid temperatures.
- The response time in this application is relatively long (between 1 and 5 s. is required to approach 100 percent response).

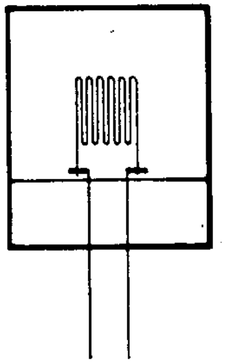


Figure 7.1.1-3 Resistance Temperature Detector for Surface Temperature Measurements

- Resistance temperature detectors for surface temperature measurements utilize either a thin-wire element, or a thin-film element that resembles an electrical resistance strain gage and is fabricated by using the photoetching process.
- The foil sensors are available on either polyimide or glass-fiber-reinforced epoxy resin carriers.
- The wire models are available with either teflon or phenolic-glass carriers or as free filaments.
- The sensors with carriers are bonded to the surface with an adhesive suitable for the temperature range to be encountered.
- The free filaments are normally mounted by flame spraying.
- The response time of a thin-film sensor compares favorably with a small thermocouple; therefore, measurement of rapidly changing surface temperatures is possible.

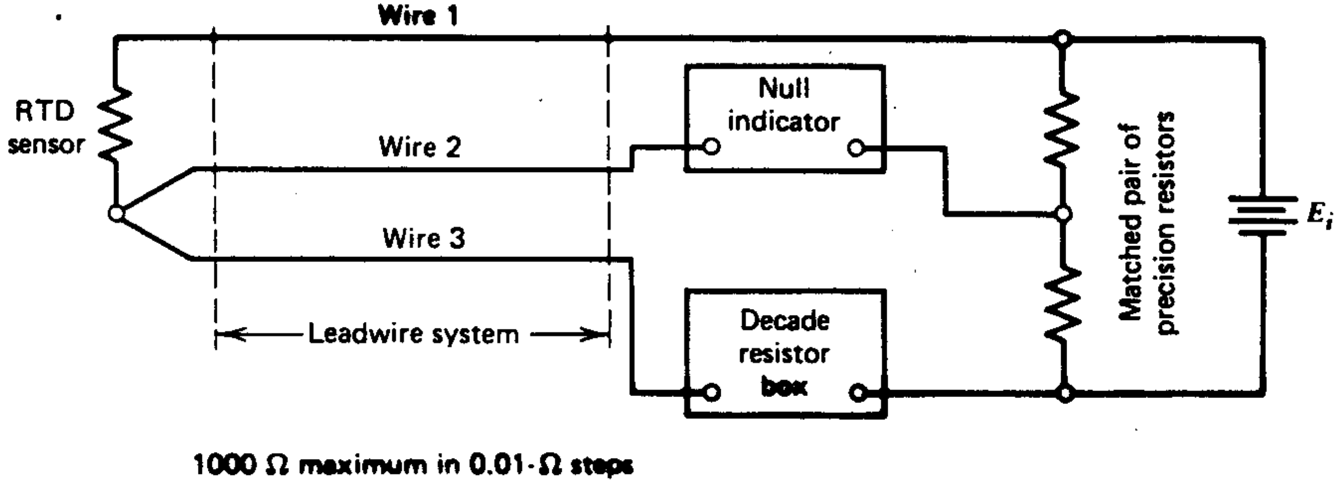


Figure 7.1.1-4 Wheatstone-Bridge Circuit with Lead-Wire Compensation and Manual Reading of the Output form a Resistance Temperature Detector

- The output from a resistance temperature detector (RTD) is a resistance change $\Delta R/R$ that can be conveniently monitored with a Wheatstone bridge.
- The RTD is installed in one arm of the bridge, a decade resistance box is placed in an adjacent arm, and a matched pair of precision resistors are inserted in the remaining arms to complete the bridge.
- With the three-lead-wire arrangement, any temperature-induced resistance change in the lead wires is canceled.
- The Wheatstone bridge shown in the figure can be balanced by adjusting the decade resistance box.

- In the null position, the reading on the box is exactly equal to the resistance of the RTD.
- The temperature is then determined from a table of resistance versus temperature for the specific RTD being used.
- The error occurring due to self-heating of the sensor can be avoided by maintaining excitation at 0.25 V or less.
- The resistance change with temperature in the RTD is large; therefore, adequate resolution of temperature can be achieved with very low excitation voltages.

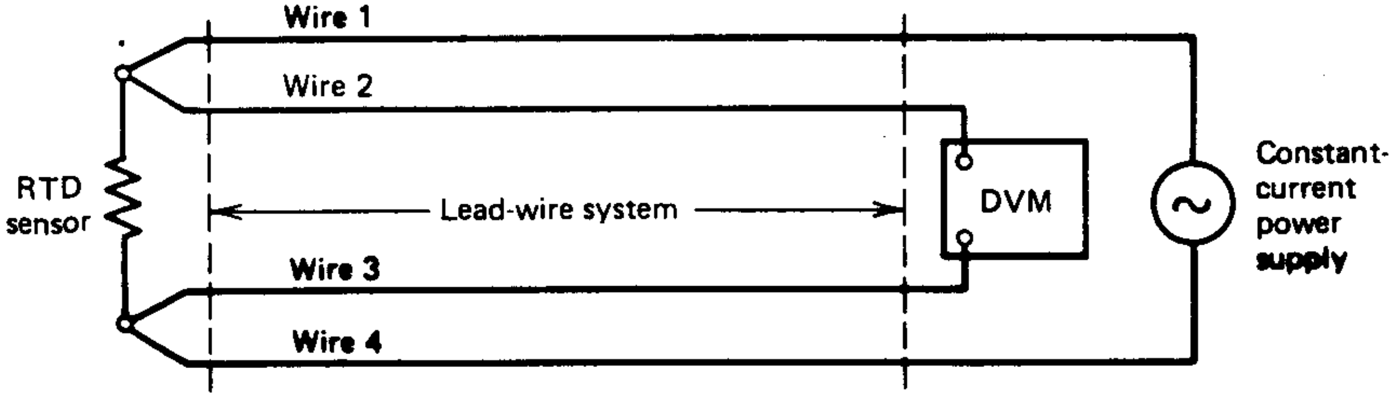


Figure 7.1.1-5 Constant Current Potentiometer Circuit with Lead-Wire Compensation and Automatic Reading of the Output from an RTD Sensor

- Another circuit is the constant-current potentiometer circuit.
- The output voltage $E = IR$ from this circuit can be monitored with a digital voltmeter (DVM). If a constant current is supplied to the sensor, the output of the digital voltmeter converts easily to resistance ($R = E/I$).
- The temperature is determined from a resistance-temperature table for the sensor.
- Errors due to resistance changes in the lead wires are also eliminated by using the four-lead-wire system when R_M of the DVM is high.

- Since the sensor resistance *R* is a nonlinear function of temperature *T*, tables must be used to relate the measured resistance to the temperature.

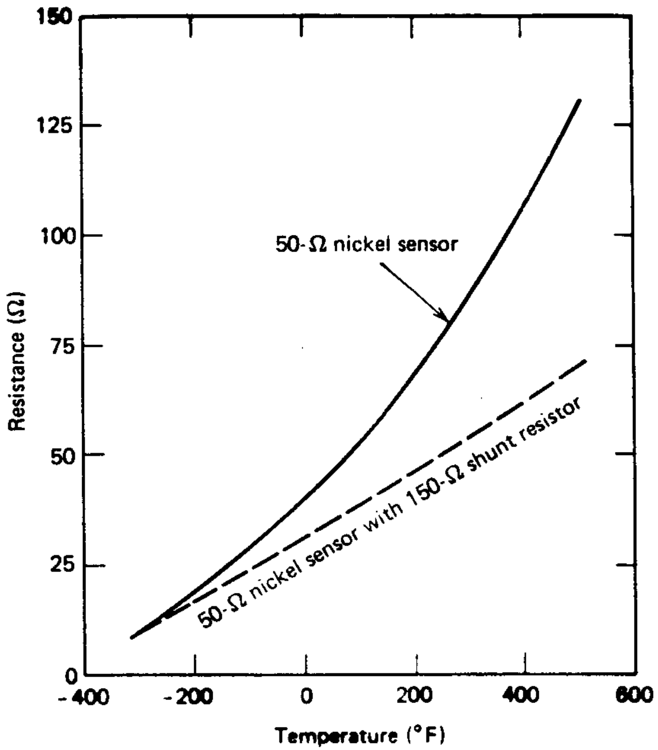


Figure 7.1.1-6 Response of Nickel Foil Resistance Temperature Detectors

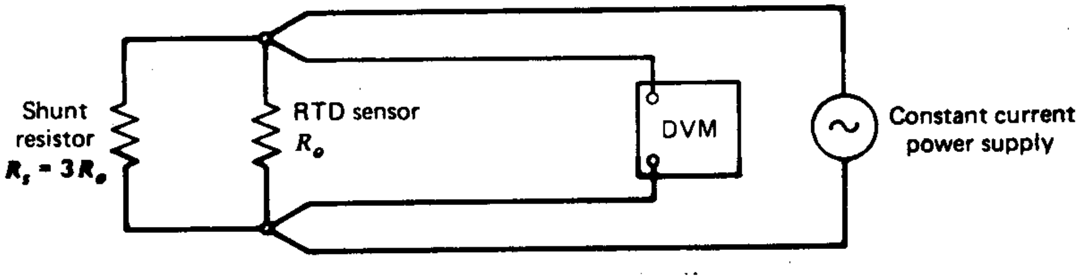


Figure 7.1.1-7 Shunt Method for Improving the Linearity of Bonded RTD Sensors

- The nonlinear response of the bonded RTD can be significantly improved by utilizing the simple shunting circuit. A shunt resistor, having a resistance value three times that of the sensor resistance, improves the linearity but reduces the output of the sensor.
- Use of a shunt resistor in the circuit does not completely compensate for the nonlinear relationship between sensor resistance and temperature; however, the deviation from linearity is small and within acceptable limits for many applications.

7.1.2 Thermistors

- Thermistors are temperature-sensitive resistors fabricated from semiconducting materials, such as oxides of nickel, cobalt, or manganese and sulfides of iron, aluminum, or copper.
- Thermistors with improved stability are obtained when oxide systems of manganese-nickel, manganese-nickel-cobalt, or manganese-nickel-iron are used.
- Conduction is controlled by the concentration of oxygen in the oxide semiconductors.
- N-type oxide semiconductors are produced when the metal oxides are compounded with a deficiency of oxygen that results in excess ionized metal atoms in the lattice (Frankel defects).
- P-type oxide semiconductors are produced when there is an excess of oxygen that results in a deficiency of ionized metal atoms in the lattice (Schottky defects).
- Semiconducting materials, unlike metals, exhibit a decrease in resistance with an increase in temperature.

