SAND2008-0462P

EXPERIMENTAL MECHANICS (ESP 500)

Session 10

1/08/2008

Pressure and Flow Measurements

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Course Schedule

Week	Date	Topic	Instructor
1	10/16/07	Introduction, measurement basics, uncertainty	O'Hern
2	10/23/07	Data Acquisition	O'Hern
3	10/30/07	Dynamic Measurements (Transducers)	Simmermacher
4	11/06/07	Measurement of Structural Dynamic Input/Response	Mayes
5	11/13/07	Structural Dynamics Lab	Stasiunas
6	11/27/07	Laser Optics and Applications	O'Hern
7	12/04/07	Non-contacting measurements for solid mechanics	Reu
8	12/11/07	Digital image correlation in practice	Reu
9	12/18/07	~~Micromechanics~~	~~Sumali~~
10	**01/08/08**	**Pressure and Flow Measurements**	**O'Hern**
11	01/15/08	Micromechanics	Sumali
12	01/22/08	High Speed Photography	Nissen
13	01/29/08	Thermal Characterization	Phinney
14	02/05/08	Rheology and Complex Fluids	Grillet

Outline

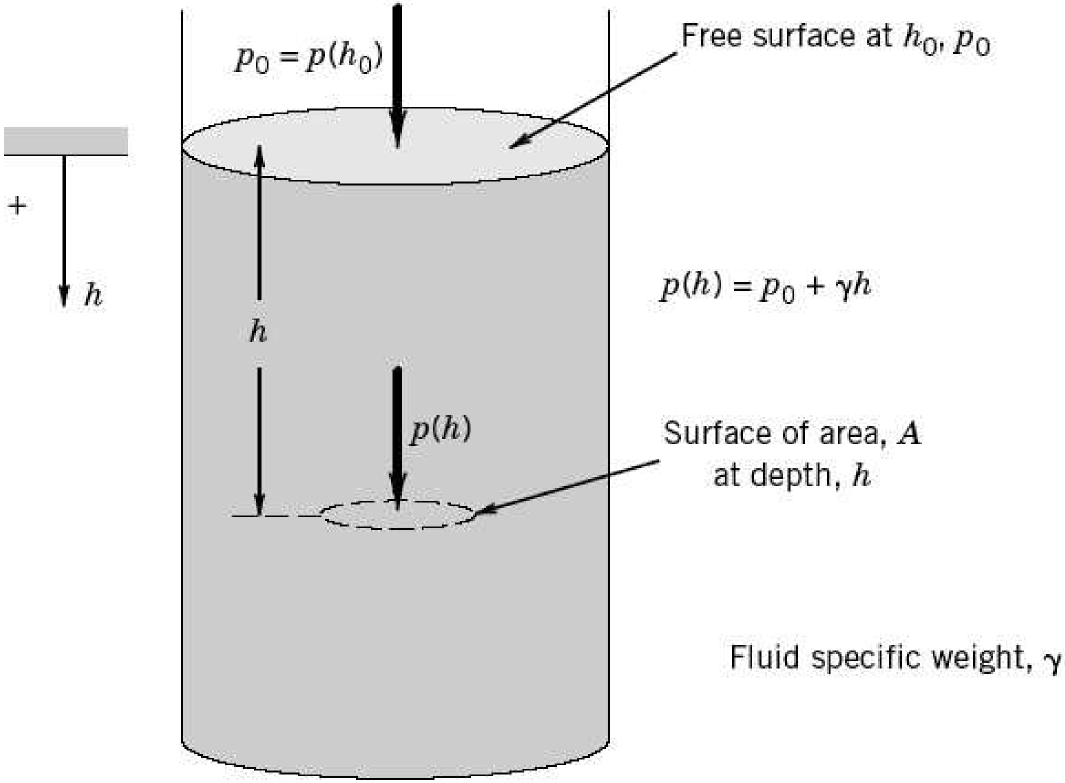
- Pressure Measurements
  - A little about pressure
  - Types of pressure transducers
    - Basic operating principles
    - Some discussion of performance
    - Not detailed product information – see vendors for that
  - Calibration techniques
  - Pressure measurements in moving fluids
  - Pressure measurement system design considerations
- Velocity measurements in moving fluids
- Flow Meters
  - Types of flow meters
    - Basic operating principles
    - Some discussion of performance
    - Not detailed product information – see vendors for that
  - Calibration

Note: Most figures in today's handout are from Theory and Design for Mechanical Measurements, 4th edition, R. S. Figliola and D. E. Beasley, John Wiley & Sons, Inc., 2006

Other major references are Beckwith et al. and Holman books (see Session 1 slides for references)

Pressure

- Normal force per unit area exerted by a medium
- Caused by molecular impact (e.g., on vessel walls)



$\gamma = \rho g$

γ = specific weight

ρ = density

g = gravitational constant

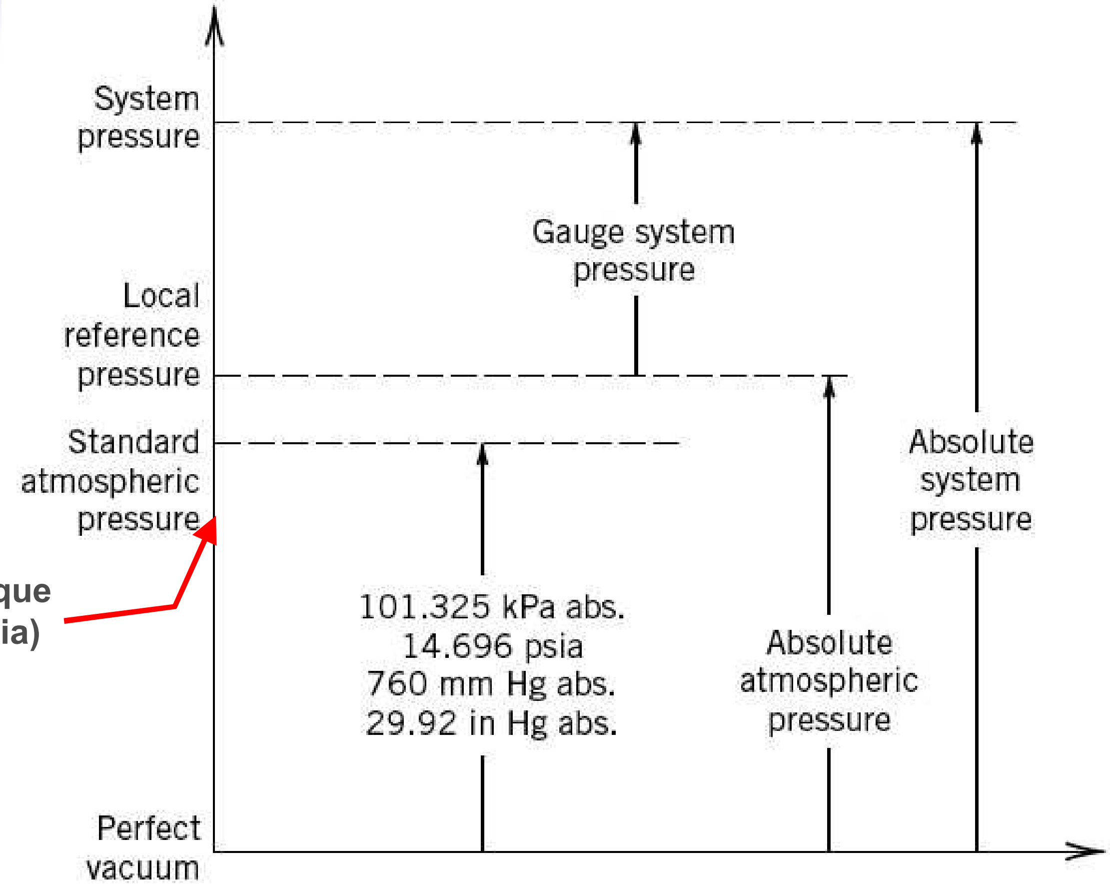
Therefore changes in temperature or density will change pressure

Pressure

- Gage vs. absolute
- Units
  - psi (psia, psig)
  - Pa
  - Atmospheres
  - Bars
  - Inches Hg
  - Inches (or feet) H_2O
- 1 atm = 14.7 psi =

101325 Pa = 1.013 bar =

29.92 in Hg = 760 mm Hg = 760 Torr = 33.9 ft H_20



Pressure

- Differential pressure (psid)
  - Absolute pressure can be considered differential pressure relative to perfect vacuum
  - Gage pressure is differential pressure relative to atmospheric pressure
- Caution: The pressure reported by the weather bureau is generally NOT the actual air pressure. Instead, to simplify comparisons, they typically "normalize" the air pressure to sea level 760 mm (29.92 inches) of mercury.
- **e.g., recent weather check shows:**

Time EST (UTC)		Temperature F (C)	Dew Point F (C)	Pressure Inches (hPa)	Wind MPH	Weather
7 PM (0)	Jan 06	41.0 (5.0)	35.1 (1.7)	29.86 (1011)	WSW 9	
6 PM (23)	Jan 06	42 (6)	35 (2)	29.86 (1011)	W 21	light rain
5 PM (22)	Jan 06	46.0 (7.8)	37.0 (2.8)	29.83 (1010)	WSW 15	
4 PM (21)	Jan 06	45.0 (7.2)	37.9 (3.3)	29.83 (1010)	SW 14	
3 PM (20)	Jan 06	44 (7)	37 (3)	29.83 (1010)	W 26	light rain
2 PM (19)	Jan 06	52.0 (11.1)	34.0 (1.1)	29.85 (1010)	SSW 12	light rain
1 PM (18)	Jan 06	53.1 (11.7)	32.0 (0.0)	29.89 (1012)	SSW 14	
Noon (17)	Jan 06	50.0 (10.0)	32.0 (0.0)	29.9 (1012)	SSW 13	

From http://weather.noaa.gov/weather/current/KABQ.html

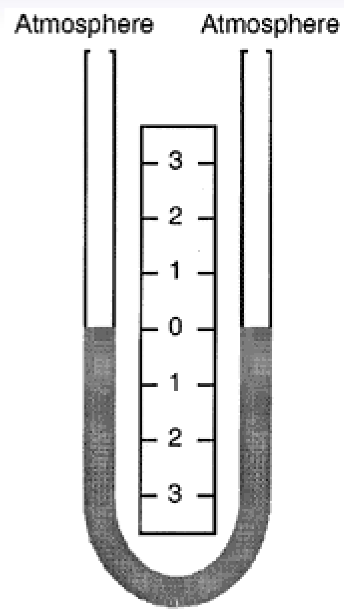
Transducer Properties

Physical Quantity — Transducer — Output signal S(t)

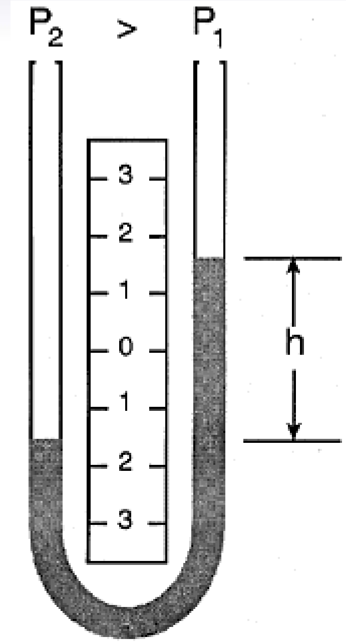
- Ideal Transducer
  - Output signal proportional to magnitude of physical quantity
  - Output signal tracks physical quantity without frequency distortion
  - Low noise in output signal (high SNR)
  - Transducer does not interfere with physical process
  - Output not influenced by other variables in system
- “Real” Transducer
  - Static transfer function (calibration curve)
  - Spatial resolution (finite size of measurement volume)
  - Temporal resolution (finite frequency response)
  - Signal-to-noise ratio
  - Interference effects
  - Multivariate response

Manometers: U-tube

- Very simple concept
- The pressure difference between the two legs pushes the fluid in the manometer until its weight balances the applied pressure
- Compares applied pressure to hydrostatic pressure of liquid column
- $\Delta p = p_2 - p_1 = \rho g h$



With both legs of a U-tube manometer open to the atmosphere or subjected to the same pressure, the liquid maintains the same level in each leg, establishing a zero reference.

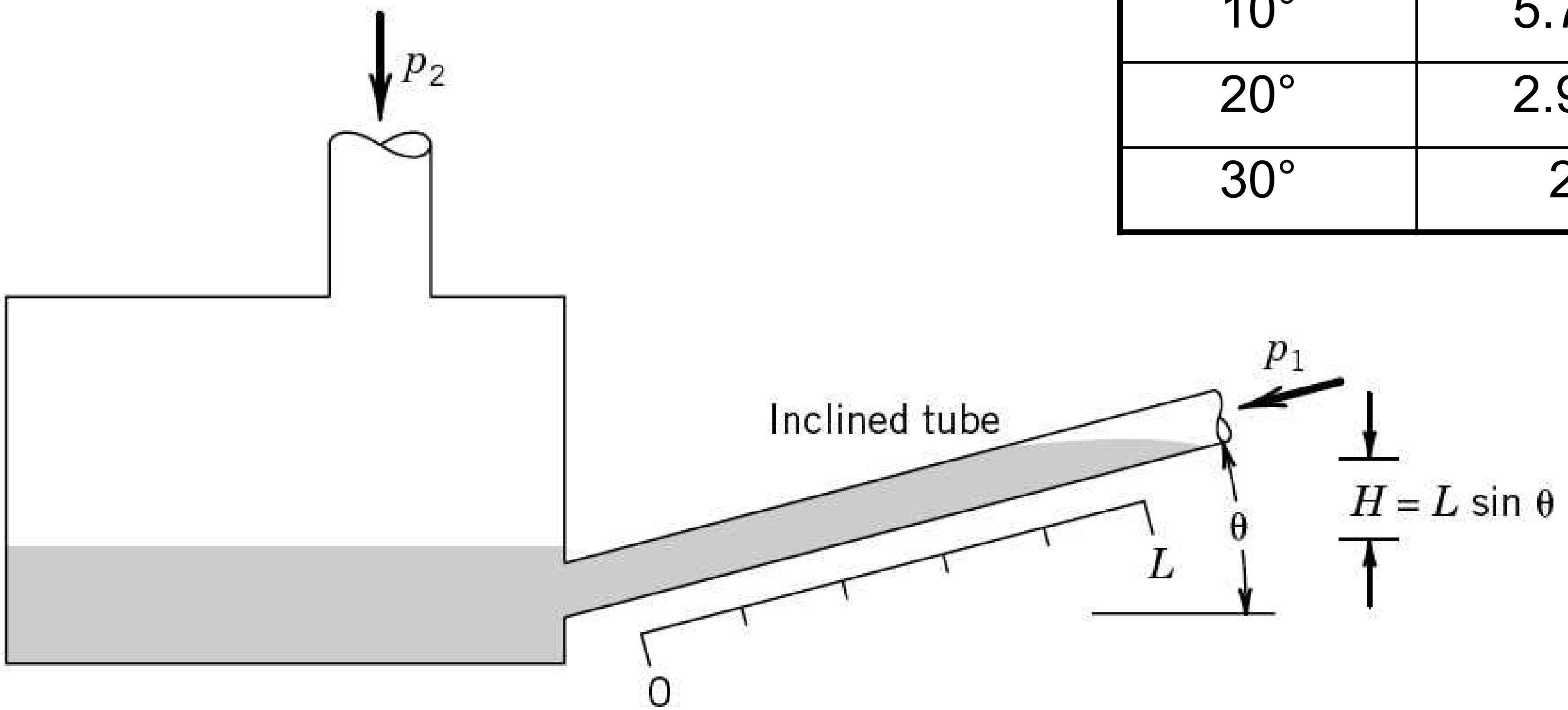


With greater pressure applied to the left side of a U-tube manometer, the liquid lowers in the left leg and rises in the right leg. The liquid moves until the liquid weight, as indicated by h, exactly balances the pressure.

Manometers: Inclined Tube

- Same concept, but increased sensitivity over standard U-tube manometer by a factor of 1/sinθ

θ	**1/sinθ**
10°	5.76
20°	2.92
30°	2



Pressure Transducers

- Converts a measured pressure into a mechanical or electrical signal
- The primary sensor is usually an elastic element that deforms or deflects under applied pressure
- A secondary sensor then converts this deformation or deflection into a usable signal

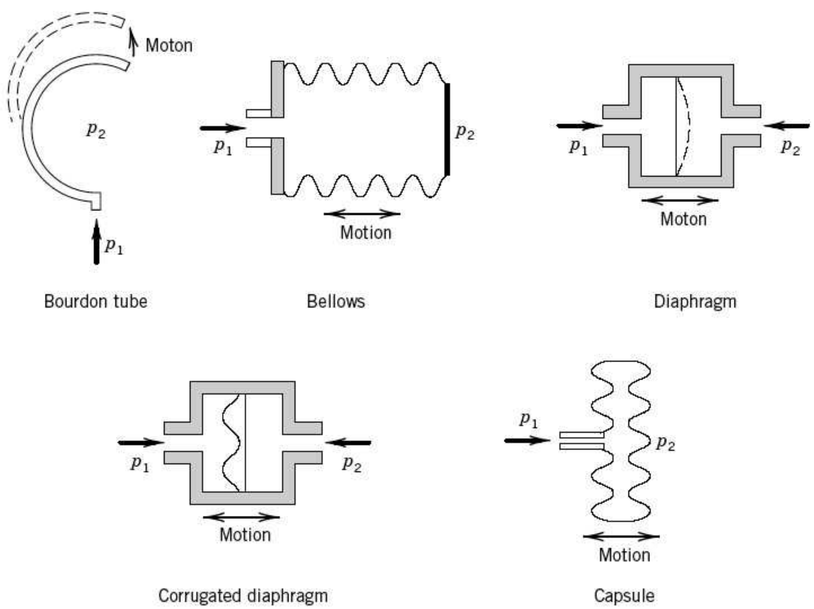
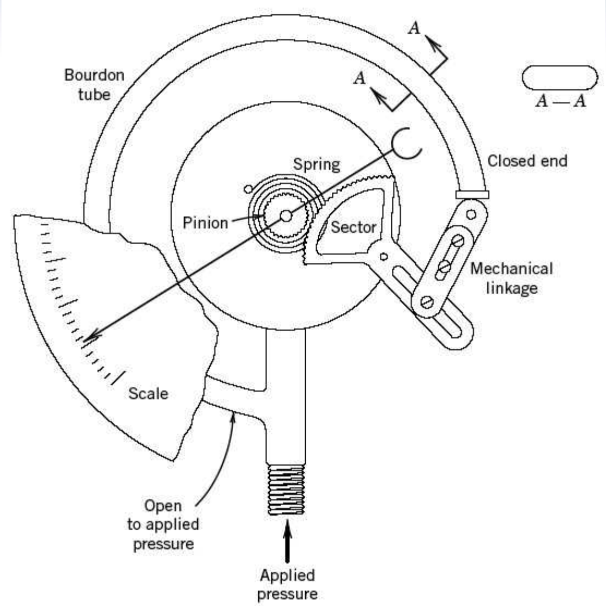


Figure 9.9 Elastic elements used as pressure sensors.