The resistance-temperature relationship for a thermistor,

$$\ln(R/R_0) = \beta(1/T - 1/T_0) \qquad (7.1.2\text{-}1)$$

$$R = R_0 e^{\beta(1/T - 1/T_0)} \qquad (7.1.2\text{-}2)$$

where R : resistance of the thermistor at temperature T, R_0 : resistance of the thermistor at reference temperature T_0,

β : material constant that ranges from 3000 K to 5000 K, and T and T_0 : absolute temperatures in K.

The sensitivity S of a thermistor,

$$S = \frac{\Delta R / R}{\Delta T} = -\frac{\beta}{T^2} \tag{7.1.2-3}$$

- The very high sensitivity of thermistors results in a large output signal and good accuracy and resolution in temperature measurements.
- This very large resistance change can be converted to a voltage with a simple bridge circuit.
- Thermistors are produced by mixing two or more semiconducting oxide powders with a binder to form a slurry. Small drops (beads) of the slurry are formed over the lead wires, dried, and fired in a sintering furnace. During sintering, the metallic oxides shrink onto the lead wires and form an excellent electrical connection. The beads are then hermetically sealed by coating the beads with glass. The glass coating improves stability of the thermistor by eliminating water absorption into the metallic oxide.
- Thermistors are also produced in the form of disks, wafers, flakes, rods, and washers to provide sensors of the size and shape required for a wide variety of applications.

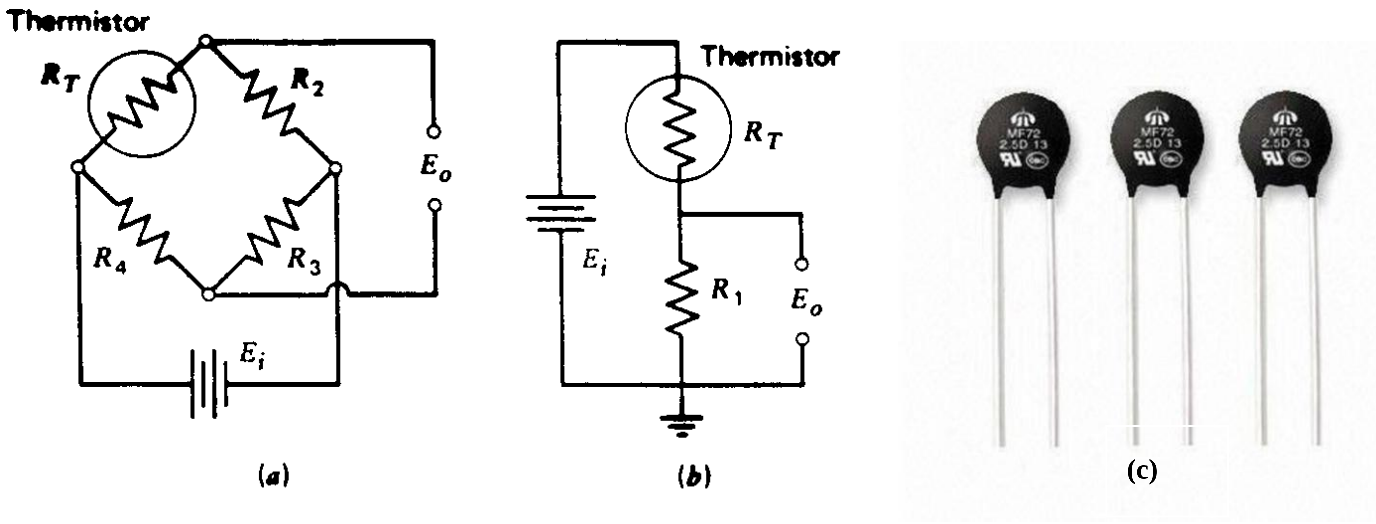


Figure 7.1.2-1 (a) Constant-Voltage Wheatstone Bridge (b) Potentiometer Circuit (c) Thermistors

If the Wheatstone bridge is initially balanced ($R_T R_3 = R_2 R_4$) and if resistors R_2, R_3, and R_4 are fixed-value precision resistors, then the output voltage ΔE_o produced by a temperature-induced change in resistance ΔR_T in the thermistor,

$$\frac{\Delta E_o}{E_i} = \frac{\Delta R_T R_3}{(R_T + \Delta R_T + R_2)(R_3 + R_4)} \qquad (7.1.2\text{-}4)$$

For the common case where $R_2 = R_3$ and $R_T = R_4$,

$$\frac{\Delta E_o}{E_i} = \frac{\Delta R_T / R_T}{(1 + \Delta R_T / R_T + R_2 / R_T)(1 + R_T / R_2)} = \frac{\Delta R_T / R_T}{2 + R_T / R_2 + R_2 / R_T + \Delta R_T / R_T + \Delta R_T / R_2} \qquad 7.1.2\text{-}5)$$

For the special case of an equal-arm bridge ($R_T = R_2 = R_3 = R_4$),

$$\frac{\Delta R_T}{R_T} = \frac{4\Delta E_o / E_i}{1 - 2\Delta E_o / E_i} \quad (7.1.2\text{-}6)$$

The thermistor resistance R_T^* at any temperature T,

$$R_T^* = R_T + \Delta R_T = R_T(1 + \Delta R_T / R_T) = R_T\left(\frac{1 + 2\Delta E_o / E_i}{1 - 2\Delta E_o / E_i}\right) \quad (7.1.2\text{-}7)$$

- The value of R_T^* is converted to temperature by using tables that list T as a function of R_T^* for the specific thermistor being used.

If the thermistor is placed in the potentiometer circuit,

$$\frac{\Delta E_o}{E_i} = -\frac{\frac{r}{(1+r)^2}(\Delta R_T / R_T)}{1 + \frac{r}{1+r}(\Delta R_T / R_T)} = -\frac{\frac{r}{1+r}(\Delta R_T / R_T)}{1 + r(1 + \Delta R_T / R_T)} \quad (7.1.2\text{-}8)$$

where $r = R_T/R_1$.

For the special case of $r = 1$,

$$\frac{\Delta R_T}{R_T} = -\frac{4\Delta E_o / E_i}{1 + 2\Delta E_o / E_i} \quad (7.1.2\text{-}9)$$

The resistance of the thermistor R_T^*,

$$R_T^* = R_T + \Delta R_T = R_T(1 + \Delta R_T / R_T) = R_T\left(\frac{1 - 2\Delta E_o / E_i}{1 + 2\Delta E_o / E_i}\right) \quad (7.1.2\text{-}10)$$

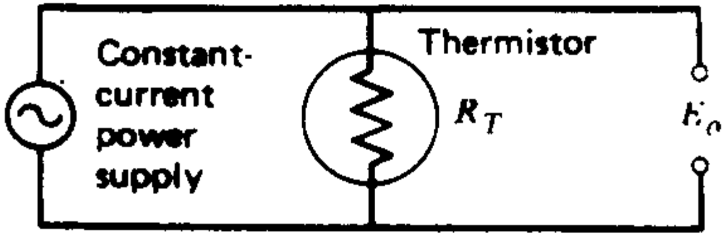


Figure 7.1.2-2 Constant-Current Potentiometer Circuit Used with Thermistors

- For determining thermistor resistance R_T^*, a circuit employs a constant-current power supply directly across the thermistor.

Since the output voltage E_o equals IR_T, the voltage change $\Delta E_o / E_o$,

$$\frac{\Delta E_o}{E_o} = \frac{\Delta R_T}{R_T} \quad (7.1.2\text{-}11)$$

The resistance of the thermistor,

$$R_T^* = R_T + \Delta R_T = R_T(1 + \Delta R_T / R_T) = R_T(1 + \Delta E_o / E_o) \quad (7.1.2\text{-}12)$$

7.2 Expansion Thermometers

The expansion (or contraction) per unit length $\Delta l/l$ of a material experiencing an increase (or decrease) in temperature ΔT,

$$\Delta l / l = \alpha \Delta T \tag{7.2-1}$$

where α : the thermal coefficient of expansion of the material.

7.2.1 Liquid-in-Glass Thermometers

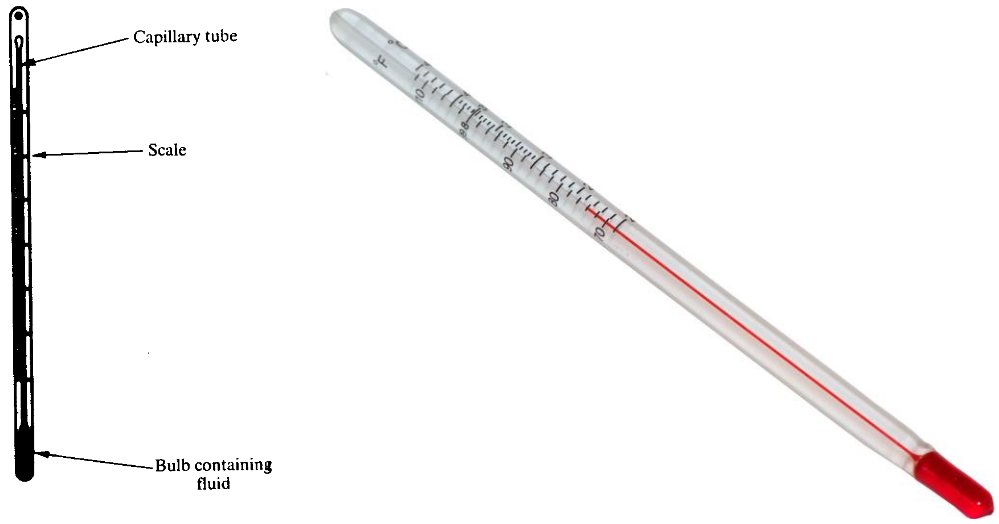


Figure 7.2.1-1 Liquid-in-Glass Thermometer

- The thermometer consists of an indexed glass capillary tube with a bulb at one end to hold a supply of fluid.
- Mercury can be used for temperatures between -39°C (-38°F) and 538°C (1000°F).
- When a lower temperature limit is needed, alcohol permits measurements at temperatures as low as -62°C (-80°F).
- Pentane can be used for measurements as low as - 218°C (-360°F).
- Glass thermometers are designed for either partial or full immersion.
- Full-immersion thermometers are calibrated to read correctly when the thermometer is completely immersed in the fluid whose temperature is being measured.
- Partial-immersion types are marked and should be immersed only to the depth indicated by the immersion mark.

7.2.2 Bimetallic Thermometers

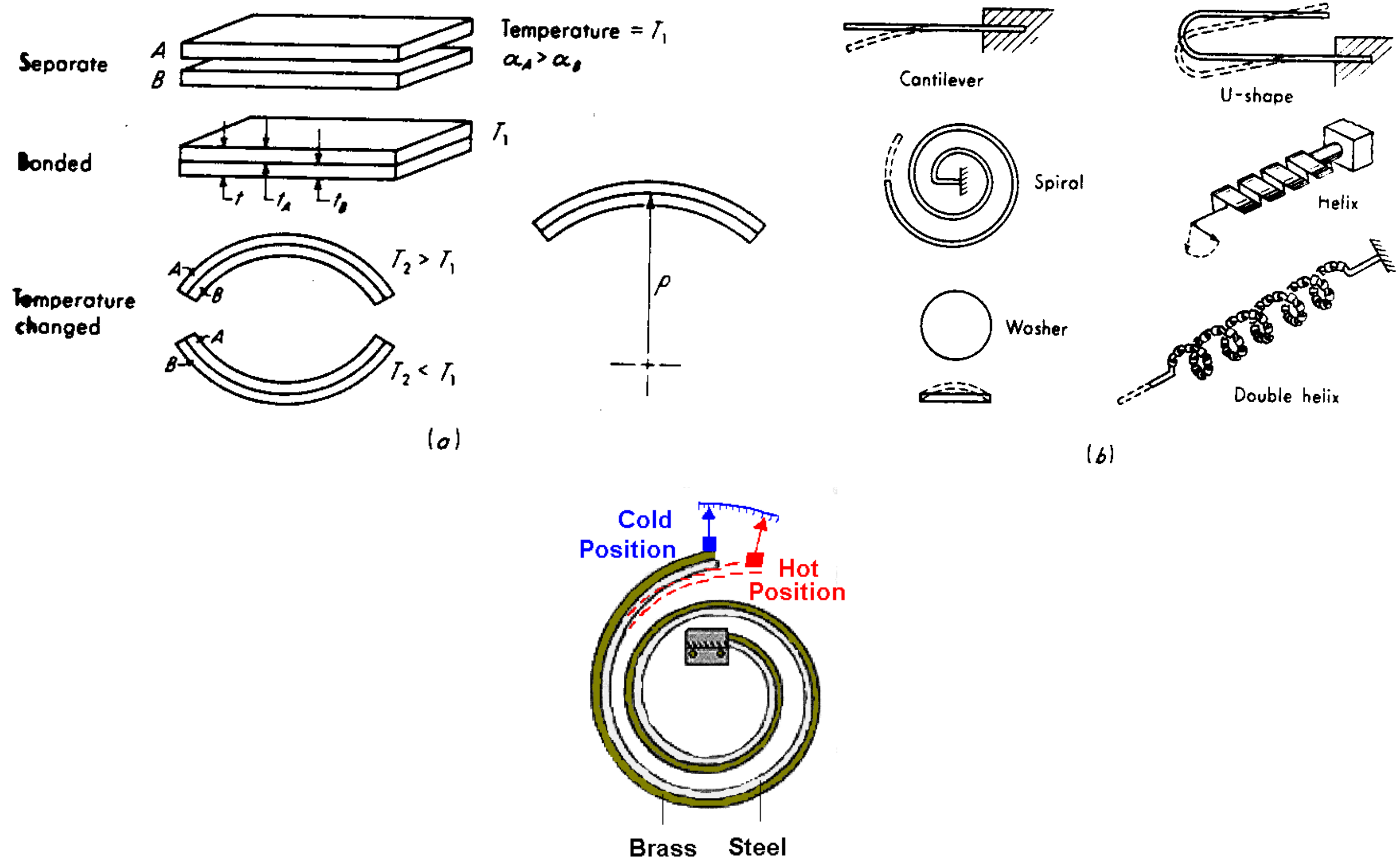


Figure 7.2.2-1 Bimetallic Element

- The sensing element in a bimetallic thermometer consists of a bonded composite of two materials.
- Material A is usually a copper-based alloy with a large coefficient of thermal expansion, while material B is usually Invar (a nickel steel), which has a very small coefficient of thermal expansion.
- When the bonded bimetallic strip is subjected to a temperature change, the differential expansion causes it to bend into a circular arc.

The radius of curvature r_a of the arc,

$$r_a = \frac{[3(1+\theta)^2 + (1+\theta e)(\theta^2 + 1/(\theta e))]t}{6(\alpha_A - \alpha_B)(1+\theta)^2 \Delta T} \tag{7.2.2-1}$$

where $\theta = t_B/t_A$: thickness ratio and $e = E_B/E_A$: modulus ratio.

- Bimetallic elements in the form of cantilever beams, spirals, washers, and helixes are inexpensive and deform significantly with relatively small changes in temperature.
- In **thermostats**, they are used to control temperature by switching the heat source on and off.

7.2.3 Pressure Thermometers

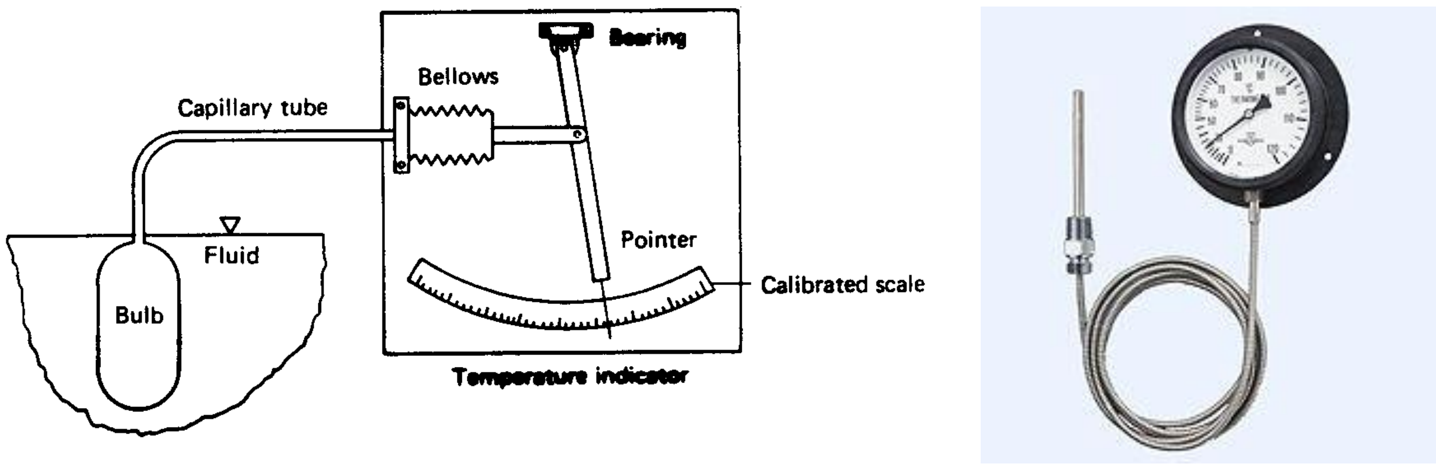


Figure 7.2.3-1 Schematic Illustration of a Pressure Thermometer

- A typical pressure thermometer consists of a bulb filled with a liquid such as mercury or xylene, a capillary tube, and a pressure sensor.
- When the bulb is subjected to a temperature change, both the bulb and the fluid experience a volume change. The differential volume change ΔV_d is proportional to the temperature change ΔT.
- The pressure is transmitted through the capillary tube to a pressure measuring transducer.

- Movement of the pointer of the pressure transducer can be transmitted through a suitable linkage system to a pointer whose position relative to a calibrated scale gives an indication of the temperature.
- The dynamic response of a pressure thermometer is poor because of the thermal lag associated with the mass of fluid in the bulb.
- Pressure thermometers filled with mercury cover the range from - 39°C to 538°C (-38°F to 1000°F), while those filled with xylene are used for the range from -100°C to 400°C (-150°F to 750°F).
- The response is linear over a large portion of the range.

7.3 Thermocouples

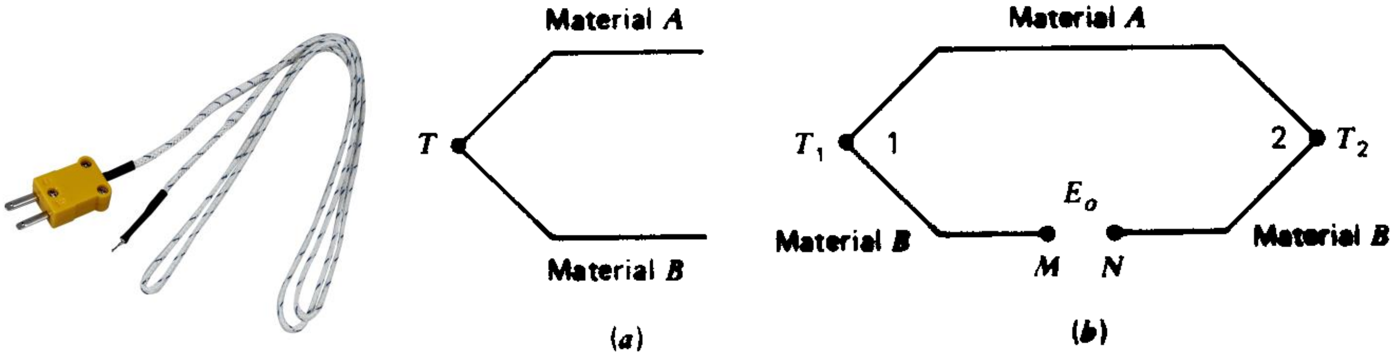


Figure 7.3-1 Thermocouple Sensor (a) Single Junction (b) Dual Junction

- A thermocouple is a very simple temperature sensor, consisting essentially of two dissimilar wires in thermal contact.
- The operation of a thermocouple is based on the Seebeck effect, which results in the generation of a thermoelectric potential when two dissimilar metals are joined together to form a junction.
- The thermoelectric effect is produced by diffusion of electrons across the interface between the two materials.
- The electric potential of the material accepting electrons becomes negative at the interface, while the potential of the material providing the electrons becomes positive.

- When this electric field becomes sufficient to balance the diffusion forces, a state of equilibrium with respect to electron migration is established.
- Since the magnitude of the diffusion force is controlled by the temperature of the thermocouple junction, the electric potential developed at the junction provides a measure of the temperature.
- The electric potential is usually measured by introducing a second junction in an electric circuit, and measuring the voltage E_o across one leg with a suitable voltmeter.