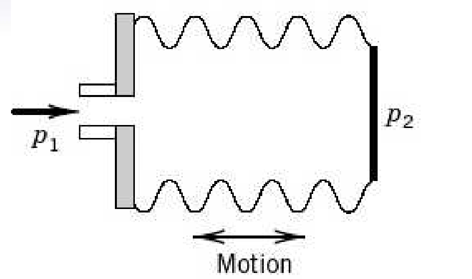
Pressure Transducers: Bourdon Tube

- Curved metal tube with an elliptical cross-section that mechanically deforms under pressure
- Generally one end is held fixed and the input pressure applied internally
- The pressure difference from inside to outside will deform the tube and deflect its free end
- Tip displacement is nearly linear with applied pressure
- Usually the outside of the tube is in air so the measurement is “gage”
- A mechanical dial can easily be attached as shown
- Can be very accurate (0.1% of full scale)

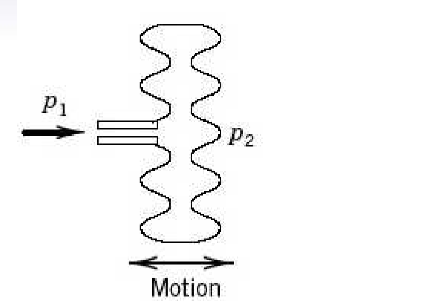


Pressure Transducers: Bellows and Capsule

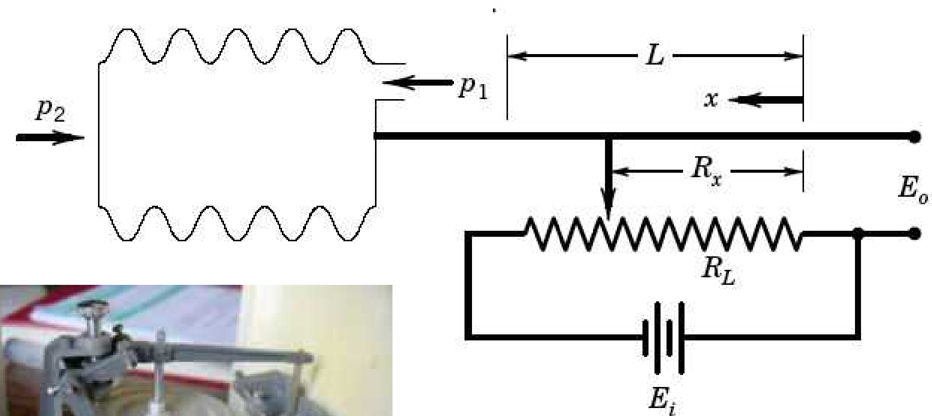
- Bellows sensing element is thin-walled, flexible metal tube formed into deep convolutions and sealed at one end
- Pressure, applied internally, causes bellows to change in length
- "Capsule" is same but generally wider and shorter
- Mechanical linkage used to convert translational displacement to measurable form, e.g., sliding arm potentiometer, linear variable displacement transducer (LVDT), or strain gauges



Bellows

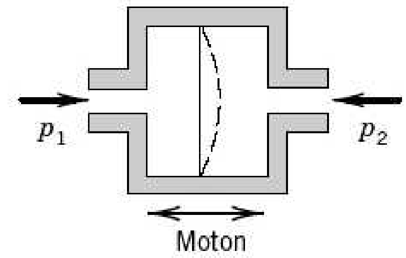


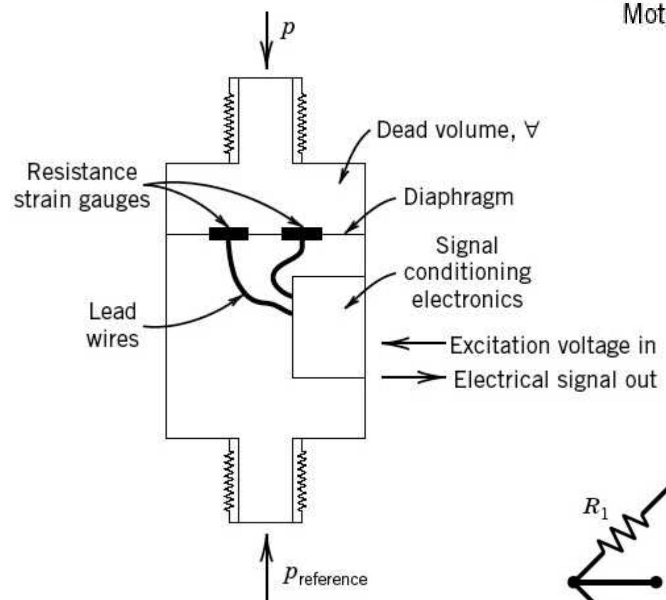
Capsule



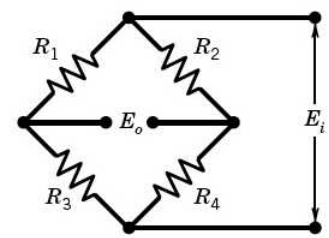
Pressure Transducers: Diaphragms

- The diaphragm is usually a thin elastic circular plate supported at its perimeter
- ΔP across the diaphragm deforms it
- Good linearity, good resolution, very good frequency response since diaphragm can have very low mass but good stiffness
- Proper diaphragm must be chosen for expected frequency range
- Deformation converted to measurable signal by several different methods including:
  - Strain gauges (shown)
  - Piezoresistive material
  - Capacitive elements (next page)

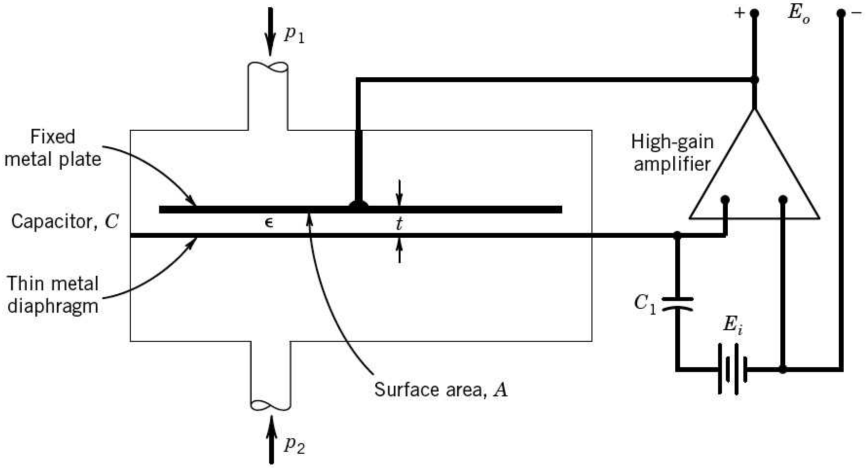




(a) Sensing scheme

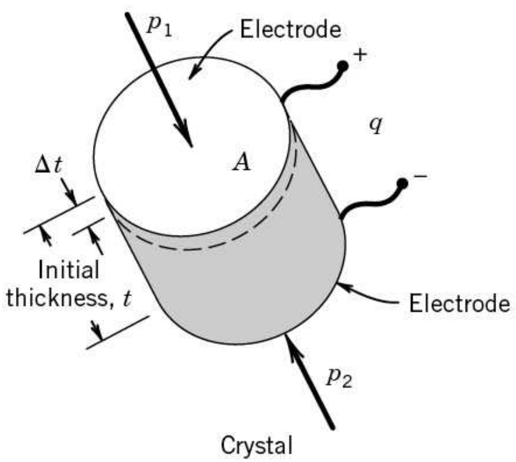


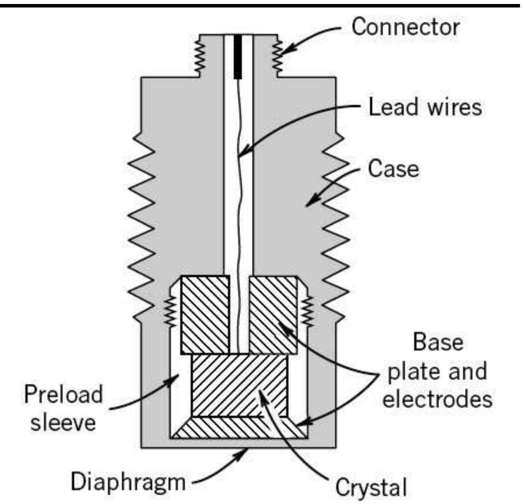
Pressure Transducers: Diaphragms



- Diaphragm is one side of variable capacitor
- Capacitance changes when distance between plates changes due to applied pressure
- Very sensitive (used in high-resolution vacuum measurements)
- Subject to temperature sensitivity and long-term drift

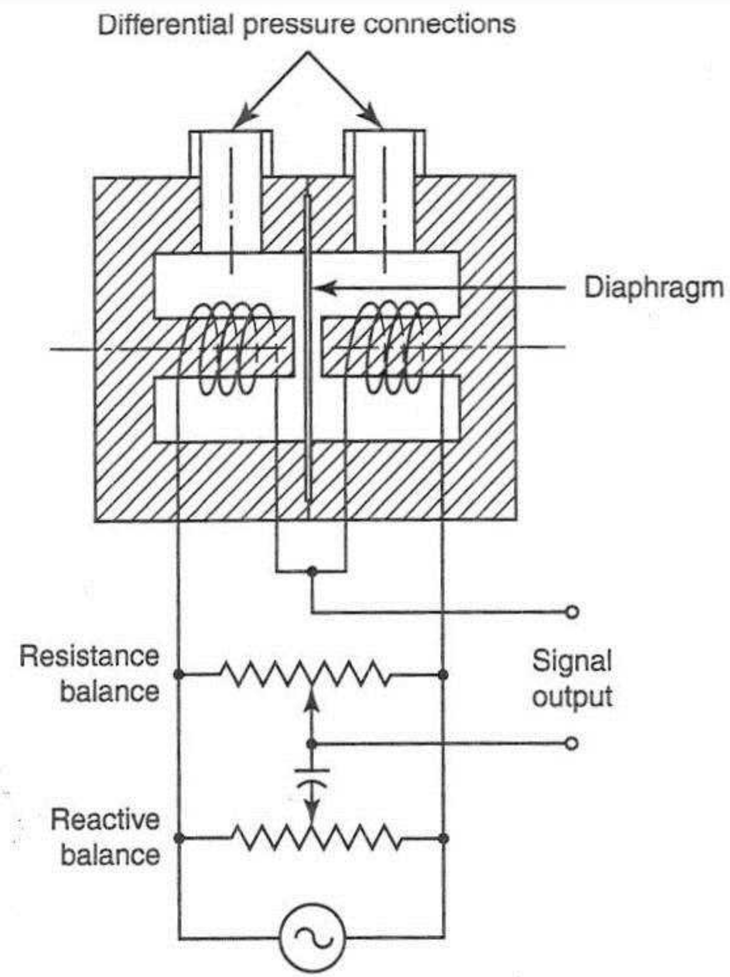
- Piezoelectric material produces charge proportional to force acting on diaphragm
- Charge dissipates fairly rapidly so best suited for dynamic pressure measurements





Pressure Transducers: Diaphragms

- Variable inductance or variable reluctance
- Validyne is a familiar supplier of variable reluctance transducers
- These transducers are a little touchy, are a little bulky, and require external ac excitation and therefore are usually limited to lab applications
- However, they are sensitive and able to cover full range scales as low as 20 Pa and as high as 70 MPa



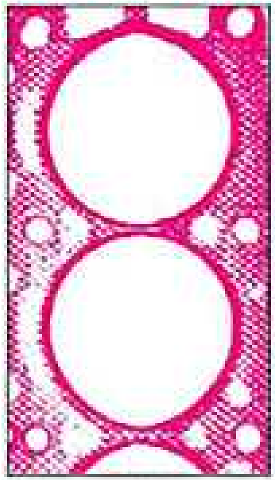
Pressure Sensitive Films

Pressurex® (Sensor Products, Inc.) shows the distribution and magnitude of pressure between any two contacting, mating or impacting surfaces.

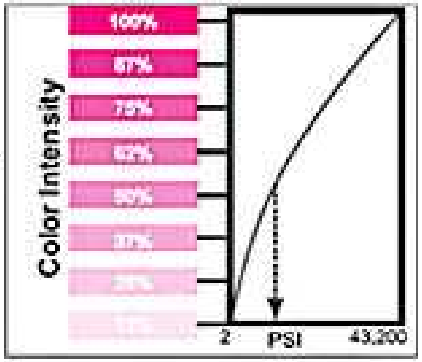
It consists of a thin mylar based film (4 to 8 mils) that contains a layer of microcapsules. Application of force upon the film causes the microcapsules to rupture, producing an instantaneous and *permanent* high resolution "topographical" image of pressure variation across the contact area.

The film is placed between any two surfaces that touch, mate or impact. Pressure is applied, removed, and immediately the film reveals the pressure distribution profile that occurred between the two surfaces. Like Litmus paper, the color intensity is directly related to the amount of pressure applied to it. The greater the pressure, the more intense the color.

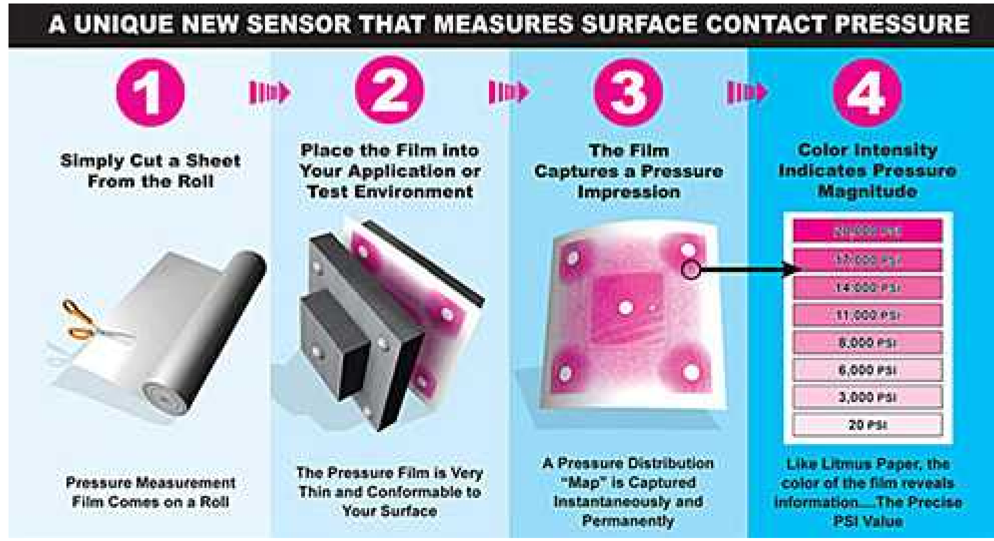
Pressure Sensitive Films

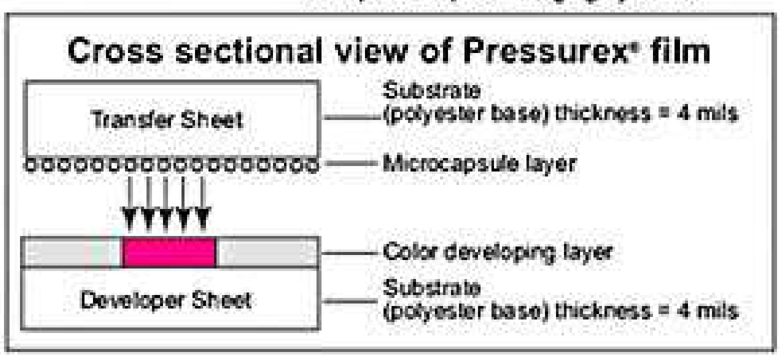


Pressure variation across a flange surface



Like Litmus paper, the color that Pressurex® sensor film turns has significance. It is directly related to PSI or kg/cm², and can be visually compared to our color correlation chart or scanned and quantified with one of our optional optical imaging systems.