The voltage E_o across terminals M-N,

$$E_o = C_1(T_1 - T_2) + C_2(T_1^2 - T_2^2) \tag{7.3-1}$$

where C_1 and C_2 : thermoelectric constants that depend on the materials used to form the junctions,

T_1 and T_2 : junction temperatures.

- In practice, junction 1 is used to sense an unknown temperature T_1, while junction 2 is maintained at a known reference temperature T_2.
- Since the reference temperature T_2 is known, it is possible to determine the unknown temperature T_1 by measuring the voltage E_o.
- Thermocouples are calibrated over the complete range of temperature for which they are useful and tables are obtained which can be used to relate temperature T_1 to the thermoelectric voltage E_o.

7.3.1 Reference Junction Temperature

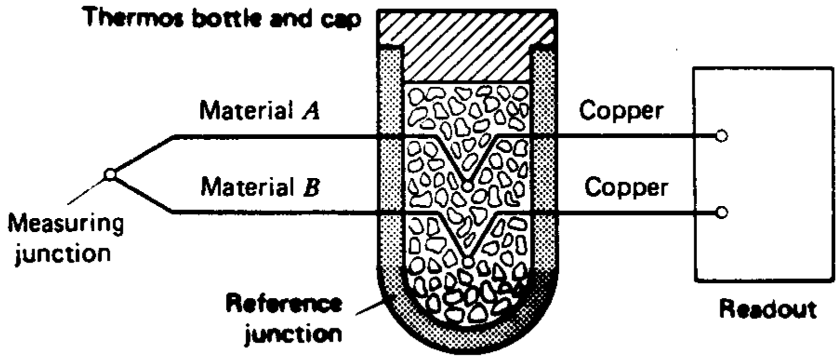


Figure 7.3.1-1 The Ice Bath Method for Maintaining a Reference Temperature at 0°C

- The reference junction is immersed in a mixture of ice and water in a thermos bottle that is capped to prevent heat loss and temperature gradients.
- An ice bath can maintain the water temperature (and thus the reference temperature) to within 0.1°C (0.2°F) of the freezing point of water.
- A very-high-quality reference temperature source employs thermoelectric refrigeration (Peltier cooling effect). Thermocouple wells in this unit contain air-saturated water that is maintained at precisely 0°C (32°F). The outer walls of the wells are cooled by the thermoelectric refrigeration elements until freezing of the water in the wells begins.

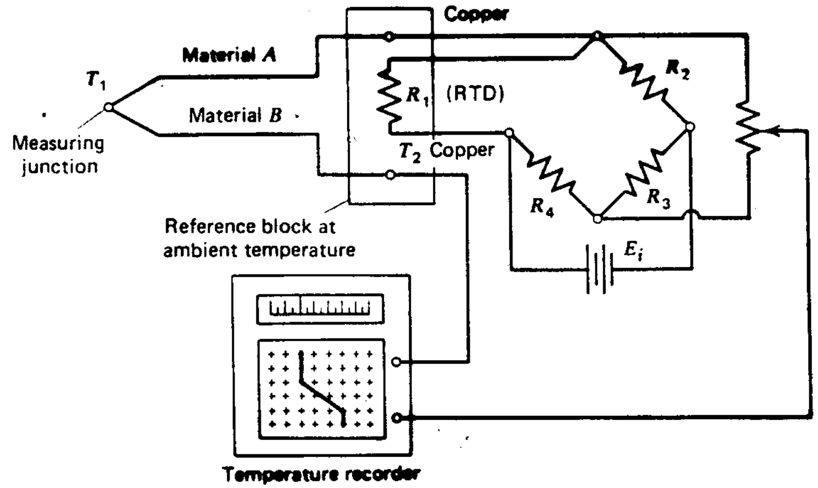


Figure 7.3.1-2 The Electrical-Bridge Method of Compensation for Changes in the Reference Temperature

- The electrical-bridge method incorporates a Wheatstone bridge with a resistance temperature detector (RTD) as the active element into the thermocouple circuit.
- The RTD and the reference junctions of the thermocouple are mounted on a reference block that is free to follow the ambient temperature.
- As the ambient temperature of the reference block varies, the RTD changes resistance. The bridge is designed to produce an output voltage that is equal but opposite to the voltage developed in the thermocouple circuit as a result of the changes in temperature T_2 from 32°F (0°C).

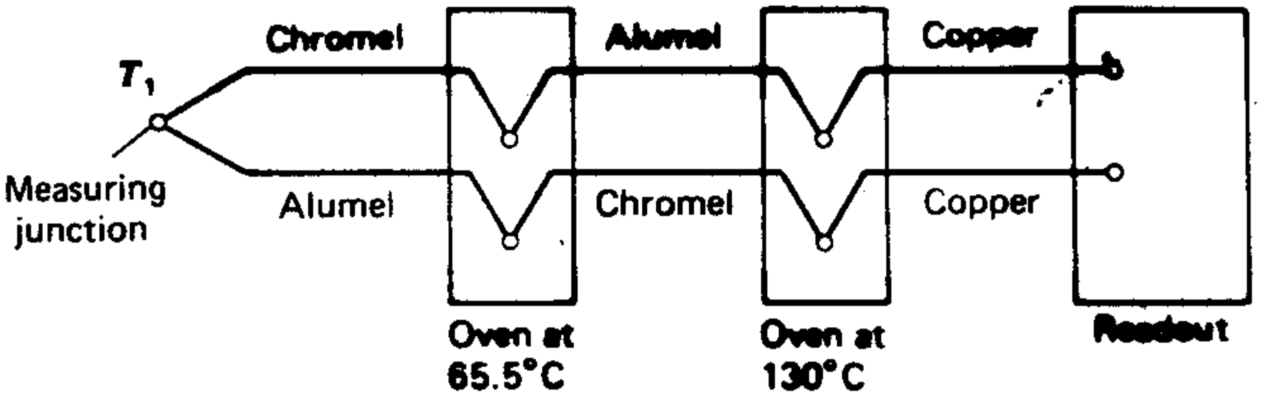


Figure 7.3.1-3 Double Oven Method for Reference Junction Control

- A technique employs two ovens at different temperatures to simulate a reference temperature of 0°C (32°F).
- Each of the junctions (one Chromel-Alumel and one Alumel-Chromel) in the first oven produces a voltage of 2.66 mV at an oven temperature of 65.5°C (150°F). This total voltage of 5.32 mV is canceled by the double junction of Alumel-copper and copper-Chromel in the second oven at a temperature of 130°C (266°F).
- The net effect of the four junctions in the two ovens is to produce the thermoelectric equivalent of a single reference junction at a temperature of 0°C (32°F).

7.3.2 Thermoelectric Behavior

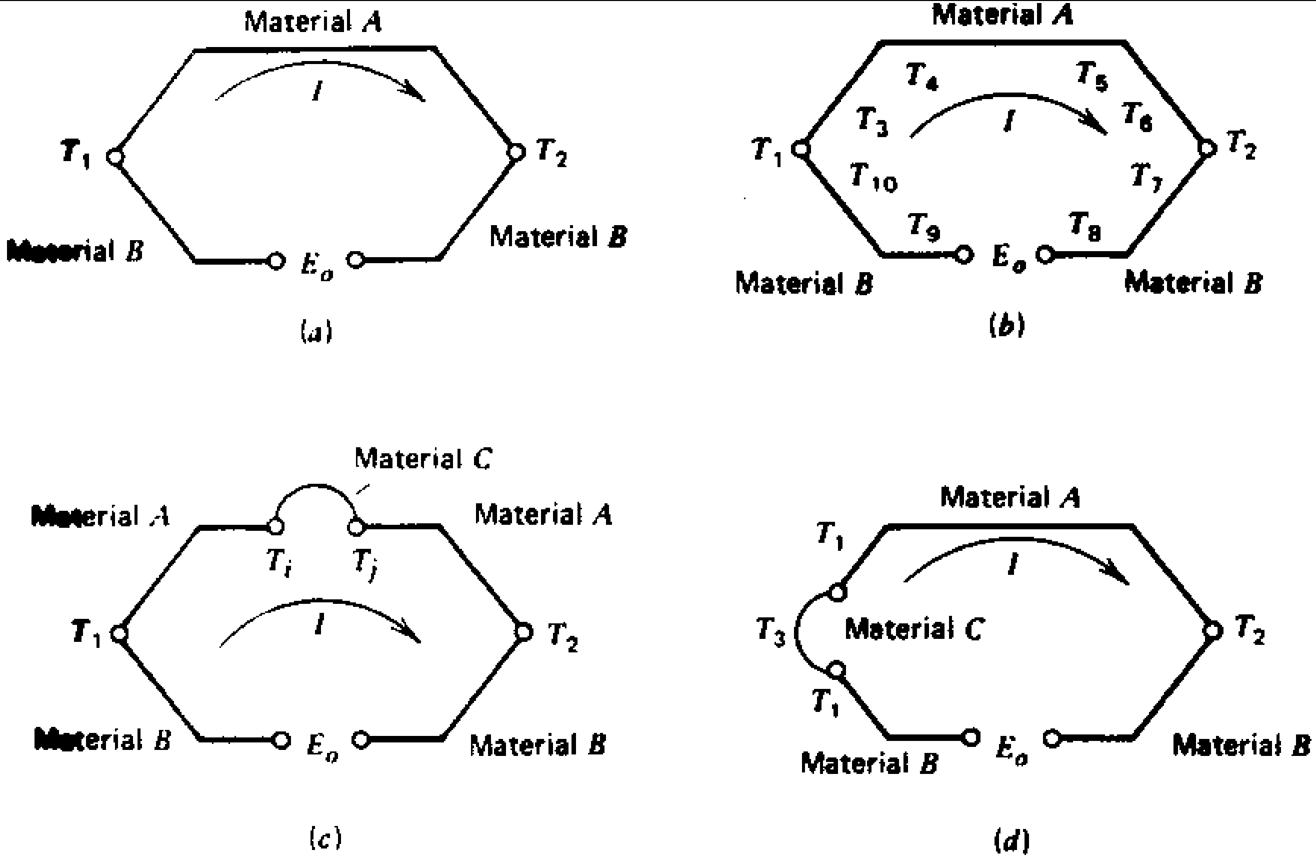


Figure 7.3.2-1 Typical Situations Encountered during Use of Thermocouples

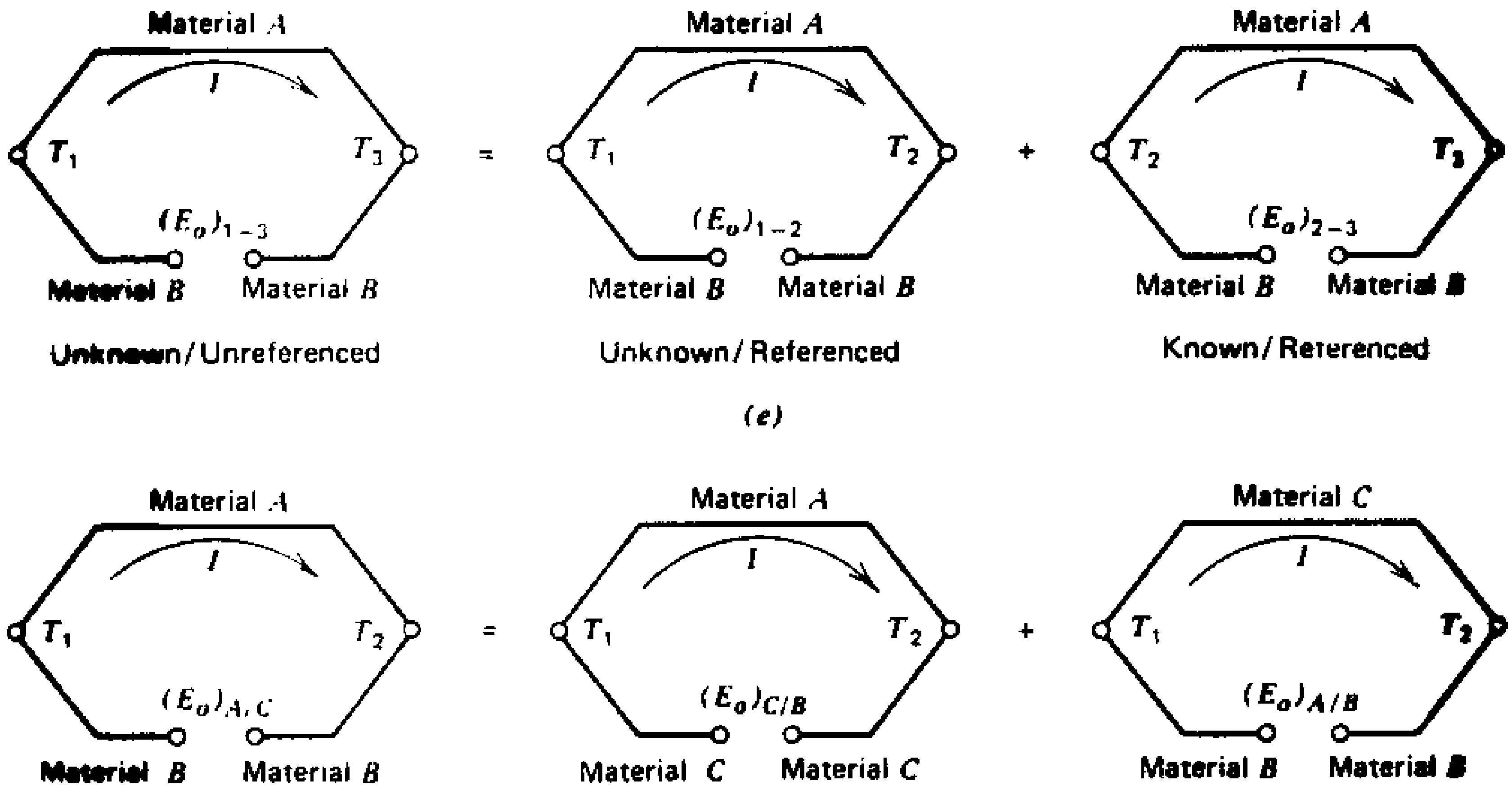


Figure 7.3.2-1 Typical Situations Encountered during Use of Thermocouples (cont')

Principles of Thermocouple Behavior

1. A thermocouple circuit must contain at least two dissimilar materials and at least two junctions.
2. The output voltage E_o of a thermocouple circuit depends only on the difference between junction temperatures (T_1 – T_2) and is independent of the temperatures elsewhere in the circuit.
3. If a third metal C is inserted into either leg (A or B) of a thermocouple circuit, provided the two new junctions A/C and C/A, the output voltage E_o is not affected if the two new junctions are maintained at the same temperature.
4. The insertion of an intermediate metal C into a junction, provided the two new junctions formed by the insertion (A/C and C/B), does not affect the output voltage E_o if the two new junctions are maintained at the same temperature T_1.
5. A thermocouple circuit with temperatures T_1 and T_2 produces an output voltage $(E_o)_{1\text{-}2} = f(T_1 - T_2)$, and one exposed to temperatures T_2 and T_3 produces an output voltage $(E_o)_{2\text{-}3} = f(T_2 - T_3)$. If the same circuit is exposed to temperatures T_1 and T_3, the output voltage voltage $(E_o)_{1\text{-}3} = f(T_1 - T_3) = (E_o)_{1\text{-}2} + (E_o)_{2\text{-}3}$.
6. A thermocouple circuit fabricated from materials A and C generates an output voltage $(E_o)_{A/C}$, when exposed to temperatures T_1 and T_2, while a similar circuit fabricated from materials C and B generates an output voltage $(E_o)_{C/B}$, Furthermore, a thermocouple fabricated from materials A and B generates an output voltage $(E_o)_{A/B} = (E_o)_{A/C} + (E_o)_{C/B}$.

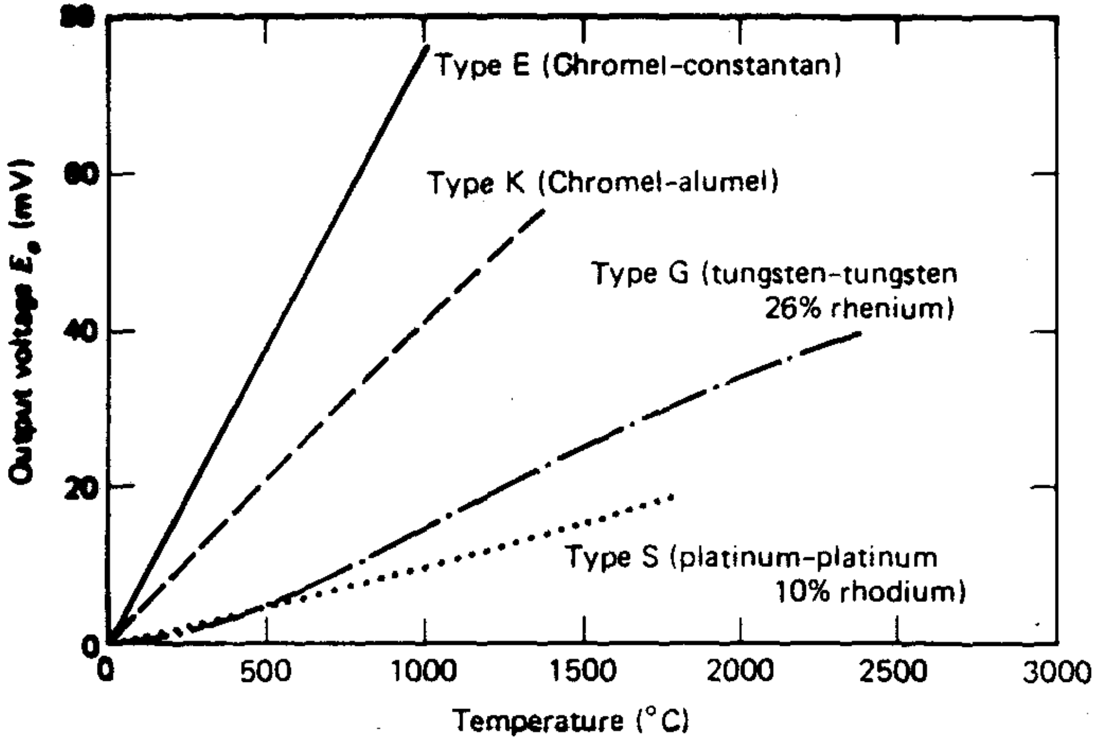
Thermoelectric Sensitivity *S* of Several Materials in Combination with Platinum at 0°C (32°F)

Material	Sensitivity S μV/°C	Sensitivity S μV/°F	Material	Sensitivity S μV/°C	Sensitivity S μV/°F
Bismuth	−72	−40	Copper	+ 6.5	+ 3.6
Constantan	−35	−19.4	Gold	+ 6.5	+ 3.6
Nickel	−15	− 8.3	Tungsten	+ 7.5	+ 4.2
Alumel	−13.6	− 7.6	Iron	+ 18.5	+ 10.3
Platinum	0	0	Chromel	+ 25.8	+ 14.3
Mercury	+ 0.6	+ 0.3	Germanium	+300	+167
Carbon	+ 3	+ 1.7	Silicon	+440	+244
Aluminum	+ 3.5	+ 1.9	Tellurium	+500	+278
Lead	+ 4	+ 2.2	Selenium	+900	+500
Silver	+ 6.5	+ 3.6			

Sensitivity as a Function of Temperature for Six Different Types of Thermocouples (μV/°C)

Temperature (°C)	E[b]	J[c]	K[d]	R[e]	S[f]	T[g]
−200	25.1	21.9	15.3	—	—	15.7
−100	45.2	41.1	30.5	—	—	28.4
0	58.7	50.4	39.5	5.3	5.4	38.7
100	67.5	54.3	41.4	7.5	7.3	46.8
200	74.0	55.5	40.0	8.8	8.5	53.1
300	77.9	55.4	41.4	9.7	9.1	58.1
400	80.0	55.1	42.2	10.4	9.6	61.8
500	80.9	56.0	42.6	10.9	9.9	—
600	80.7	58.5	42.5	11.3	10.2	—
700	79.8	62.2	41.9	11.8	10.5	—
800	78.4	—	41.0	12.3	10.9	—
900	76.7	—	40.0	12.8	11.2	—
1000	74.9	—	38.9	13.2	11.5	—

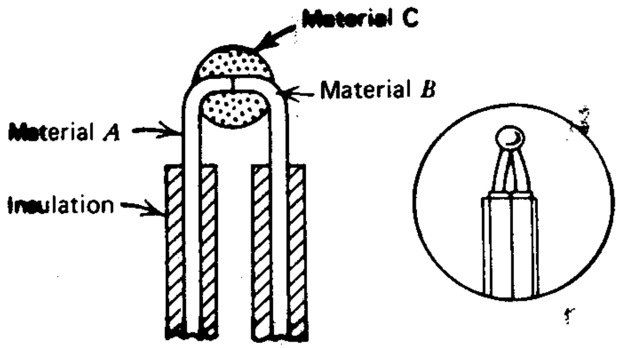
[a] From NBS Monograph 125, March 1974.
[b] Chromel–constantan thermocouple (E type).
[c] Iron–constantan thermocouple (J type).
[d] Chromel–Alumel thermocouple (K type).
[e] Platinum 13 percent rhodium–platinum thermocouple (R type).
[f] Platinum 10 percent rhodium–platinum thermocouple (S type).
[g] Copper–constantan thermocouple (T type).