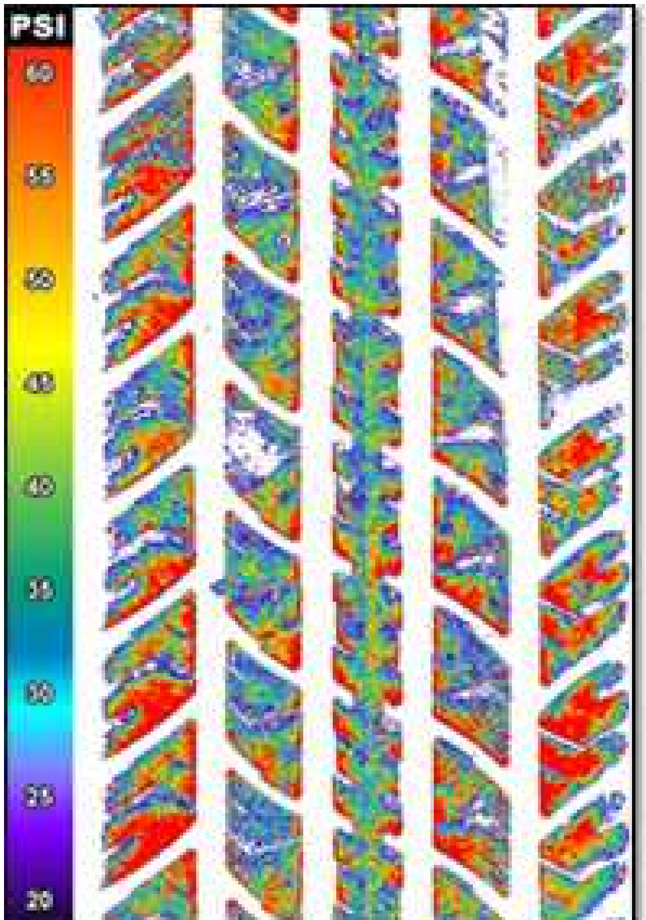




Other suppliers: Fuji (Prescale film), ...

http://sensorprod.com/pressurefilm/home.php

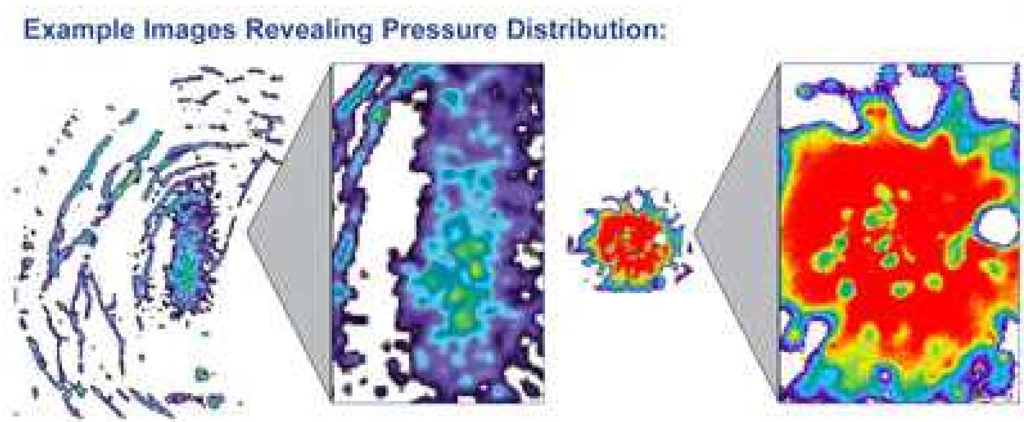
Pressure Sensitive Films



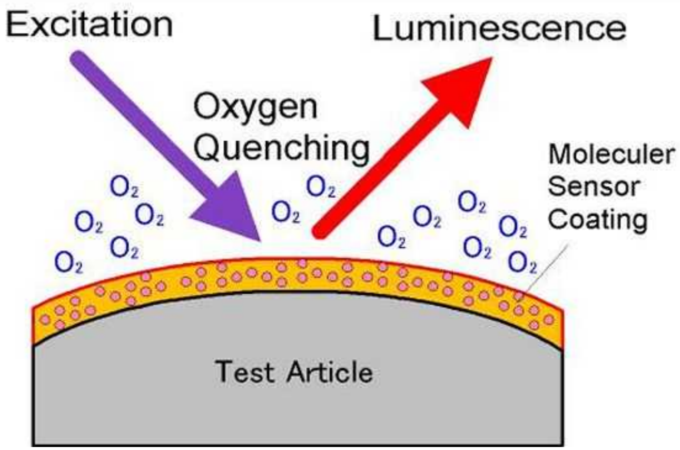
Tire tread application (left)

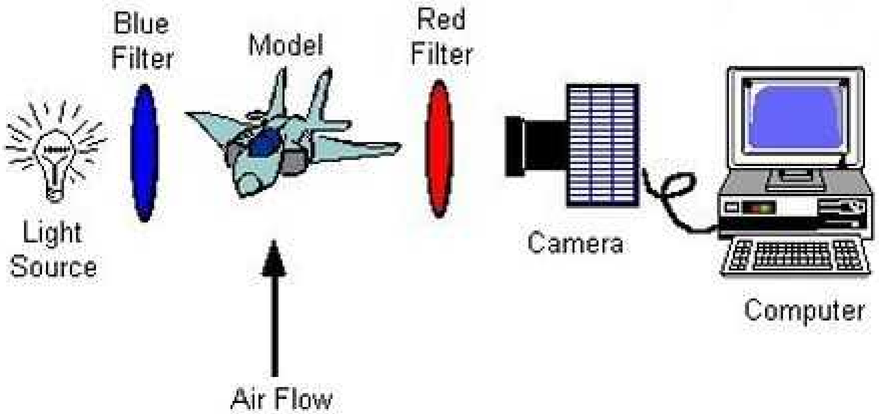
Impact and spray applications (below)

For more applications, see http://sensorprod.com/pressurefilm/home.php



Pressure Sensitive Paint (PSP)





Operating technique: PSP is applied to a model, which is then illuminated. The intensity of the emitted fluorescence varies with the oxygen concentration in the flow (as pressure increases, intensity decreases). Mean flow pressure maps can be generated, like having a large number of local pressure transducers.

The fluorescence signal is usually also temperature-dependent, so temperature changes must be corrected

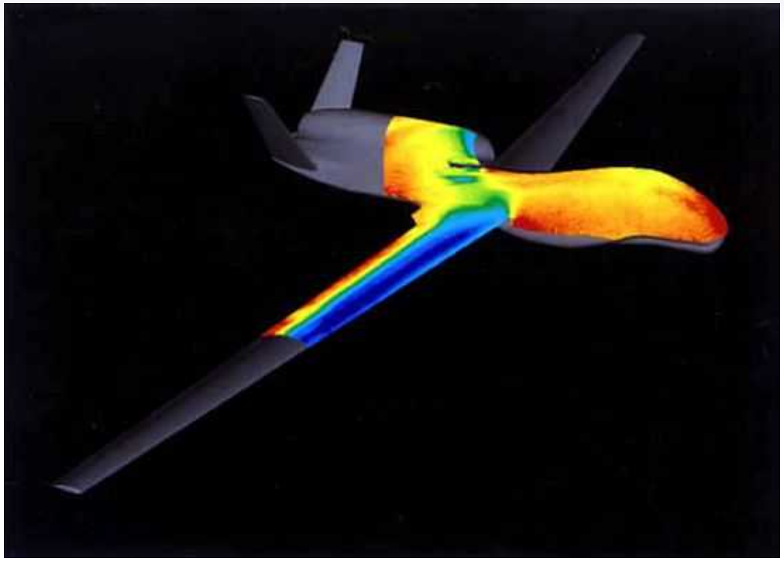
Improvements are still needed in paint quality, increasing frequency response of paints, and optimizing data processing to decrease uncertainty

http://www.aerospaceweb.org/design/psp/main.shtml

Pressure Sensitive Paint (PSP)

- **Brief Description**: PSP allows global surface pressure measurements to be made using an optical detector (camera). The surface is coated with PSP, made up of a luminescent probe molecule held in an oxygen-permeable binder. The probe molecule is chosen such that its luminescence is quenched by oxygen. When more oxygen is present, less luminescence is observed, all other variables remaining constant. Since air is made up of 28% oxygen, as the air pressure changes, the oxygen content changes by 0.28 of the pressure ratio. This change in intensity is converted to a change in pressure via an appropriate calibration. Two techniques currently are in use.
- **Parameter Space Covered:** Measurements have been made from 90 mph in atmospheric tunnels to Mach 4.5 in heated blowdown facilities.
- **Limitations:** High pressure, low speed applications are difficult. Due to the nature of the technique, absolute pressure is sensed, not differential. All surfaces where pressure is to be determined must be visible by the detector. Most PSPs are sensitive to temperature as well as pressure, although a few have been designed to minimize temperature sensitivity.
- **Uncertainty:** Several percent of full scale (absolute).
- **Comments:** Lighting must be steady and well characterized

http://www.aiaa.org/tc/amt/techniques/psp.html



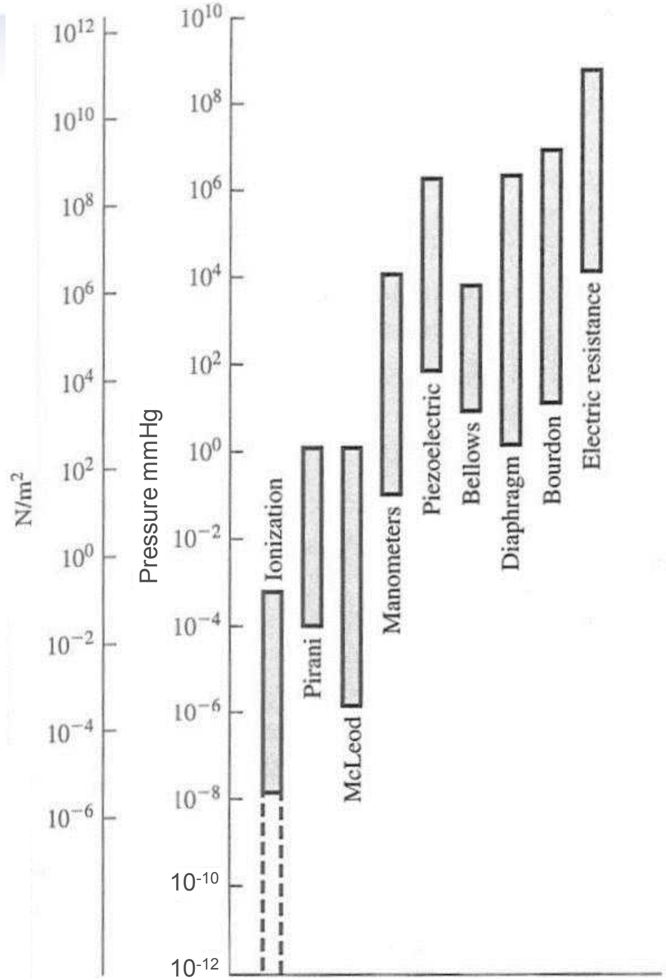
UAV model with PSP

http://www.aerospaceweb.org/design/psp/main.shtml

Other Pressure Measurement Techniques

- Pressure cell
  - Cylinder instrumented with strain gauges to detect pressure-induced deformation
- Electrical resistance pressure gauges (Bridgman gauge)
  - High pressure changes shape of coil of fine wire and therefore changes its resistance
  - 0.1% accuracy
- Pirani thermal conductivity gauges (low pressure)
  - Measures heat loss from heated wire to environment, which is controlled by gas density and therefore pressure
  - Only sensitive over range ~1 Pa to 130 Pa
  - Slow response so steady pressures only
- Ionization gauge (extremely low pressures)
  - Measures rate of gas ionization by heated filament – 10^{-6} Pa to 0.1 Pa
  - Alpha radiation version good from 0.01 Pa to atmospheric pressure

Pressure Summary



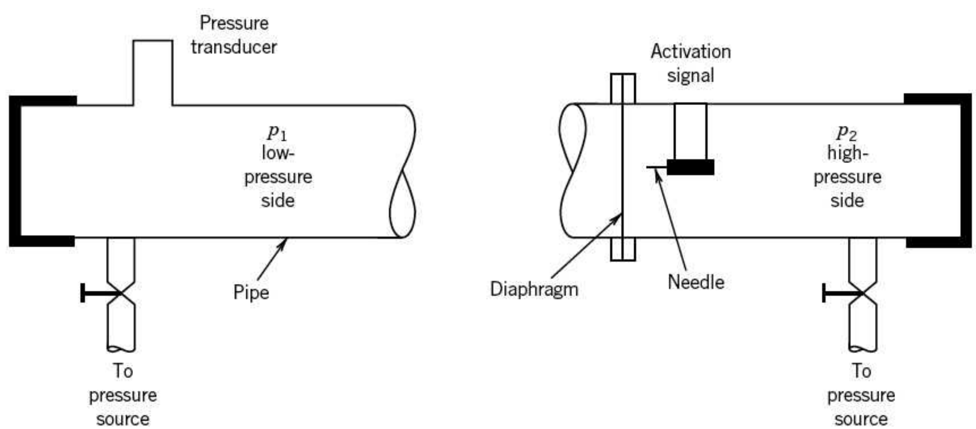
<u>Experimental Methods for Engineers</u>, 7th edition, J. P. Holman, McGraw-Hill, 2001, Figure 6.21

Pressure Summary

Type	Pros and Cons (and comments)
Manometer	+ Inexpensive + Typical uncertainty 0.02 to 0.2% of reading – Need to correct for temperature (density), elevation (precise g value) – Use tube with greater than 6 mm bore to minimize meniscus effects – Poor dynamic response – Impractical for p > ~30 psi
Bourdon tube	+ Inexpensive + With care, uncertainty can be as good as 0.1% of full scale, typically 0.5-2% + Good over very wide range of pressures – Poor dynamic response (backlash, hysteresis)
Diaphragm gauge	+ Good frequency response (>100 kHz) for small, thin diaphragms + Piezoresistive are used in most auto engines and battery-powered handheld pressure transducers + Piezoresistive full scale range from 150 Pa to 100 MPa + Special LVDT versions sensitive to 0.25 Pa + Various strain gauge and bridge configurations to increase sensitivity and to provide temperature compensation – Need to choose diaphragm to match expected pressure range, linearity only when deflection is 30% of the diaphragm thickness or less
Bellows	+ 3 kPa to 10 MPa full scale + Typical uncertainty ±0.5% of full scale – Hysteresis and zero shift can be a problem – Poor dynamic response (large relative motion and mass)

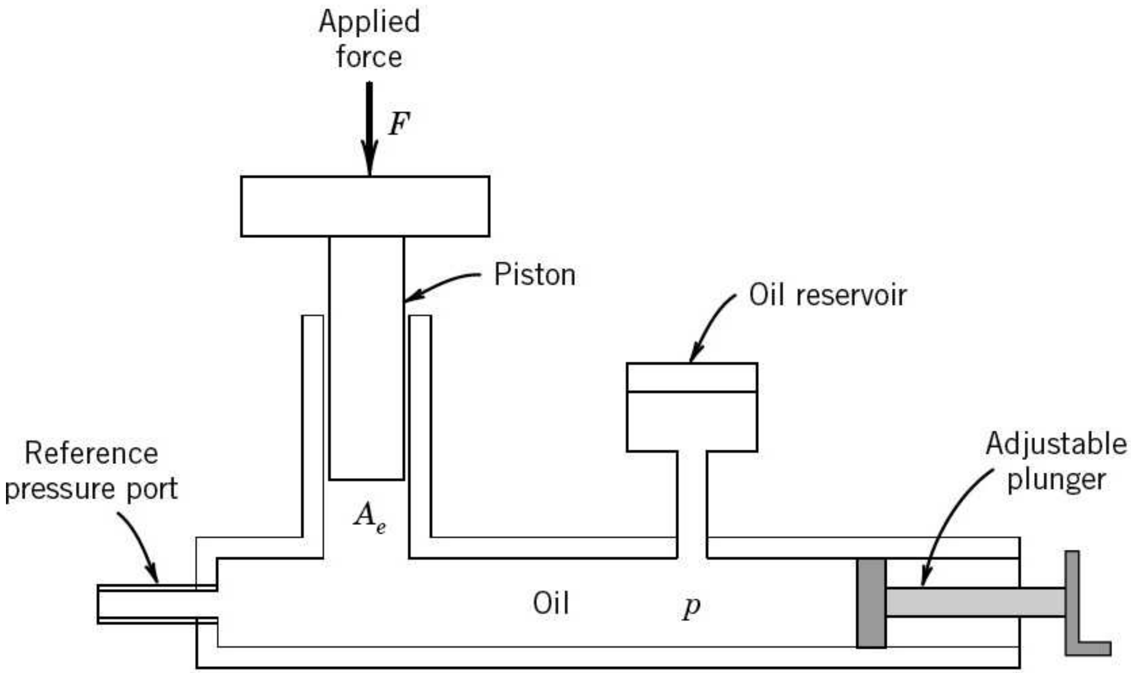
Calibration

- Static:
  - Done by direct comparison of transducer with pressure standard or with another calibrated transducer
  - Typically use a manometer for low pressures and a deadweight tester for high ranges
- Dynamic:
  - Step change in pressure needed to measure rise time
    - Electrical switching valve not always fast enough
    - Could use shock tube (shown) for faster events (shock wave passes in <1 μs)
  - Frequency response by using periodic input signals
    - Piston or loudspeaker



Calibration: Deadweight Tester

- Uses the fundamental definition of pressure as a force per unit area to create a given pressure in a sealed chamber
- $p = F/A_e + \Sigma \text{errors}$
- Lab standard over typical range 0.01 to ~150,000 psi (1 GPa)



Pressure Measurement in Moving Fluids

- Consider the flow around a bluff body as shown, with uniform, steady upstream conditions and negligible losses
- Flow along streamline A slows and eventually stops at the stagnation point 2
- For streamlines going around body (e.g., B), the flow accelerates so that $U_4 > U_3$

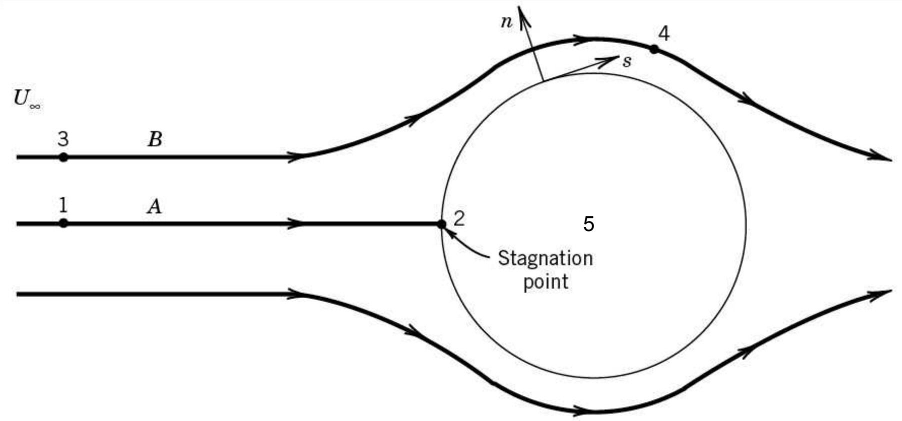


Figure 9.17 Streamline flow over a bluff body.