Output voltage E_o versus temperature T_1 with a reference temperature T_2 = 0°C for several types of thermocouples.

Operating Range and Voltage Span for Several Different Types of Thermocouples

Type of Thermocouple	Temperature Range °C	Temperature Range °F	Voltage Span (mV)
Copper–constantan	−185 to 400	−300 to 750	−5.284 to 20.805
Iron–constantan	−185 to 870	−300 to 1600	−7.52 to 50.05
Chromel–Alumel	−185 to 1260	−300 to 2300	−5.51 to 51.05
Chromel–constantan	0 to 980	32 to 1800	0 to 75.12
Platinum 10% rhodium–platinum	0 to 1535	32 to 2800	0 to 15.979
Platinum 13% rhodium–platinum	0 to 1590	32 to 2900	0 to 18.636
Platinum 30% rhodium–platinum 6% rhodium	38 to 1800	100 to 3270	0.007 to 13.499
Platinel 1813–Platinel 1503	0 to 1300	32 to 2372	0 to 51.1
Iridium 60% rhodium 40% iridium	1400 to 1830	2552 to 3326	7.30 to 9.55
Tungsten 3% rhenium–tungsten 25% rhenium	10 to 2200	50 to 4000	0.064 to 29.47
Tungsten–tungsten 26% rhenium	16 to 2800	60 to 5072	0.042 to 43.25
Tungsten 5% rhenium–tungsten 26% rhenium	0 to 2760	32 to 5000	0 to 38.45



Fabrication details for a thermocouple junction.

Characteristics of Thermocouple-Wire Insulation

Material	Abrasion Resistance	Flexibility	Temperature (°C) Max.	Temperature (°C) Min.	Temperature (°F) Max.	Temperature (°F) Min.
Polyvinyl chloride	Good	Excellent	105	−55	220	−65
Polyethylene	Good	Excellent	75	−75	165	−100
Nylon	Excellent	Good	150	−55	300	−65
Teflon-FEP	Excellent	Good	200	−165	390	−265
Silicone rubber	Fair	Excellent	200	−75	390	−100
Asbestos	Good	Good	540	−75	1000	−100
Glass	Poor	Good	540	−75	1000	−100
Refrasil	Poor	Good	980	−75	1800	−100

7.4 Two-Terminal Integrated-Circuit Temperature Transducers

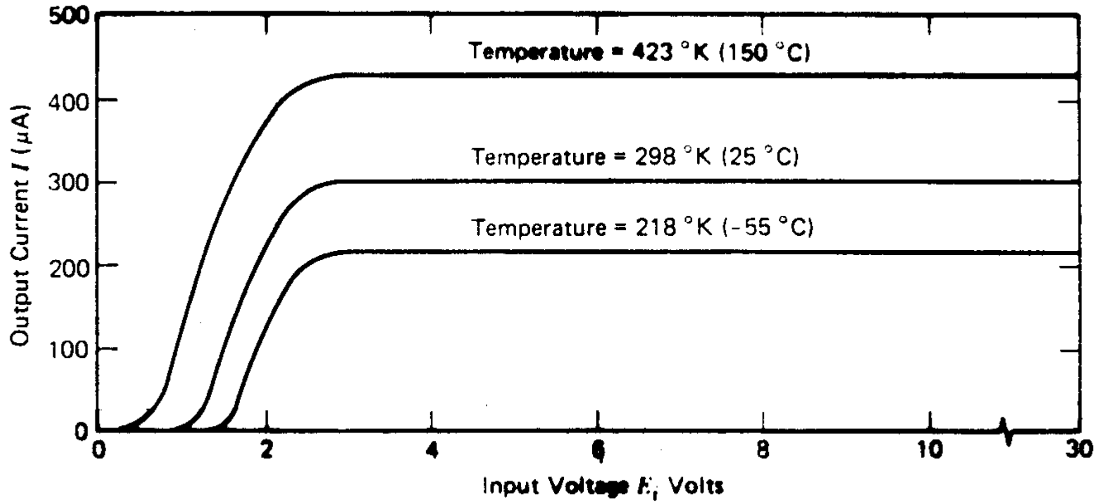


Figure 7.4-1 Input Voltage-Current-Temperature Characteristics of a Two-Terminal Integrated-Circuit Temperature Transducer

- The two-terminal integrated-circuit temperature transducer is a device that provides an output current *I* that is proportional to absolute temperature T_A when an input voltage E_i (between 4 and 30 V) is applied to the terminals of the transducer.
- This type of temperature transducer is a high-impedance constant-current regulator over the temperature range from -55°C (-70°F) to 150°C (300°F).

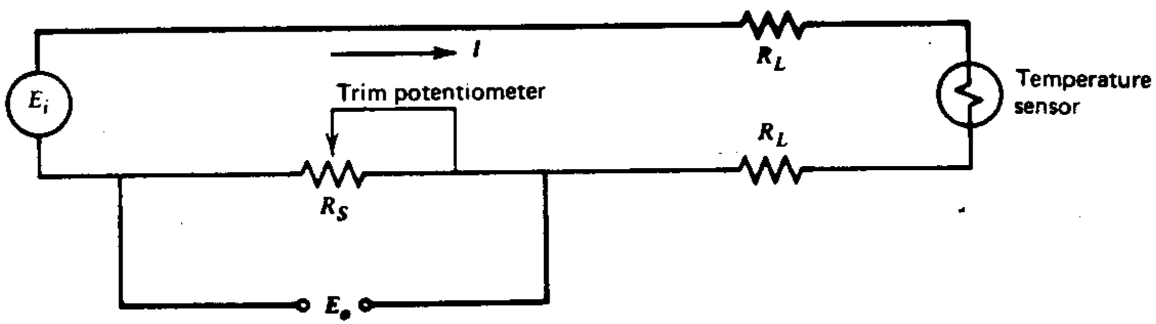


Figure 7.4-2 Two-Terminal Temperature Sensor Circuit with Leadwire Resistance and a Series Output Resistance with Trim Potentiometer for Standardizing Sensitivity

- The output voltage E_o, from the two-terminal temperature sensor circuit is controlled by series resistance R_S.

Since the temperature sensor serves as a current source, the output voltage,

$$E_o = IR_S = S_I T_A R_S = S_T T_A \quad (7.4\text{-}1)$$

where S_I : current sensitivity of the sensor, R_S : series resistance across which the output voltage is measured, T_A : absolute temperature, I : current output at absolute temperature T_A, and S_T : voltage sensitivity of the circuit.

- The output resistance R_S often contains a trim potentiometer, which is used to standardize the output voltage. This trim adjustment also permits the sensor's calibration error at a given temperature to be adjusted so as to improve accuracy over a given range of temperatures.

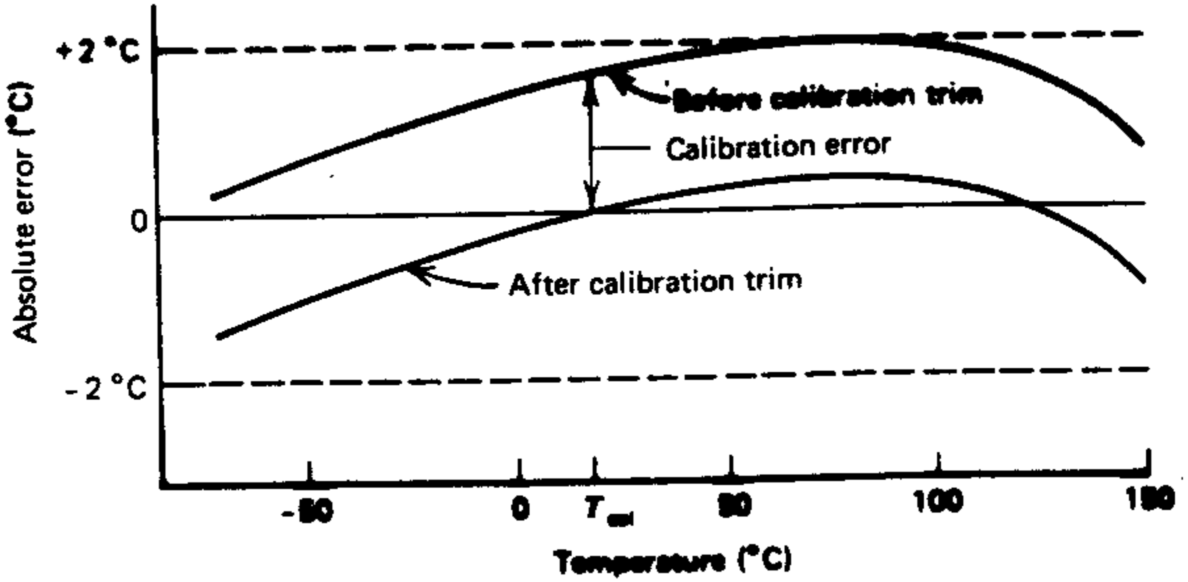


Figure 7.4-3 Typical Nonlinearity and Calibration Error for a Two-Terminal Integrated-Circuit Temperature Transducer

- The two-terminal integrated-circuit temperature transducer is limited to use in the range of temperatures from -55°C to 150°C. In this temperature range, it is an excellent temperature measuring device.