- Conservation of energy yields:

$$P_1 + \frac{1}{2}\rho u_1^2 = P_2 + \frac{1}{2}\rho u_2^2$$

$$P_3 + \frac{1}{2}\rho u_3^2 = P_4 + \frac{1}{2}\rho u_4^2$$

- But $u_2 = 0$ so $P_2 = P_1 + \frac{1}{2}\rho u_1^2$ is the total (or stagnation) pressure

Pressure Measurement in Moving Fluids

- So there are two components of total pressure
  - The *static* pressure that a fluid element senses as it moves with the flow (e.g., at locations 1, 3, and 4)
  - The *dynamic* pressure, or kinetic energy per unit mass of the moving fluid
- We will discuss ways to measure each of these components of the total pressure

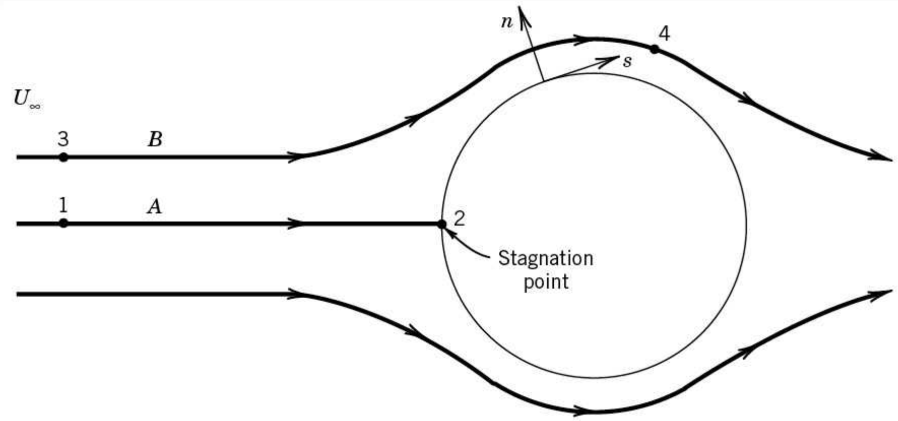
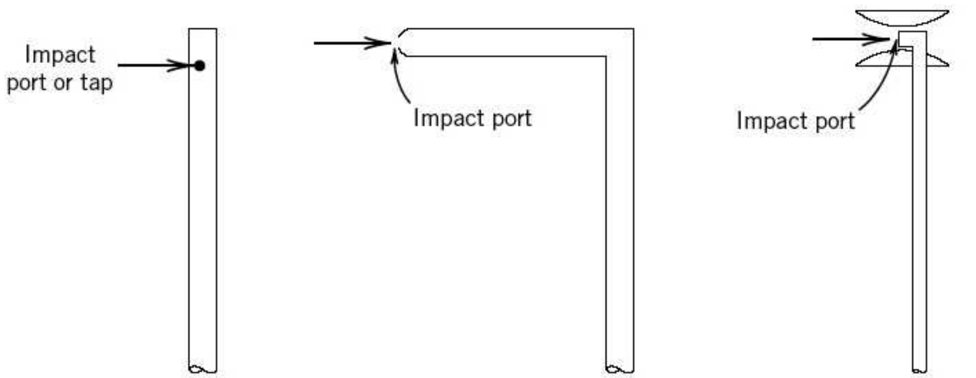


Figure 9.17 Streamline flow over a bluff body.

Pressure Measurement in Moving Fluids: Total Pressure

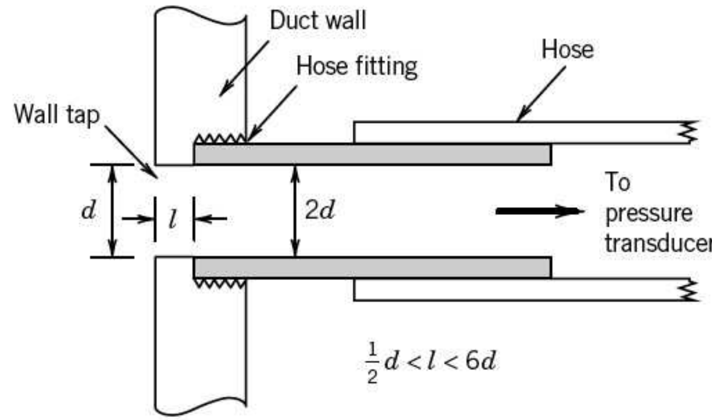
- Impact probes measure total pressure
  - A small hole is aligned with the flow and the flow stagnates at that measurement tap
  - The sensed pressure is connected to a manometer or transducer for measurement
  - Hole must be aligned with flow pretty well, e.g., ~1% changes in measured pressure over ±7° for designs (a) and (b). Design (c) forces the flow into the shroud and therefore is not sensitive to misalignment for up to ±40°

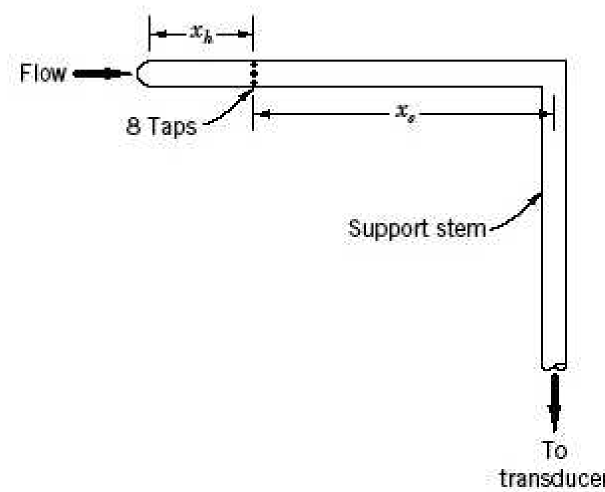


(a) Impact cylinder (b) Pitot tube (c) Kiel probe

Pressure Measurement in Moving Fluids: Static Pressure

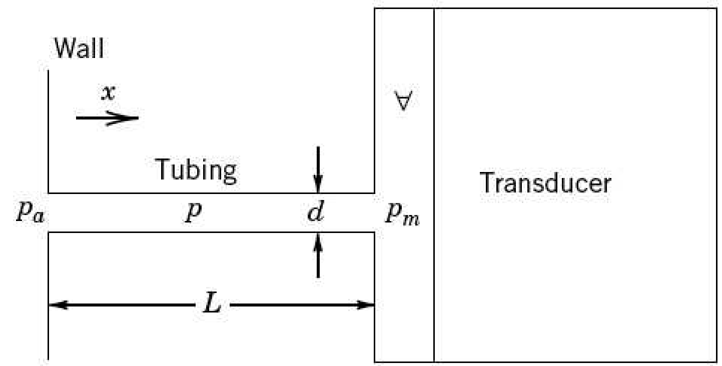
- Static pressure measurements:
  - At wall using pressure taps
    - Must be small, burr-free holes perpendicular to the surface
  - In flow using static pressure probe
    - Must be small
    - Sensing holes must be located in region of straight (not curved, accelerating) streamlines
  - Pitot static tube makes both static and dynamic pressure measurements (more later)

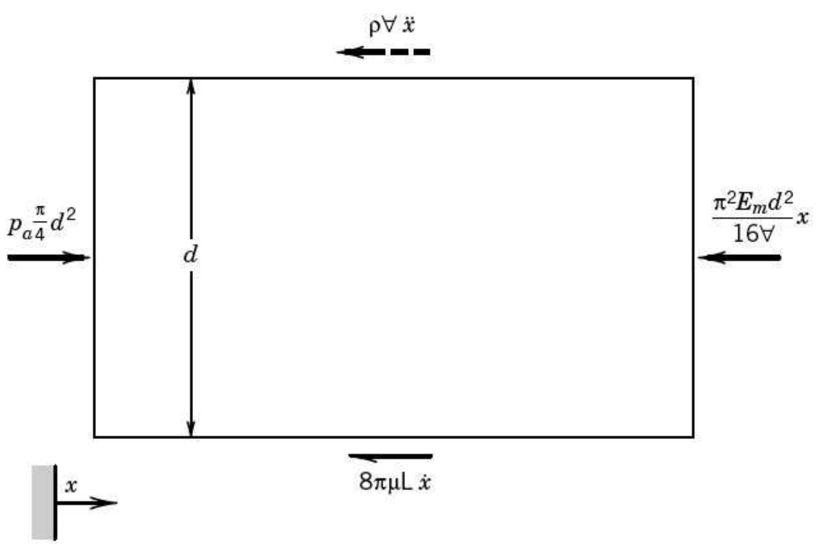




Pressure System Design Considerations

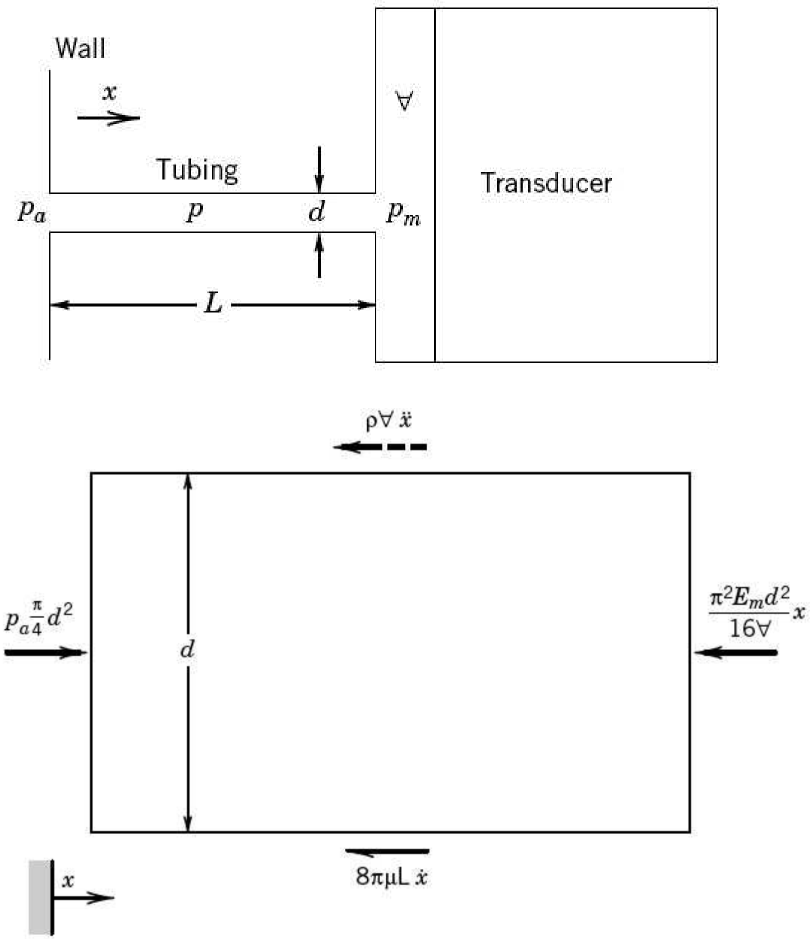
- The size of the pressure tap and the length of tubing between the pressure tap and the pressure-measuring system can affect the dynamic response characteristics of the overall pressure system.
- For a setup with a rigid tube of length L and diameter d that connects a pressure tap to transducer with internal volume V.
- The transducer is assumed to measure the correct static pressure under steady conditions, but we want to examine the effect of the pressure system on the dynamic response





Pressure System Design Considerations

- Consider the forces acting on a fluid element in the connecting tubing
- If the system is filled with gas, compressibility must be taken into consideration, through use of the fluid bulk modulus of elasticity, E_m. Pressure changes will try to move the fluid element by a distance x within the tube
- A force balance on the fluid element shows:
  - A driving pressure force $p_o \pi d^2/4$
  - A damping force due to fluid shear forces, $8\pi\mu L\dot{x}$
  - A compression-restoring force $\pi^2 E_m d^2 x/16V$.



Pressure System Design Considerations

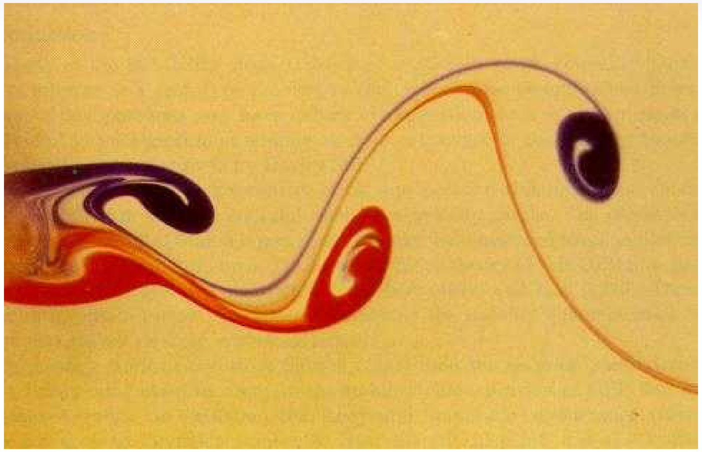
- Summing using Newton's 2nd law: $\frac{4L\rho V}{\pi E_m d^2}\ddot{p}_m + \frac{128\mu LV}{\pi E_m d^4}\dot{p}_m + p_m = p_a(t)$
- Where p_m is the measured pressure and p_a is the applied pressure.
- Analysis of this second order system yields a system natural frequency ω_n and damping ratio ζ of:

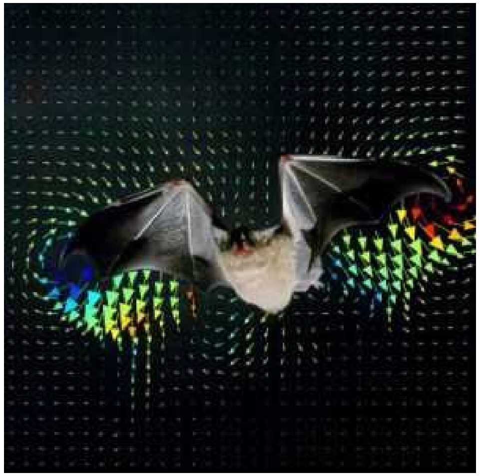
$$\omega_n = \frac{d\sqrt{\pi E_m / \rho LV}}{2} \qquad \zeta = \frac{32\mu\sqrt{VL/\pi\rho E_m}}{d^3}$$

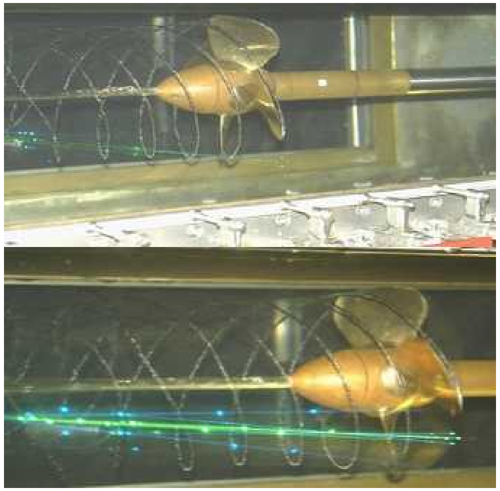
- There are corrections depending on tube vs. transducer volume, etc., and the gas properties can replace E_m, but in any case a *larger diameter* and *shorter tube* improves the pressure system dynamic response.
- If the system is filled with liquid, pressure changes are transported quickly (due to high speed of sound in liquid), but the fluid has more inertia, so results follow the same general trends

Velocity Measurement in Moving Fluids

- Considerations:
  - Required spatial resolution
  - Velocity range
  - Sensitivity to small changes in velocity
  - Sensitivity to velocity only
  - Temporal resolution
  - Probe blockage
  - Robustness; hostile environments
  - Calibration requirements
  - Cost
  - Ease of use





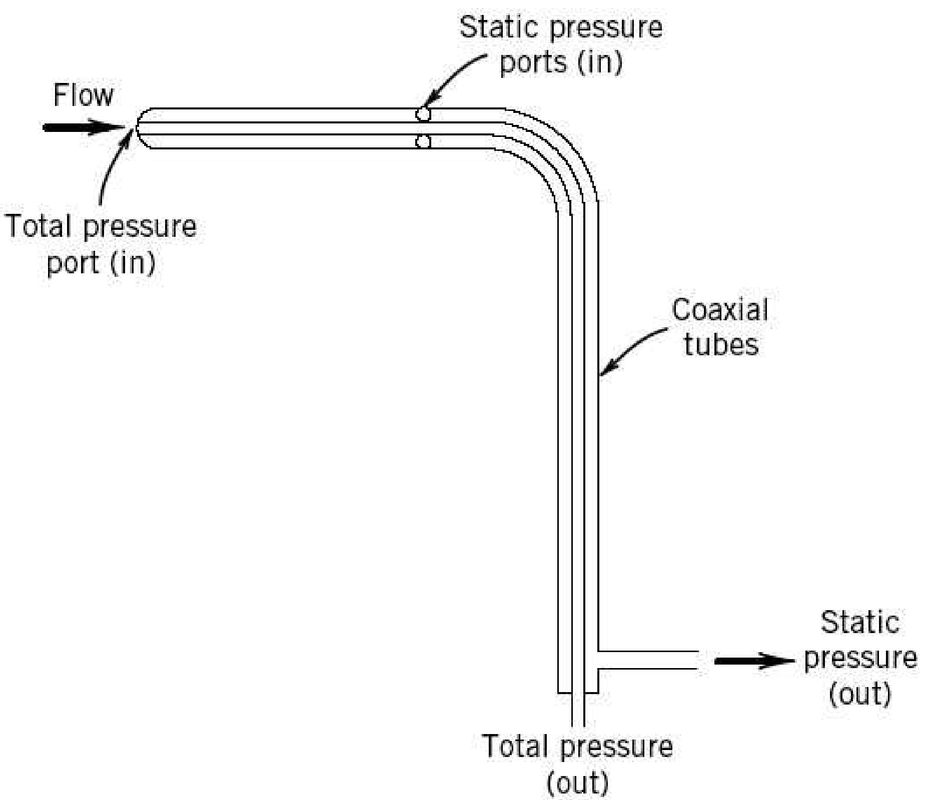


Velocity Measurement in Moving Fluids

- Pitot-static probe measures total and static pressure, difference is dynamic pressure from which velocity can be calculated

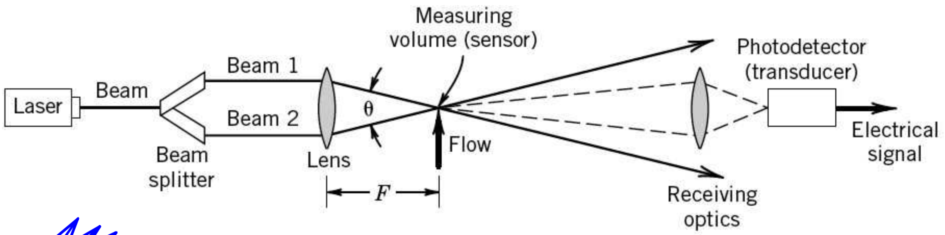
$$u_T = \sqrt{\frac{2(P_T - P_1)}{\rho}}$$

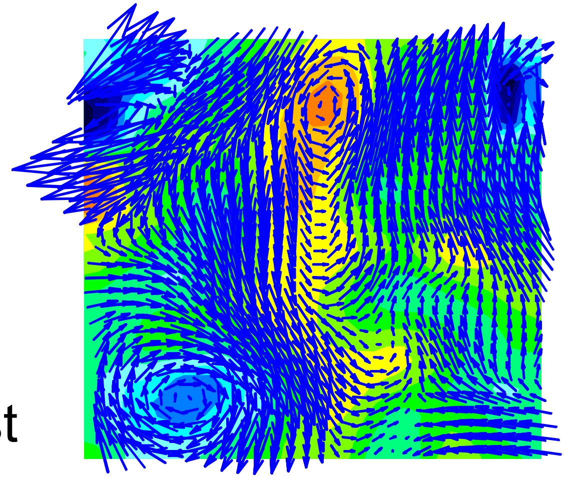
- Relatively insensitive to angular misalignment (±2% error) over ±15° yaw, and probe can usually be aligned by maximizing DP signal real time
- Large errors in very low speed flows due to viscous effects. Not a problem for Reynolds numbers (based on probe radius) greater than 500.
- Compressibility effects significant for high Mach number flows but corrections are readily available

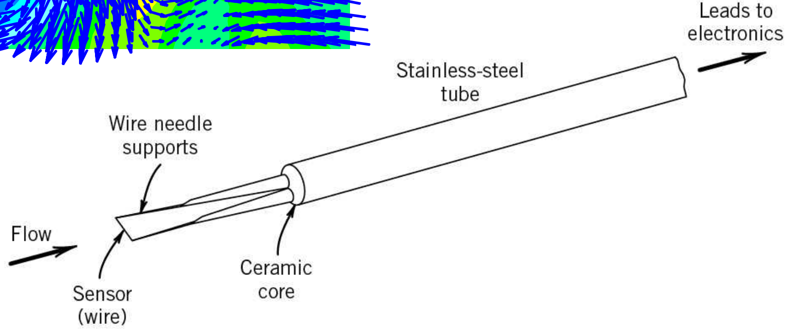


Velocity Measurement in Moving Fluids

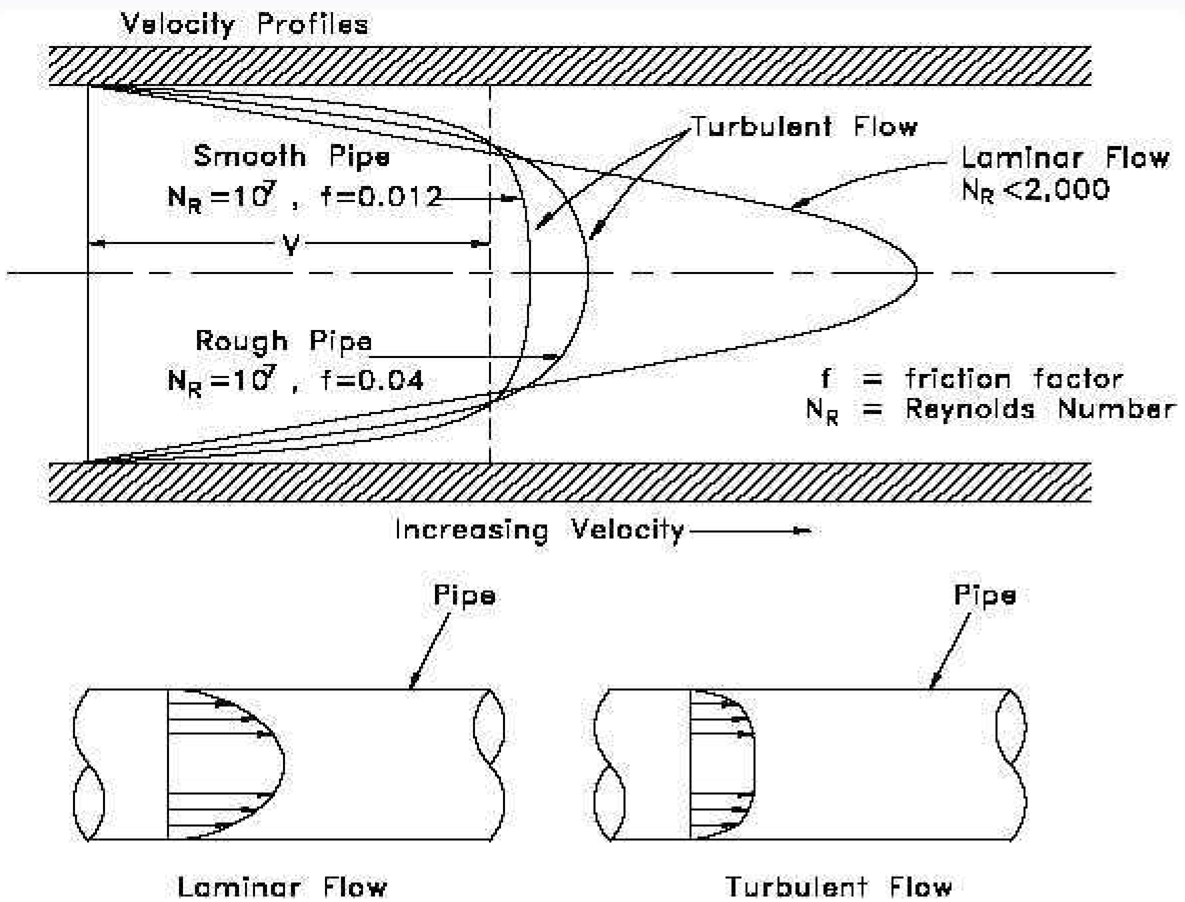
- Review from Session 6 (Lasers and Laser Applications)
  - Laser Doppler Velocimetry
  - Particle Image Velocimetry
- Hot wire anemometry
- These techniques give point velocity values, some with sufficient frequency response to measure turbulent statistics, etc. (PIV can be exception)
- However, to get flowrate one must either integrate the measured velocity profile or use a flow meter.







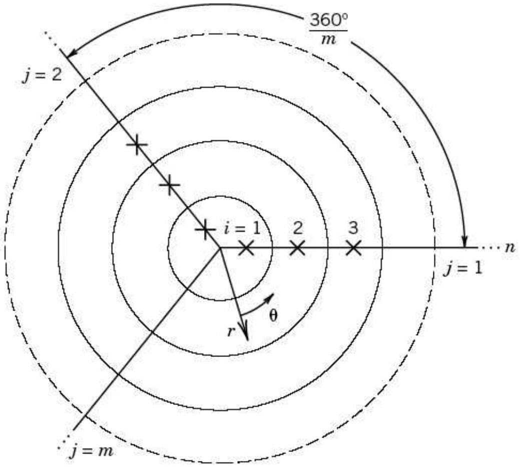
Integrate the velocity profile



Integrate the velocity profile

- Example: Integrate velocity profile to get flowrate

	U (m/s)		
r/R	Line 1	Line 2	Line 3
0.3536	8.71	8.62	8.78
0.6124	6.26	6.31	6.2
0.7906	3.69	3.74	3.79
0.9354	1.24	1.2	1.28



$$\langle Q \rangle = \frac{1}{3}\sum_{j=1}^{3} Q_j = \frac{1}{3}\sum_{j=1}^{3}\left(2\pi\int_0^R U r dr\right) \approx \frac{1}{3}\sum_{j=1}^{3} 2\pi \sum_{i=1}^{4} U_{ij} r \Delta r$$

- Where *i* indicates radial location and *j* indicates which line, and Δr is the radial distance between each measurement. This can be simplified if the measurements are made at the centroids of equally-sized areas *A*

$$Q_j = \frac{A}{4}\sum_{i=1}^{4} U_{ij} \Rightarrow \langle Q \rangle = \frac{1}{3}(0.252 + 0.252 + 0.254)\frac{m^3}{s} = 0.252\frac{m^3}{s}$$

- This is typically a one-time measurement, e.g., to verify performance of a duct system, etc.

Velocity Measurement in Moving Fluids

Type	Comments
Pitot-static probe	• No calibration needed • Inexpensive • Simplest method; often used in field • Particles in flow can clog small taps • Blockage: only when probe size significant portion of flow channel • Need to be aligned with flow – no good for reversing flows • DP is very small for low velocities
Thermal anemometry	• Excellent frequency response • Good spatial resolution • Best suited for clean fluids with constant temperature and density • Very fragile (although films generally more robust than wires) • Directional ambiguity – cannot distinguish + from – flow direction • Need to be calibrated often • Expensive for good ones, inexpensive for robust, steady flow types
Ultrasonic Doppler	• Able to handle reversing flows • Poor spatial resolution • Moderate cost

Type	Comments
LDV	• Noninvasive but requires optical access • Excellent temporal resolution – size and density of particles determine system frequency response • Good for hostile environments • Good spatial resolution • Able to handle reversing flows • No calibration required (only need to know laser wavelength and angle of beam crossing) • Expensive • Usually involves Class 4 lasers • Measures velocity of seed particles, not fluid directly, so seeding must be done carefully
PIV	• Excellent spatial resolution (velocity can be measured for each particle using particle tracking) • Excellent temporal resolution – size and density of particles determine system frequency response • Able to handle reversing flows • Noninvasive but requires optical access • Usually expensive • Usually involves Class 4 lasers • Measures velocity of seed particles, not fluid directly, so seeding must be done carefully

Flowmeters

- Flowrate is either *volumetric* (volume/unit time, e.g., gallon/min, etc.) or *mass* (mass/unit time, e.g., lbs/hr, etc.)
- Critical to economy (water, oil, natural gas, gasoline, etc.) so lots of choices are available
- Considerations:
  - Size
  - Accuracy
  - Cost
  - Pressure drop
  - Turndown ratio (high to low flow rate)
  - Laminar or turbulent
  - Steady state or transient
  - Gas, liquid, solid or combinations
  - Compatibility with the fluid

Flowmeters

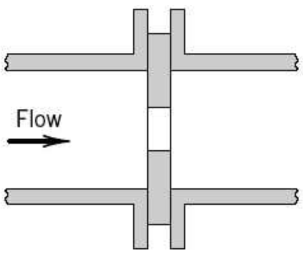
- There are many different types of flowmeters for different applications. We will cover some of the basic types here:
  - Pressure differential
    - Obstruction (orifice plate, venturi, nozzle)
    - Sonic nozzles
    - Laminar flow elements
  - Electromagnetic
  - Vortex shedding
  - Rotameters
  - Turbine meters
  - Transit time and Doppler (ultrasonic) flow meters
  - Positive displacement meters
  - Mass Flow Meters
    - Thermal
    - Coriolis
- http://www.mccrometer.com/forms/form_evaluation.aspx
- http://www.omega.com/techref/flowtable.html

Flowmeters: Pressure Differential

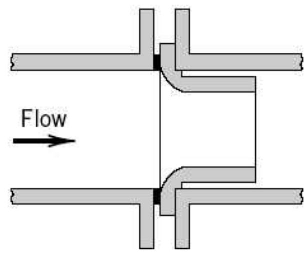
- Pressure differential meter is based on the relationship between volumetric flow rate and pressure drop $\Delta p = p_1 - p_2$ along the flow path, i.e., $Q \propto (p_1 - p_2)^n$
- There are no moving parts, so meters can be very robust
- Obstruction meters reduce the flow area
  - Orifice plate
  - Nozzle
  - Venturi

$$Q = K_0 A_0 \sqrt{\frac{2\Delta p}{\rho}}$$

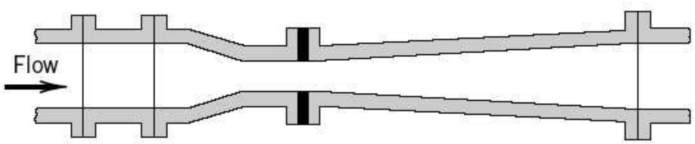
where K_0 is the flow coefficient (tabulated) and A_0 is the throat diameter.



(a) Square-edge orifice plate



(b) ASME long-radius nozzle



(c) ASME Herschel venturi

For compressible gases, an adiabatic expansion factor must be calculated

Obstruction Flowmeters: Orifice Plate

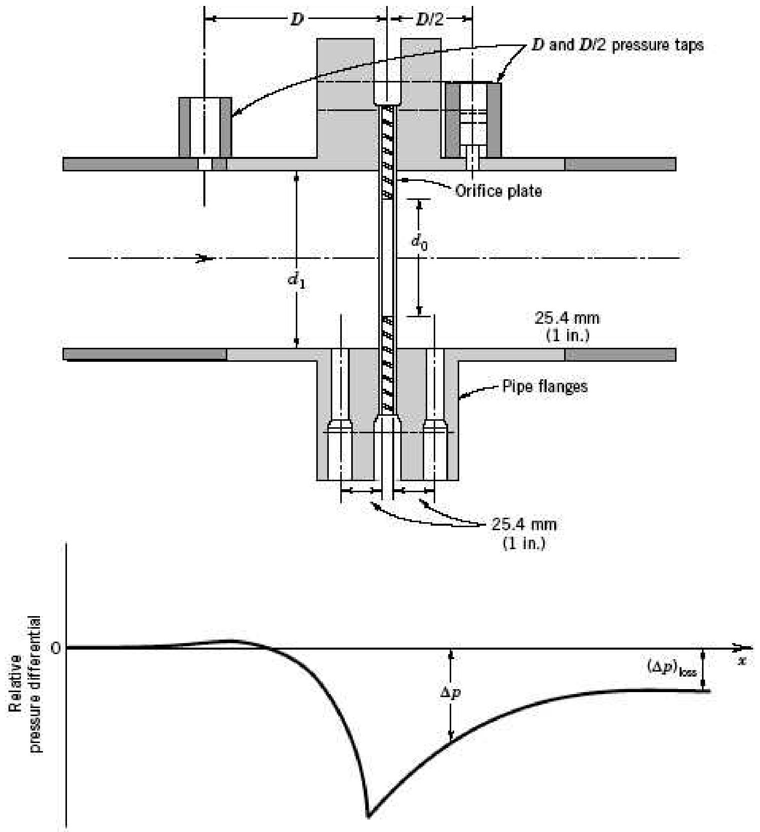
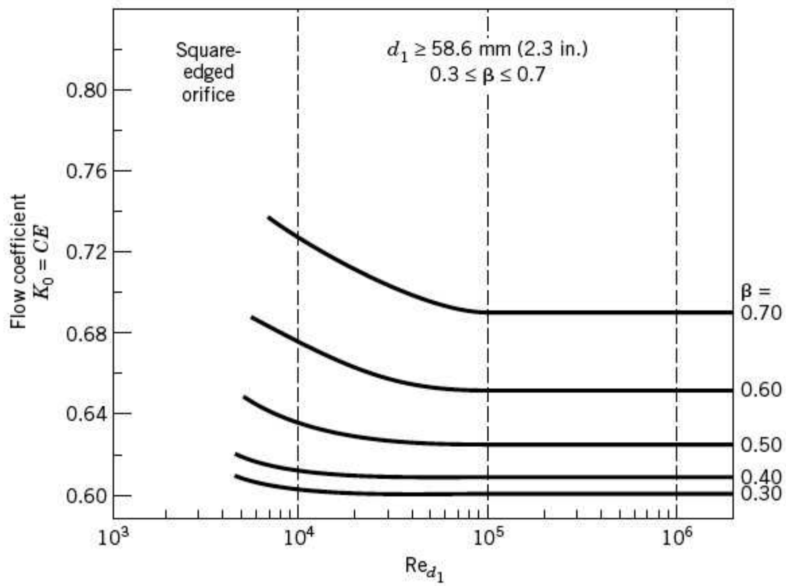


Figure 10.5 Square-edged orifice meter installed in a pipeline with optional 1 D and ½ D, and flange pressure taps shown. Relative flow pressure drop along pipe axis is shown.



$$K_0 = \frac{1}{(1-\beta^4)^{1/2}}\left(0.5959 + 0.0312\beta^{2.1} - 0.184\beta^8 + 91.71\beta^{2.5}Re_{d_1}^{-0.75}\right)$$

Figure 10.6 Flow coefficients for a square-edged orifice meter having flange pressure taps. (Compiled from data in [2]).