7.5 Radiation Methods (Pyrometry)

- Pyrometry infers temperature from a measurement of the radiation emitted by the body.
- Advantages of using pyrometry
    - Very high temperature measurement
    - A noncontact method of measurement
    - Temperature field measurement

7.5.1 Principles of Radiation Measurements of Temperature

- When a body, is heated it radiates energy. The relationship between intensity of radiation, wavelength of the radiation, and temperature is known as Planck's Law.

$$W_\lambda = \frac{2\pi c^2 h}{\lambda^5 (e^{hc/(k\lambda T)} - 1)} = \frac{C_1}{\lambda^5 (e^{C_2/(\lambda T)} - 1)} \quad (7.5.1\text{-}1)$$

where W_λ : spectral radiation intensity for a black body (W/m^3), λ : wavelength of the radiation (m),

T : absolute temperature (K), h : Planck's constant = 6.626x10^{-34} (J·s), c : velocity of light = 299.8x10^6 (m/s),

k : Boltzmann's constant = 1.381x10^{-23} (J/K).

$$C_1 = 2\pi c^2 h = 3.75\text{x}10^{-16}\ (\text{W}\cdot\text{m}^2) \text{ and } C_2 = hc/k = 1.44\text{x}10^{-2}\ (\text{m}\cdot\text{K}) \quad (7.5.1\text{-}2)$$

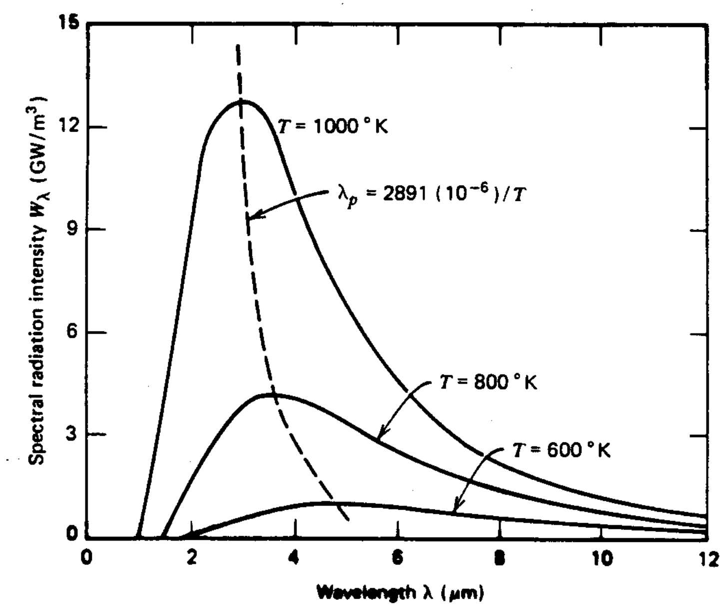


Figure 7.5.1-1 Blackbody Radiation at Different Temperatures

- The spectral radiation intensity W_λ is the amount of energy emitted by radiation of wavelength λ from a flat surface at temperature T into a hemisphere.
- The spectral radiation intensity W_λ depends upon both wavelength λ and temperature T.
- W_λ peaks at a specific wavelength, which depends on temperature, and that the wavelength associated with the peak W_λ increases as the temperature decreases.

The wavelength λ_p associated with the peak in W_λ,

$$\lambda_p = 2891x10^{-6} / T \quad (7.5.1\text{-}3)$$

- The area under each of the radiation intensity curves is the total power *W* emitted at the particular temperature *T*.

Stefan-Boltzmann Law with the emissivity ε equal to unity (ε = 1),

$$W = \int_\lambda W_\lambda d\lambda = 6.67x10^{-8} T^4 \text{ (W/m}^2\text{)} \quad (7.5.1\text{-}4)$$

1. The total power *W* increases as a function of the fourth power of the temperature.
2. The peak value of spectral radiation intensity W_λ occurs at shorter wavelengths as the temperature increases.

   Both of these physical principles are used as the basis for a measurement of temperature.

7.5.2 The Optical Pyrometer

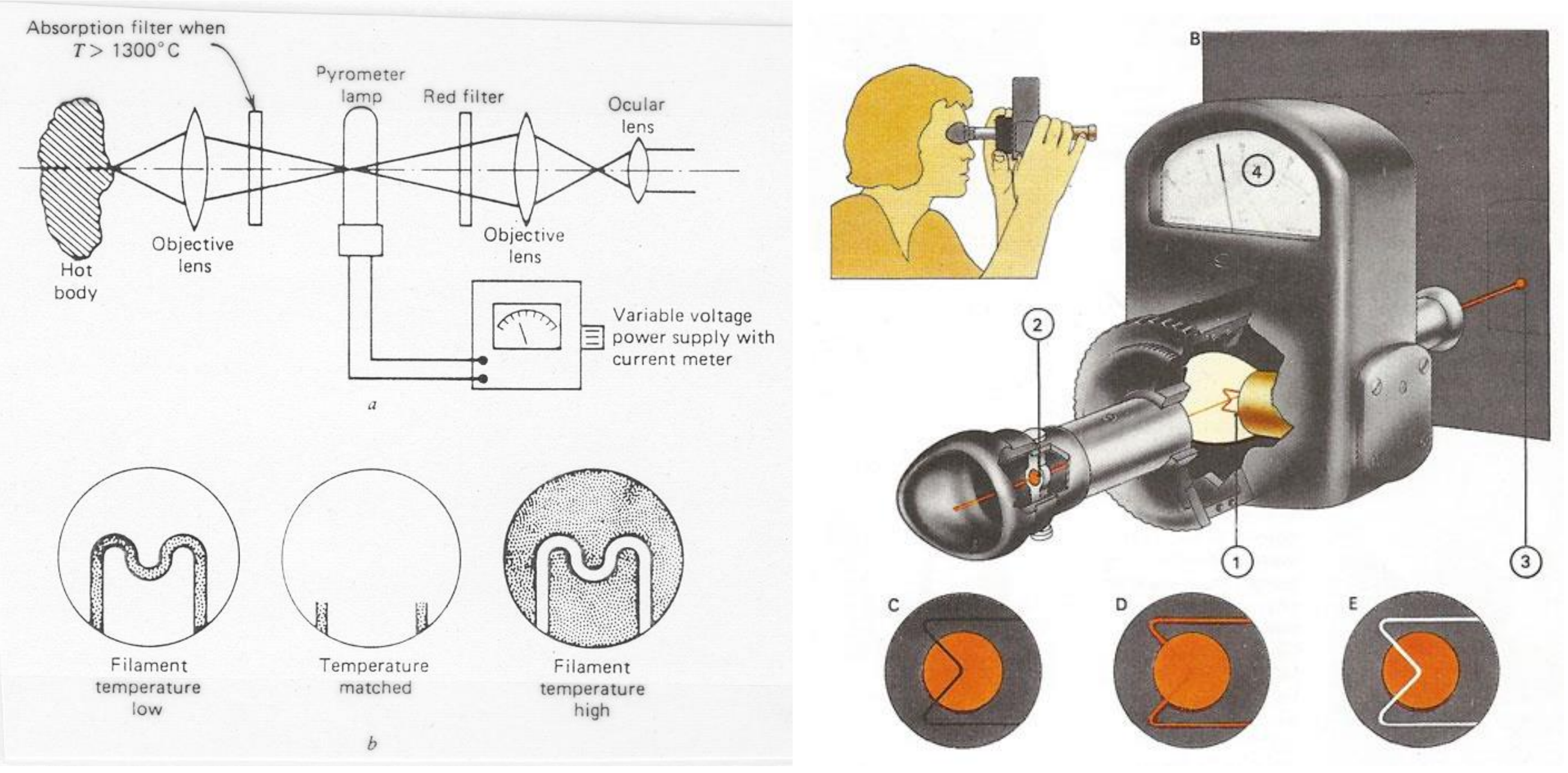


Figure 7.5.2-1 (a) Schematic Illustration of the Optical Pyrometer

(b) Filament Brightness Adjustment in an Optical Pyrometer.

- The optical pyrometer is used to measure temperature over the range from 700°C to 4000°C.
- The radiant energy emitted by the body, is collected with an objective lens and focused onto a calibrated pyrometer lamp.
- An absorption filter is inserted into the optical system between the objective lens and the pyrometer lamp when the temperature of the body exceeds 1300°C.
- The radiant energy from both the hot body and the filament of the pyrometer lamp is then passed through a red filter with a sharp cutoff below $\lambda = 0.63\ \mu m$.
- The light transmitted through the filter is then collected by an objective lens and focussed for viewing with an ocular lens.
- The image observed through the eyepiece of the pyrometer is that of the lamp filament superimposed on a background intensity due to the hot body.
- The current to the filament of the pyrometer lamp is adjusted until the brightness of the filament matches that of the background.
- Under a matched condition, the filament disappears (hence the commonly used name-disappearing-filament optical pyrometer).

- The current required to produce the brightness match is measured and used to establish the temperature of the hot body. Pyrometers are calibrated by visually comparing the brightness of the tungsten filament with a blackbody source of known temperature ($\varepsilon = 1$).

When the brightness of the background and the filament are matched,

$$\frac{\varepsilon}{e^{C_2/(\lambda_r T)} - 1} = \frac{1}{e^{C_2/(\lambda_r T_f)} - 1} \tag{7.5.2-1}$$

where λ_r : wavelength of the red filter ($\lambda_r = 0.63$ μm), ε : emissivity of the surface of the hot body at $\lambda = 0.63$ μm, T_f : temperature of the filament, and T : unknown surface temperature.

When $T < 4000$°C, the term $e^{C_2/(\lambda T)} >> 1$,

$$T = \frac{1}{\lambda_r (\ln \varepsilon)/C_2 + 1/T_f} \tag{7.5.2-2}$$

$T = T_f$ only when $\varepsilon = 1$. If $\varepsilon \neq 1$, then $T \neq T_f$

The change in temperature as a function of change in emissivity,

$$\frac{dT}{T} = -\frac{\lambda T}{C_2}\frac{d\varepsilon}{\varepsilon} \tag{7.5.2-3}$$

Material	Solid	Liquid	Material	Solid	Liquid
Beryllium	0.61	0.61	Thorium	0.36	0.40
Carbon	0.80–0.93	—	Titanium	0.63	0.65
Chromium	0.34	0.39	Tungsten	0.43	—
Cobalt	0.36	0.37	Uranium	0.54	0.34
Columbium	0.37	0.40	Vanadium	0.35	0.32
Copper	0.10	0.15	Zirconium	0.32	0.30
Iron	0.35	0.37	Steel	0.35	0.37
Manganese	0.59	0.59	Cast Iron	0.37	0.40
Molybdenum	0.37	0.40	Constantan	0.35	—
Nickel	0.36	0.37	Monel	0.37	—
Platinum	0.30	0.38	90 Ni–10 Cr	0.35	—
Rhodium	0.24	0.30	80 Ni–20 Cr	0.35	—
Silver	0.07	0.07	60 Ni–24 Fe–16 Cr	0.36	—
Tantalum	0.49	—			