Obstruction Flowmeters: Long Nozzle

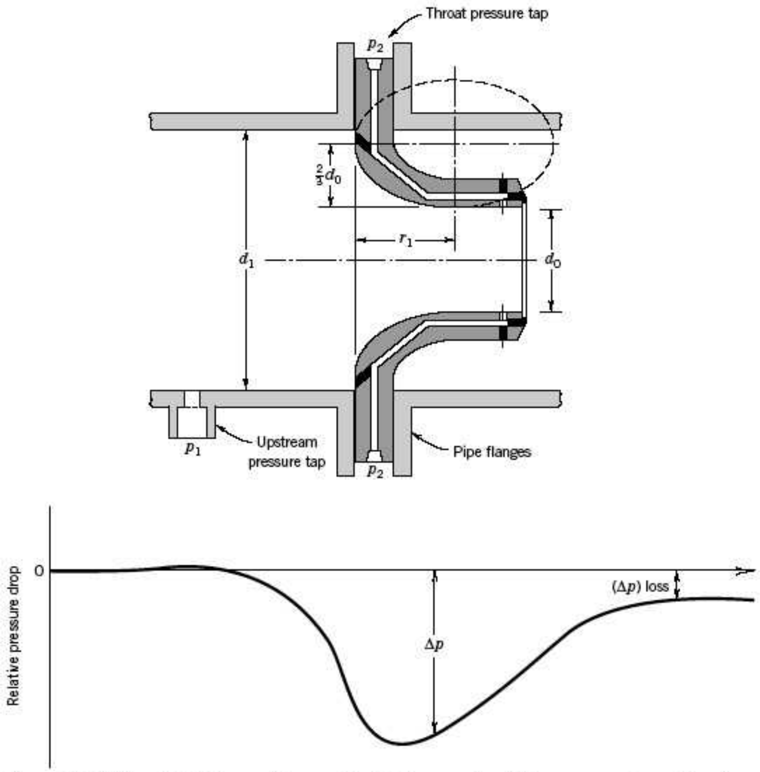


Figure 10.10 The ASME long-radius nozzle with the associated flow pressure drop along its axis.

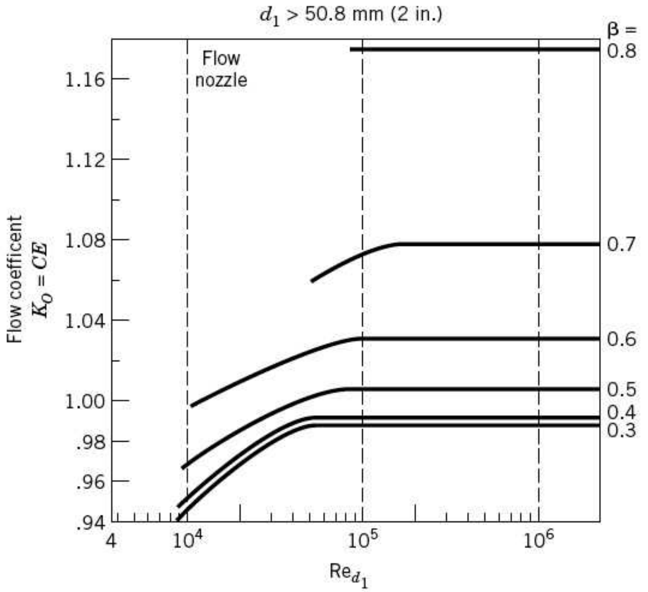


Figure 10.11 Flow coefficients for an ASME long-radius nozzle with a throat pressure tap. (Compiled from [2].)

Obstruction Flowmeters: Venturi

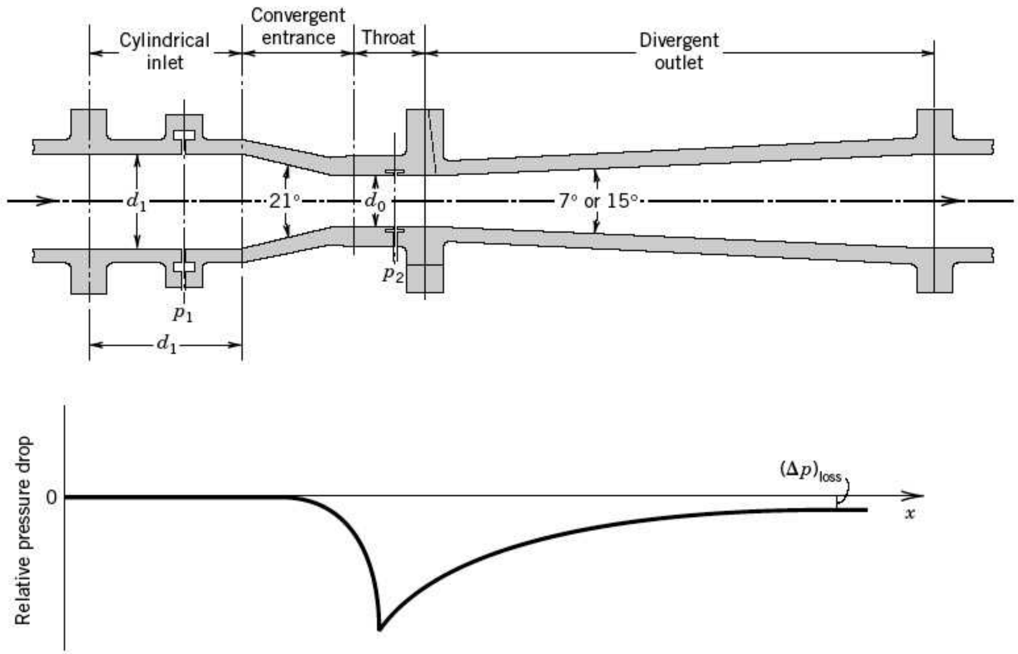


Figure 10.9 The Herschel venturi meter with the associated flow pressure drop along its axis.

For pipe diameters greater than 7.6 cm (3 in.) the discharge coefficient is nearly constant (C = 0.984 for cast units; C = 0.995 for machined units).

Obstruction Flowmeters

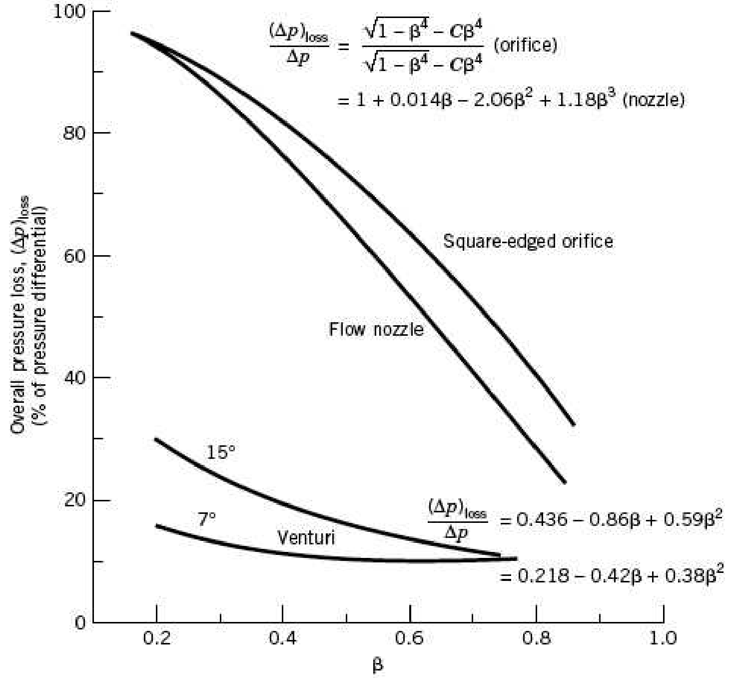


Figure 10.8 The permanent pressure loss associated with flow through common obstruction meters. (Courtesy of American Society of Mechanical Engineers, New York, NY; compiled and reprinted from [2].)

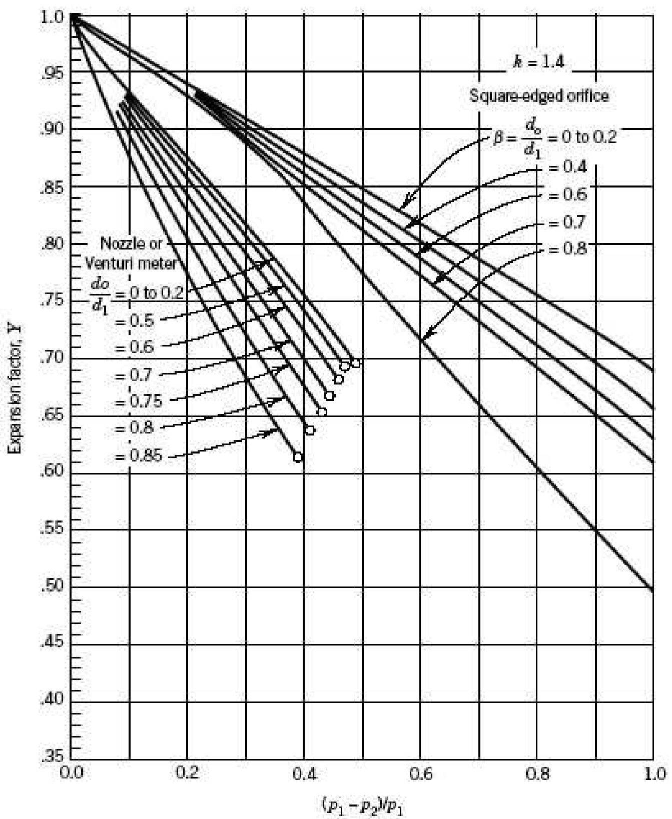
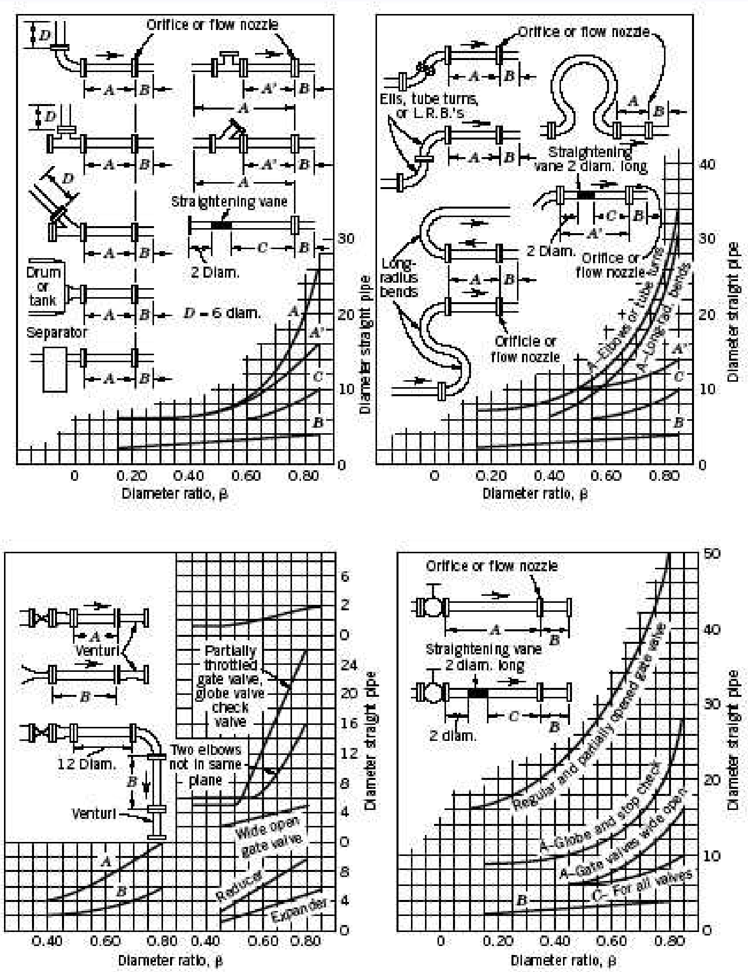


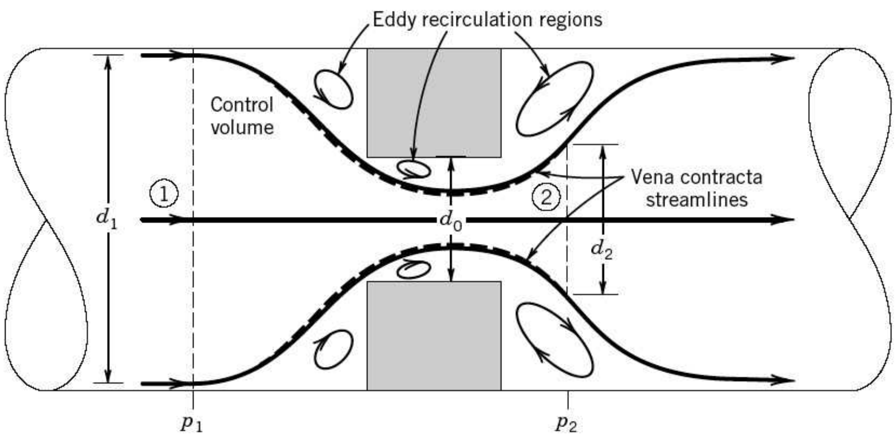
Figure 10.7 Expansion factors for common obstruction meters with $k = c_p/c_v = 1.4$. (Courtesy of American Society of Mechanical Engineers, New York; compiled and reprinted from [2].)

Obstruction Flowmeters: Installation Guidelines

This table is for obstruction meters but there are similar guidelines for essentially all other types

The basic factors are typically avoiding swirl and excessive turbulence





Flowmeters: Sonic Nozzles

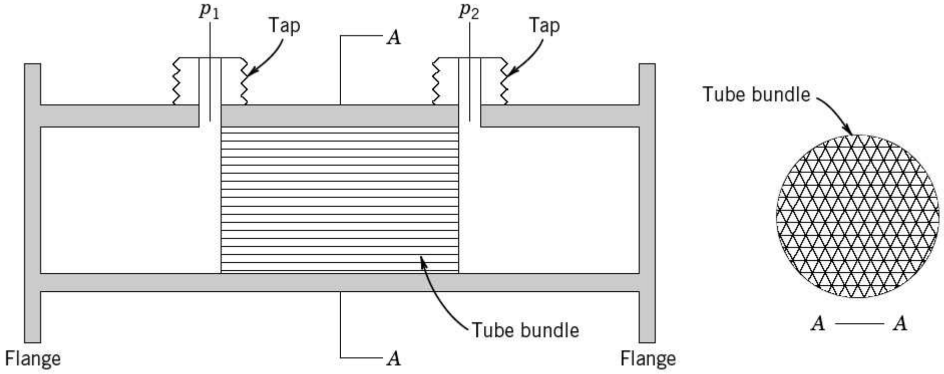
- Sonic nozzles are used to meter and control the flow rate of *compressible gases*
- Various shapes are available
- In each case, the flow rate becomes high enough that the sonic condition is reached at the orifice throat (gas velocity = speed of sound of the gas)
- At this point the flow is *choked*, i.e., the mass flow rate is at a maximum for the given inlet conditions
  - Further increases in pressure drop across the meter will *not* increase the mass flow rate
- For ideal gases at the sonic condition, the mass flow rate can be calculated

$$\dot{m}_{\max} = \rho_1 A \sqrt{2RT_1} \sqrt{\frac{k}{k+1}\left(\frac{2}{k+1}\right)^{2/(k-1)}}$$

  where k is the gas specific heat ratio
- Often used as a local calibration standard for compressible gases

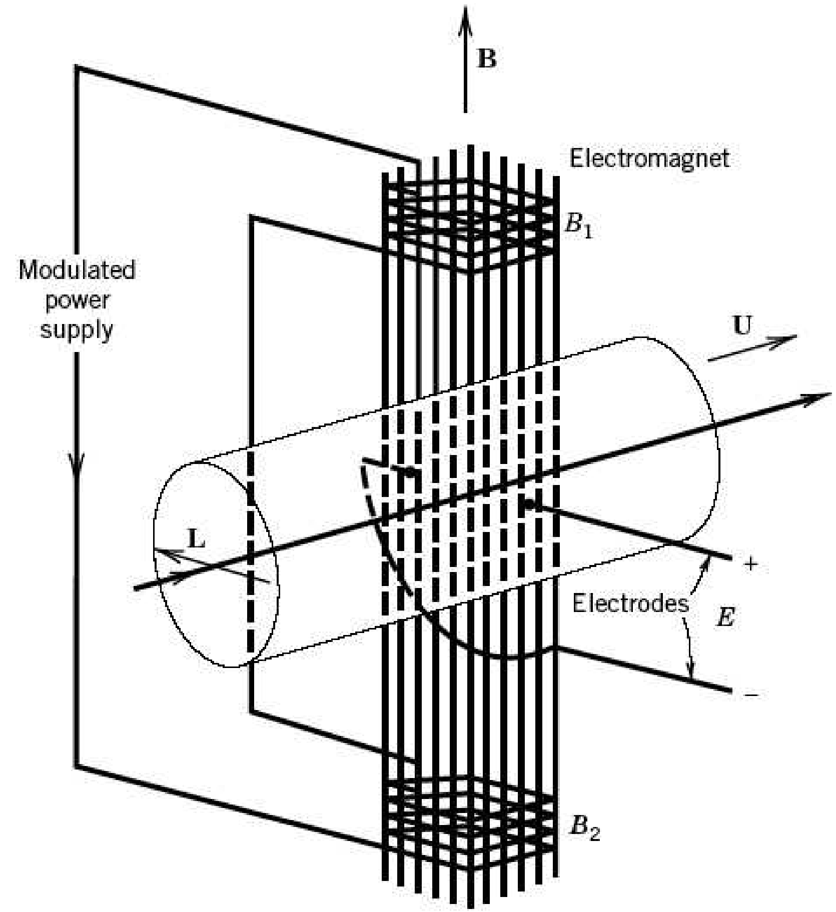
Flowmeters: Laminar Flow Elements

- In laminar flow there is a known relation between flowrate and pressure drop, given by the Poiseulle equation: $$Q = \frac{\pi d^2}{128\mu}\frac{p_1 - p_2}{L}$$
- However, most applications where we need to measure flowrate do not have laminar flow
  - Pipe flows generally transition from laminar to turbulent at a Reynolds number of 2000 $$\mathrm{Re}_d = \frac{\rho U d}{\mu} = \frac{Ud}{\nu}$$
- Laminar flow elements are bundles of small tubes that are inserted into a larger pipe
  - The flow within each tube is laminar and *Q* can be calculated from ΔP, also accounting for entrance and exit losses)



Flowmeters: Electromagnetic

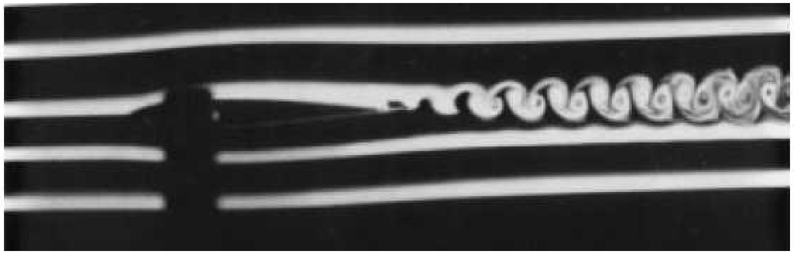
- The fundamental principle is that an electromotive force of electric potential *E* is induced in a conductor of length **L** which moves with velocity **U** through a magnetic field of magnetic flux **B** (Faraday) E = $\mathbf{U} \times \mathbf{B} \cdot \mathbf{L}$
- This is shown in the figure for an *electrically conductive* liquid
- Fluid flows through pipe, a short section of which is subjected to a transverse magnetic flux.
- The magnitude of the induced voltage E is a linearly related to the average velocity $\overline{U}$
- E is detected by electrodes at walls

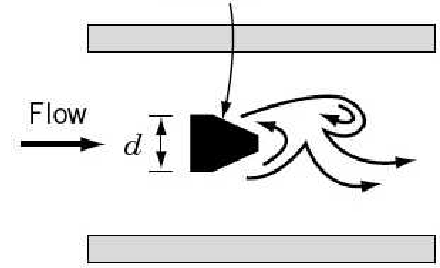


Flowmeters: Electromagnetic

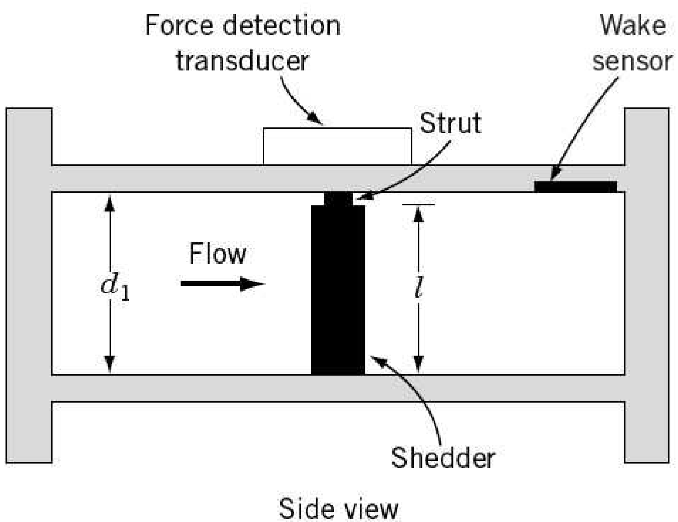
- Typical installation uses electrodes mounted in or on pipe wall, often supplied as a package (as shown) so that electrodes directly contact the fluid
- Some can clamp over existing nonmagnetic pipes (including arteries)
- Very low pressure loss
- No internal parts
- Not sensitive to density or viscosity, only average velocity
- Often used in dirty, corrosive applications (e.g., sewage treatment) since no moving parts
- Flow can be laminar or turbulent, but should have a fairly symmetric velocity profile
- Steady or instantaneous output

Flowmeters: Vortex Shedding





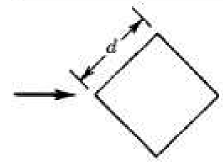
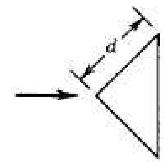
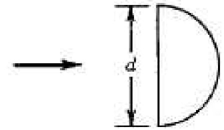
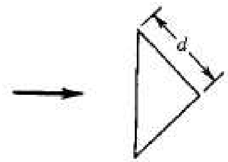
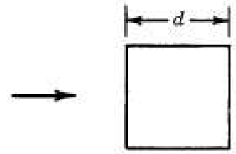
- Flow past a bluff body forms vortices that shed and continue downstream in a Karman vortex street
- The shedding frequency *f* is a function of the average velocity *U* and the shape of the body. They are related by the Strouhal number $St = fd/U$, where *d* is a characteristic dimension of the shedding body.



Flowmeters: Vortex Shedding

- St is generally a function of the Reynolds number but there are a range of body shapes (some proprietary to flowmeter manufacturers) that give a fixed St over a wide range of Re
- In the vortex meter, the shedding frequency is measured by changes in strain, capacitance, or pressure
- Lower flow rate limit at Re ≈ 2×10^4
- Upper flow limit restricted by cavitation in liquids, compressibility in gases (M > 0.2)
- Not too susceptible to fluid properties
- No moving parts
- Moderate pressure drop
- Upper limit on meter size as shedding becomes harder to detect in large pipes

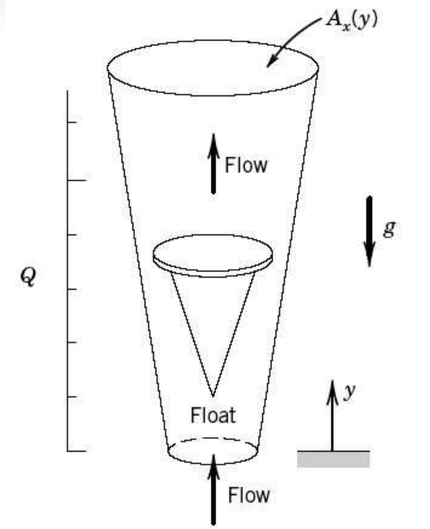
Table 10.1 Shedder Shape and Strouhal Number

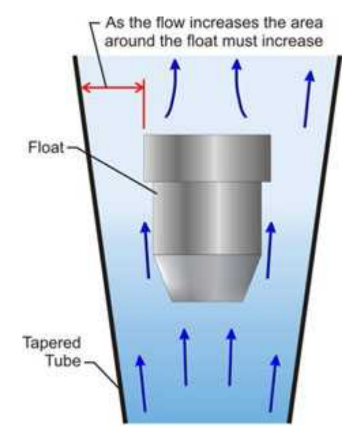
Cross Section	Strouhal Number[a]
	0.16
	0.19
	0.16
	0.15
	0.12

[a]For Reynolds number $Re_d \geq 10^4$. Strouhal number $St = fd/\bar{U}$.

Flowmeters: Rotameters

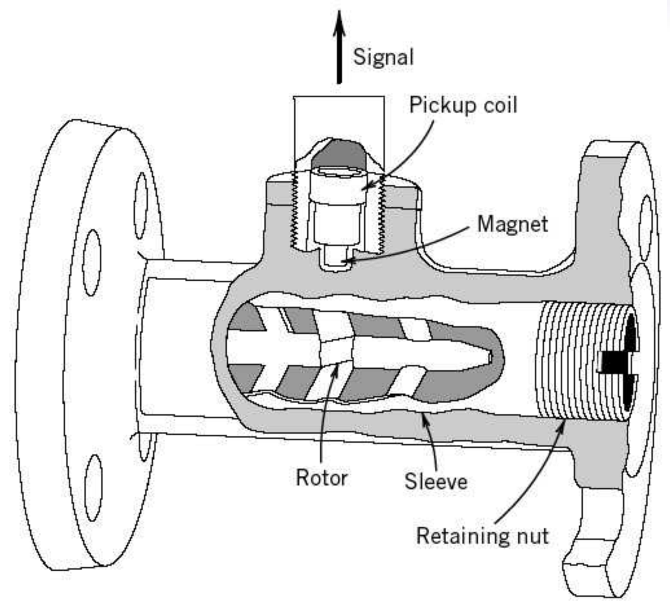
- Widely used insertion meter in vertical pipes
- Float within a tapered vertical tube (variable area - area increasing with length)
- The float is a fixed size so as it rises the gap between the float and the wall increases. As the flow rate increases the float rises to allow the flow to pass through the needed larger area.
- Stable equilibrium height of the float indicates flow rate
- The operating principle is based on the balance between the drag force on the float and its weight and buoyancy
- The float height can be read from a scale, electronically sensed with an optical cell, or detected magnetically
- Typical 10:1 turndown
- Typical systematic uncertainty ≈±2% of flow rate

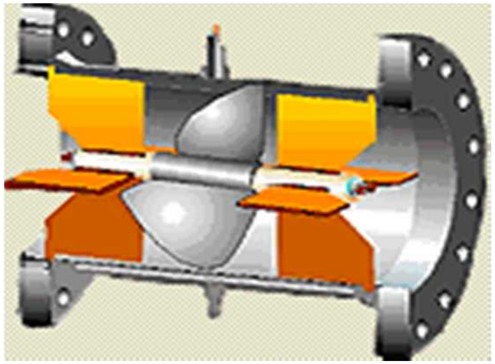




Flowmeters: Turbine Meters

- Widely used insertion meter
- Rotational speed is a function of flow rate
- Rotation measured in several different ways including variable reluctance pickup coils that can output the pulses to a data acquisition system
- Low pressure drop
- Very good accuracy
- Should only be used in clean fluids because fouling changes meter constant
- Careful installation needed (susceptible to install errors like swirl)
- Typical 20:1 turndown
- Typical systematic uncertainty ≈±0.25% of flow rate





http://www.bellflowsystems.co.uk/Turbine-Meters-c-261.html

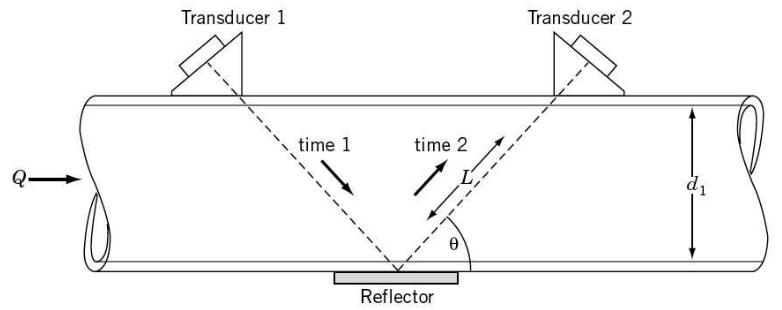
Flowmeters: Transit time and ultrasonic Doppler

- *Transit time* flow meters use the travel time of ultrasonic waves to estimate average flow velocity
- Pair of transducers, separated by known distance, are fixed to outside of pipe wall. Each transducer can transmit and receive (transceiver)
- The wave sent by one transducer is reflected off opposite pipe wall and detected by the other transducer
- The difference in transit time is directly related to the average velocity
- For a fluid with speed of sound *a*,

$$t_1 = \frac{2L}{a + \overline{U}\cos\theta} \qquad t_2 = \frac{2L}{a - \overline{U}\cos\theta} \qquad Q = \overline{U}A = \frac{K_1 \pi d_1 a^2 (t_2 - t_1)}{16\cot\theta}$$

where K_1 is a meter constant

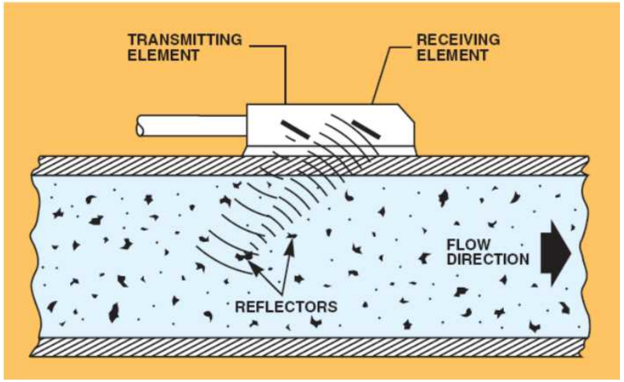
- Can strap onto outside of pipe
- Can measure time-varying flows
- Typical uncertainty ≈1-5% of flow rate
- Noninvasive, so no added pressure drop



Flowmeters: Transit time and ultrasonic Doppler

- *Ultrasonic Doppler meter* sends ultrasonic wave into liquid containing impurities (bubbles, particulates)
- The emitted wave is scattered by the impurities and detected by the transducer
- The scattered wave frequency is Doppler shifted by the velocity of the impurity
- For an incident frequency *f* and Doppler frequency f_d, the flow rate is given by:

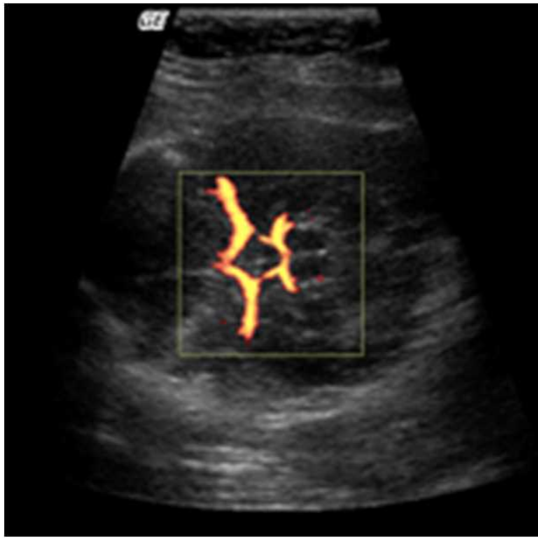
$$Q = \overline{U}A = \frac{\pi d_1^2 a f_d}{8 f \cos\theta}$$

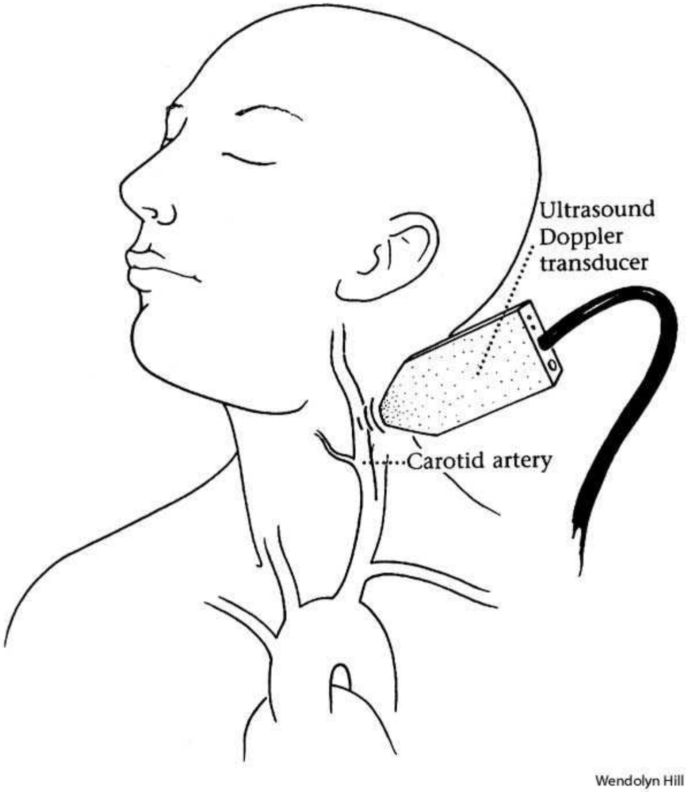


- Can measure time variations in the flow
- Typical uncertainty ≈2% of flow rate
- http://www.eesiflo.com/measuring.html

Flowmeters: Transit time and ultrasonic Doppler

- In blood flow application, the red blood cells are the scattering elements



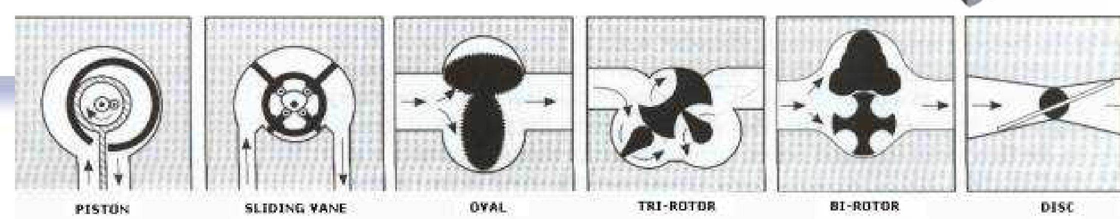


http://www.gehealthcare.com/usen/ultrasound/products/cmetcd.html

http://www.answers.com/topic/ultrasound-tests?cat=health

Flowmeters: Positive Displacement (PD)