Table 7.5.2-1 Emissivity ε of Engineering Materials at $\lambda = 0.65\ \mu m$

7.5.3 Photon Detector Temperature Instruments

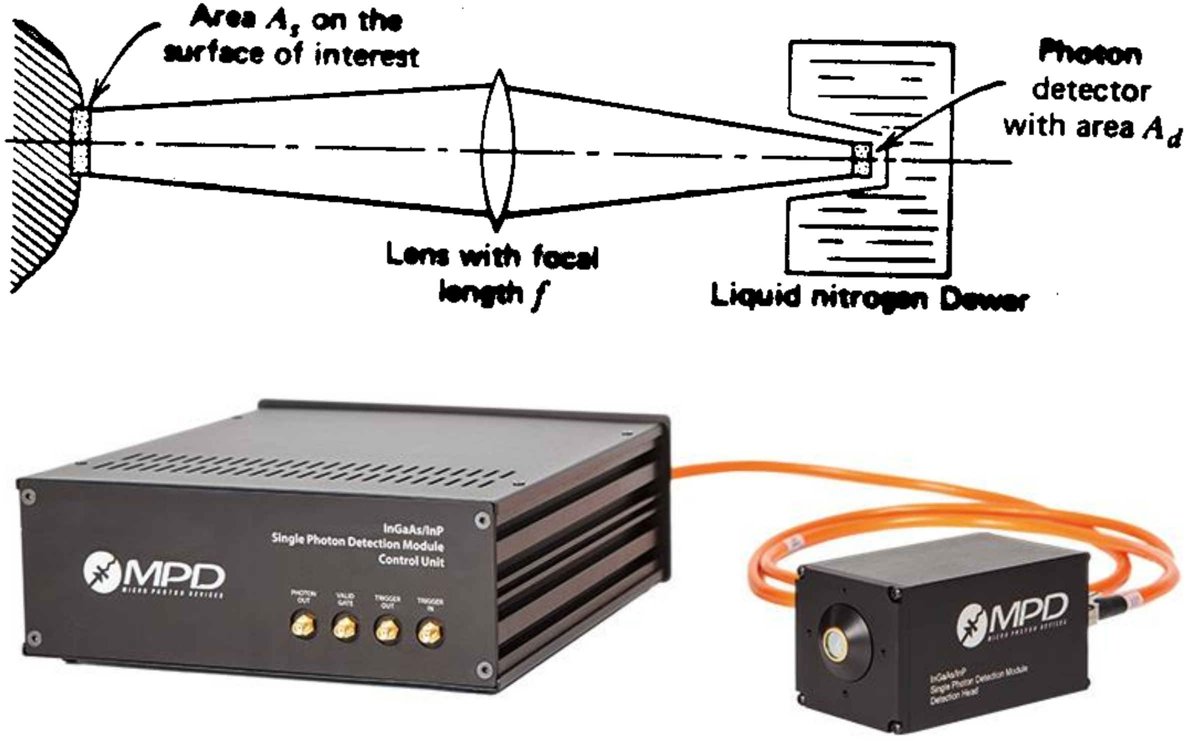


Figure 7.5.3-1 Schematic Illustration of a Temperature Measuring Instrument with a Photon Detector Type of Sensor

- A photon detector is a sensor that responds by generating a voltage that is proportional to the photon flux density ϕ impinging on the sensor.
- The photons emitted from a small area A_s of a surface (not necessarily hot) are collected by a lens and focused on a photon detector of area A_d.

The photon flux density ϕ at the detector, when the optical system is focused,

$$\phi = \frac{kD^2}{4f^2}\varepsilon g(T) \qquad (7.5.3\text{-}1)$$

where k : transmission coefficient of the lens (and filter if one is used), D : diameter of the lens,

f : focal length of the lens, $g(T)$: a known function of the temperature of the surface, and ε : emissivity of the surface.

The output voltage E_o from the detector as a result of the flux density ϕ,

$$E_o = \frac{k_t D^2}{4f^2}\varepsilon g(T) \qquad (7.5.3\text{-}2)$$

where k_t : the system sensitivity which includes the transmission coefficient of the lens, the amplifier voltage gain, and the detector sensitivity.

- The output voltage varies as a function of the cube of the temperature.

$$E_o = K\varepsilon T^3 \qquad (7.5.3\text{-}3)$$

where K : a calibration constant for the instrument.

- Photon detector measures temperatures in the range from –20 °C to 1600 °C.

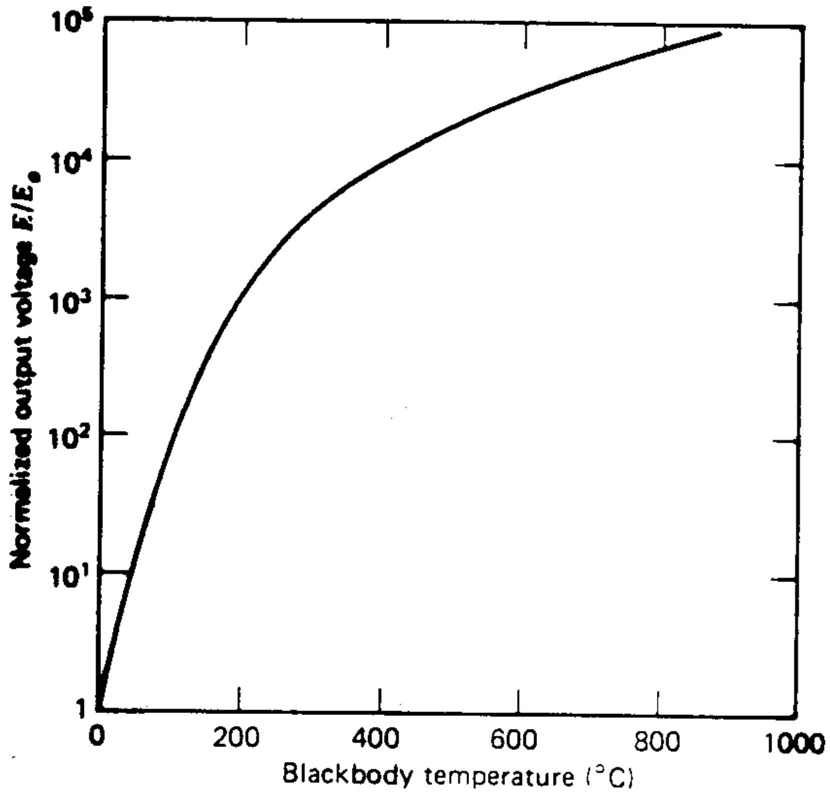


Figure 7.5.3-2 Typical Response Curve for an Indium Antimonide Photon Detector

7.6 Dynamic Response of Temperature Sensors

- Temperature sensors are classified as first-order systems, since their dynamic response is controlled by a first-order differential equation that describes the rate of heat transfer between the sensor and the surrounding medium.

$$q = hA(T_m - T) = mc\frac{dT}{dt} \quad (7.6\text{-}1)$$

where q : rate of heat transfer to the sensor by convection, h : convective heat-transfer coefficient, A : surface area of the sensor through which heat passes, T_m : temperature of the surrounding medium at time t, T : temperature of the sensor at time t, m : mass of the sensor, and c : specific heat capacity of the sensor.

$$\frac{dT}{dt} + \frac{hA}{mc}T = \frac{hA}{mc}T_m \quad (7.6\text{-}2)$$

$$T = C_1 e^{-t/\beta} \quad (7.6\text{-}3)$$

where C_1 : a constant of integration, and $\beta = mc/(hA)$: time constant for the sensor.

The response of a temperature sensor to a step-function input (sensor is suddenly immersed in a medium maintained at constant temperature T_m),

$$T = C_1 e^{-t/\beta} + T_m \quad (7.6\text{-}4)$$

For the initial condition $T(0) = 0$,

$$T = T_m(1 - e^{-t/\beta}) \quad (7.6\text{-}5)$$

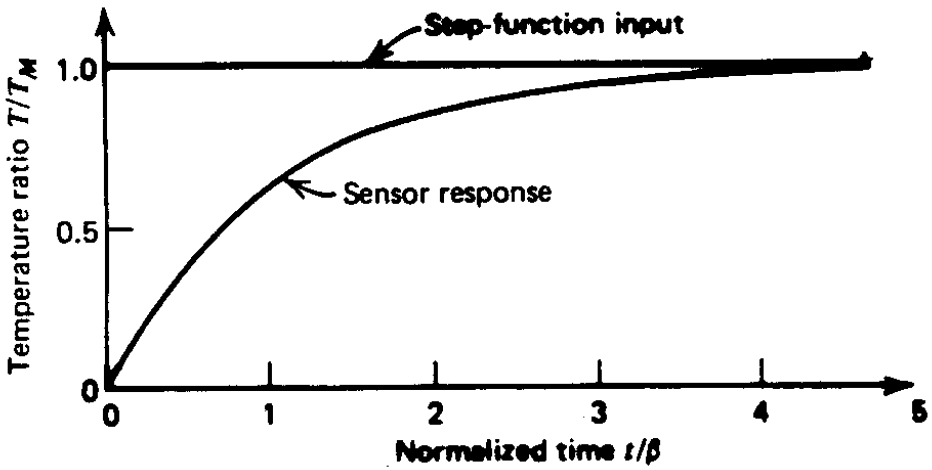


Figure 7.6-1 Response of a Temperature Sensor to a Step-Function Input

- For a ramp-function input, the sensor and the surrounding medium are initially at the same temperature; thereafter, the temperature of the medium increases linearly with time.

$$T = b(t - \beta) \tag{7.6-6}$$

where b : slope of the temperature-time ramp function.

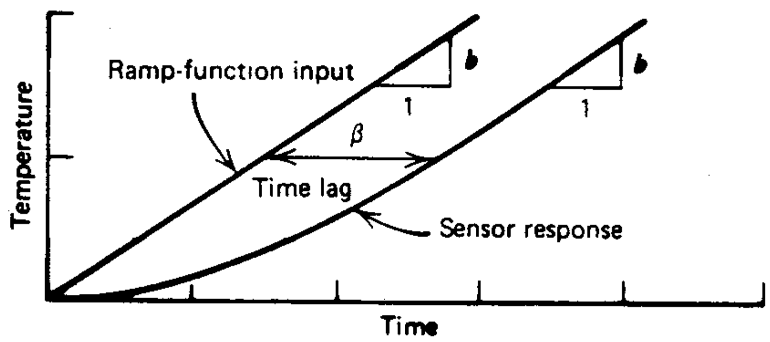


Figure 7.6-2 Response of a Temperature Sensor to a Ramp-Function Input

$$T = C_1 e^{-t/\beta} + b(t-\beta) \qquad (7.6\text{-}7)$$

For the initial condition $T(0) = T_m(0) = 0$,

$$T = b\beta e^{-t/\beta} + b(t-\beta) \qquad (7.6\text{-}8)$$

- The initial response of the sensor is sluggish; however, after a short initial interval, the sensor tracks the rise in temperature of the medium surrounding the sensor with the correct slope, but with a time lag β.