- Many different designs, but all contain a mechanical element that defines a known volume that is filled with the fluid being metered.
- Each displacement or rotation of the element is measured (Q = *volume/time*)
- Rugged, accurate
- *Diaphragm meters* contain opposing coupled flexible bellows
  - When one expands, the other collapses
  - The alternating filling and emptying is counted to measure flow rate
  - Commonly used in dry gases like natural gas or propane
- *Wobble or nutating disk meters* contain a disk seated in a chamber
  - Liquid flow through the chamber causes the disk to oscillate; each tilt releases a known volume
  - Domestic water applications
- *Rotating vane meters*
  - Oil trucks, gasoline pumps
- Typical systematic uncertainty ≈±0.2% of actual delivery



Flowmeters: PD Natural gas meters

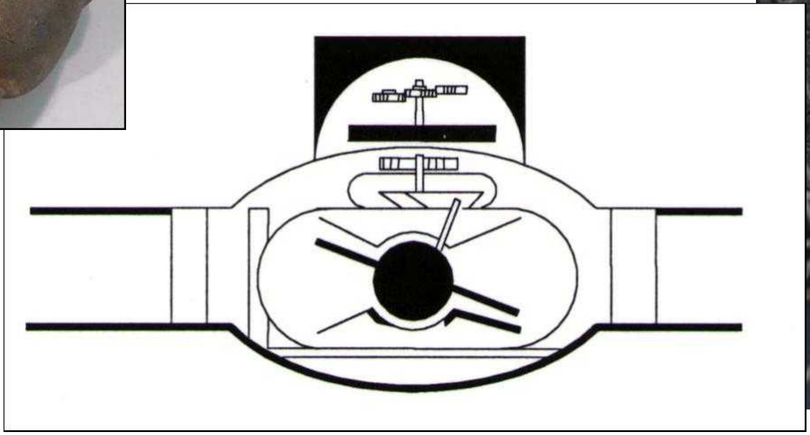
- **Diaphragm/bellows PD meters**
- These are the most common type of gas meter, seen in almost all residential and small commercial installations. Within the meter there are two or more chambers formed by movable diaphragms. With the gas flow directed by internal valves, the chambers alternately fill and expel gas, producing a near continuous flow through the meter.
- As the diaphragms expand and contract, levers connected to cranks convert the linear motion of the diaphragms into rotary motion which then drives the counter mechanism.
- Major manufactures of diaphragm meters in the US include Actaris, American Meter, and Sensus.

Flowmeters: PD Gas station meters

- Positive Displacement meter that the gasoline flows through.
- For every revolution of the mechanical element (chamber) a fixed, very accurate, volume of gasoline goes through.
- The speed of the pump may vary but the Positive Displacement meter will always measure an exact quantity of gasoline.

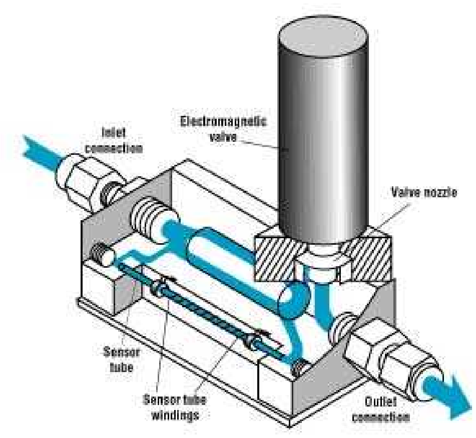
Flowmeters: PD Home water meters

- Often wobble-type (nutating disk) positive displacement meters
- Better than 1% accuracy



Flowmeters:
Mass Flow Meters

- Instead of measuring Q = *volume/time*, we sometimes need to measure $\dot{m}$ (mass per unit time)
- To do this one needs to measure the momentum per unit time $\rho\overline{U}$ to find $\dot{m} = \rho\overline{U}A$
- Of course, if density is known exactly, then $\dot{m}$ can be derived from Q, i.e., $\dot{m} = \rho Q = \rho\overline{U}A$
- But in cases where the density is not known, changes rapidly with temperature, or reducing temperature-dependent uncertainty is critical, a direct measurement of mass flow rate is preferable
- Good mass flow meters have only been around since the early 1970s



Flowmeters: Thermal Mass Flow Meter

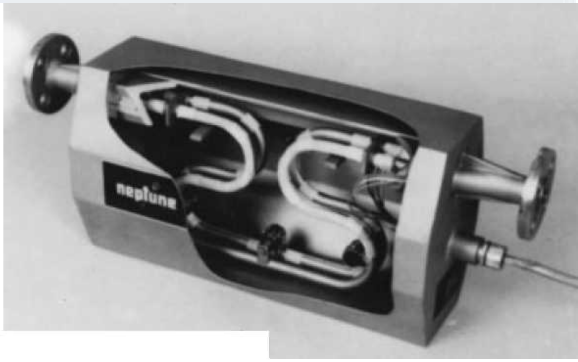
- The rate at which energy must be added to a flowing fluid to raise its temperature is related to the mass flow rate by

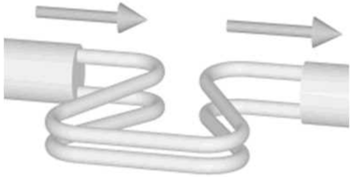
  $$\dot{E} = \dot{m} c_p \Delta T$$

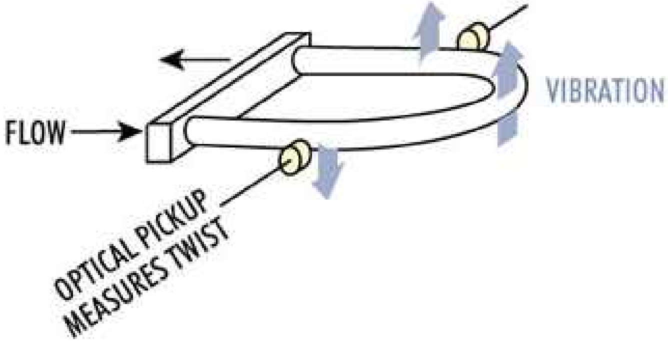
  where c_p is the fluid specific heat
- Thermal mass flow controllers use this relation to calculate mass flow rate by inputting energy to the fluid, usually by passing current through an immersed filament, and measuring the change in temperature. For known c_p, this can be used to calculate $\dot{m}$
- Widely used in gas flows, including automotive air control for fuel injection
- Typical 100:1 turndown
- Typical systematic uncertainty ≈±0.5% of flow rate
- Very low pressure drop
- Assumption of constant c_p becomes a problem for liquids and many gases for which c_p is either a strong function of temperature or is not well established

Flowmeters: Coriolis Mass Flow Meter

- Widely used insertion meter than measures mass flow rate by inducing a Coriolis acceleration on the flowing liquid and measuring the resulting forces
- Hose example: Hold loop of hose, run water, swing hose up and down in front. Since water is flowing away from you in one leg and toward you in the other, a force will develop to try to twist the loop
- In flowmeters, the swinging is done by vibrating the loop. The resulting twist is measured and is proportional to the mass flow rate

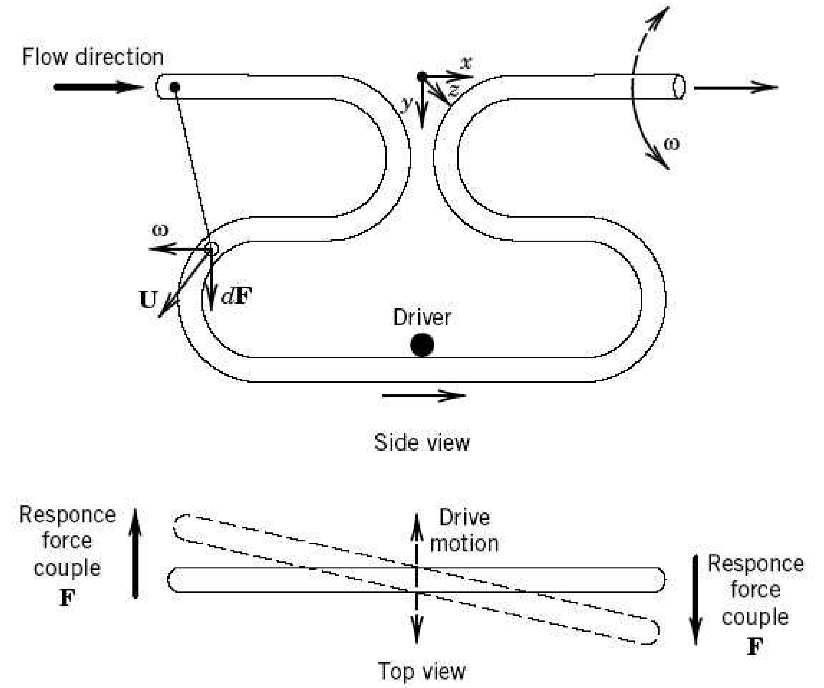


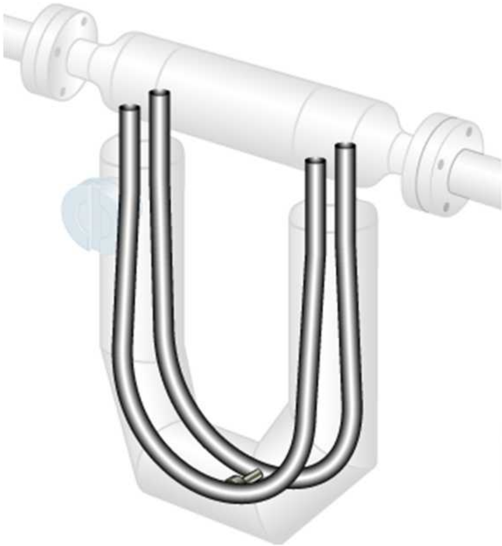




Flowmeters: Coriolis Mass Flow Meter

- Insensitive to installation position
- Typical 20:1 turndown
- Typical systematic uncertainty ≈±0.25% of flow rate, can be as good as ≈±0.10%





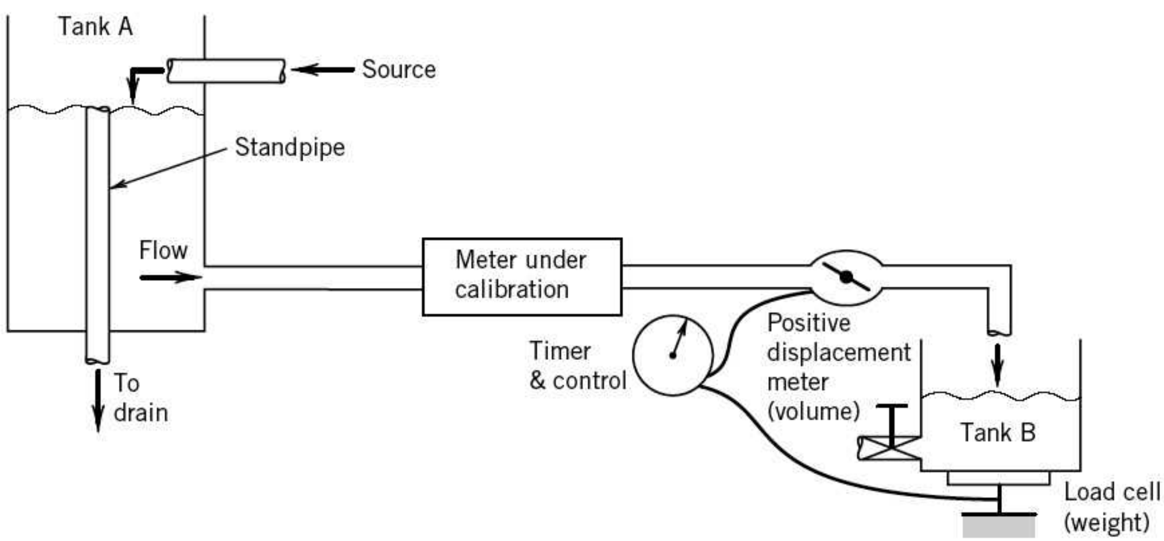
Flowmeters: Standard Flow Rate

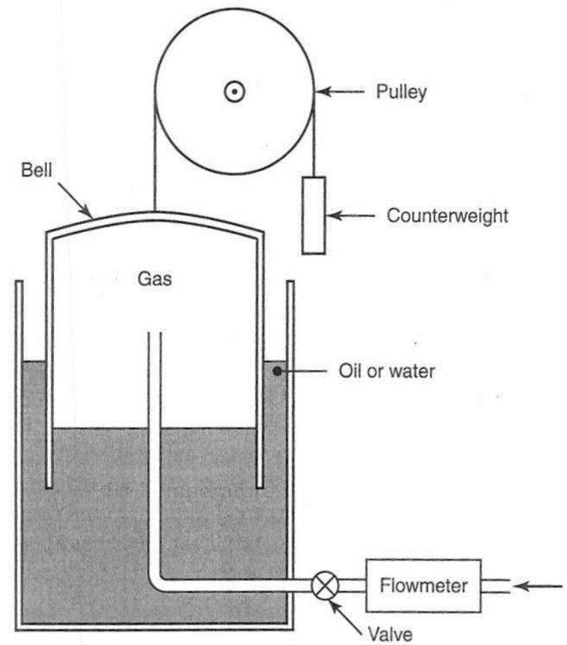
- “Actual” flow rates are generally measured over a wide range of pressures and temperatures
- The reported results are often converted to “standard” conditions for comparison
- The adjusted flow rate is the *standard flow rate*, and are reported with units such as SCFM (standard cubic feet per minute) or SCMM (standard cubic meters per minute)
- The volumetric flow changes (due to density changes):

$$Q_s = Q_a \frac{\rho_a}{\rho_s}$$

Flowmeters: Calibration and Standards

- There is no primary standard for flow rate
- Calibration is generally done by comparison of reading with that of a calibrated instrument (usually high accuracy turbine or positive displacement meter), or by testing against a "catch-and-weigh" setup (for liquids) or *bell prover* (for gases)





Flowmeter Summary

See also Experimental Methods for Engineers, 7th edition, J. P. Holman, McGraw-Hill, 2001, Table 7.2

Type	Pros and Cons (and comments)
Obstruction meters in general	+ Gas or liquid + Very simple to use – Uncertainty 1-2% of full scale reading – 5:1 turndown ratio – Resolution is not the same over full range of flow rates – ΔP proportional to flow rate squared – Approx. 10 straight pipe diameters upstream, 3 downstream
Orifice Plate	+ Inexpensive; easy installation + Extensively documented, no on-site calibration needed + Best obstruction meter for high temperatures (1100°C) and pressures (42 MPa) – Large, unrecoverable pressure loss – Sensitive to upstream disturbances – Sensitive to wear and abrasion so limited use in dirty fluids
Venturi meter	+ Much lower pressure loss than orifice + Abrasion resistant – Higher initial cost (but potential savings in pumps, blowers, etc.) – Requires lots of space for installation
Nozzle	– Similar pressure loss than orifice – Inexpensive; easy installation – Least accurate of the obstruction meters

Flowmeter Summary

Type	Pros and Cons (and comments)
Sonic Nozzles	+ Uncertainties less than 1% + Linear relation between mass flow rate and upstream pressure + Independence from downstream pressure + Widely used, especially as standards – Relatively limited range – Gases only – High pressure drop
Laminar Flow Elements	+ Uncertainty as good as 0.25% + Wide usable range (100:1 turndown ratio) + Mass flow proportional to Δp, not $(\Delta p)^2$ as in obstruction meters + Good sensitivity even at low flowrates + Does not require steady flow conditions + Gas or liquid – Upper limit on usable flow rate to maintain laminar flow – Small tubes susceptible to clogging so limited to clean fluids – Large permanent pressure loss
Electromagnetic	+ Can handle dirty liquids and slurries – calibration not sensitive to exact fluid properties + Up to 100:1 turndown + Uncertainty 0.5 to 1% of full scale – Require conductive liquid
Vortex Shedding	+ Inexpensive + Typical uncertainty 0.5 to 1.5% of flow rate + Gas or liquid + Relatively insensitive to fluid properties (density, viscosity) + Can handle somewhat dirty fluids – Re > 20,000 – Medium/high pressure drop – Difficult in highly viscous liquids (Re too low) – Special installation requirements
Rotameter	+ Uses only the inherent properties of the fluid, along with gravity + Simple device; mass manufactured out of cheap materials + Gas or liquid + Can handle corrosive fluids + Pressure drop fixed for all flow rates – 10:1 turndown – Must always be vertically oriented with fluid flowing upwards. – Graduations will only be accurate for a given fluid. Fluid density and viscosity must be known or controlled. – Normally require the use of glass (or other transparent material) to see the float, limiting use to clear fluids – Not easily adapted for reading by machine – Accuracy ~2-10% of full scale

Flowmeter Summary

Type	Pros and Cons (and comments)
Turbine meters	+ Among most accurate meters - 0.25-0.5% uncertainty for liquids, 0.25%-1.5% for gases + Low/medium cost + Gas or liquid + Transient response pretty good – Less accurate in unsteady flows – Lose accuracy at low flow rates – Periodic maintenance required (bearing wear– recalibration)
Transit Time	+ Noninvasive + No pressure drop + Minimal installation requirements (sometimes none) – Typical accuracy ±1 to 5% of flow rate – Need speed of sound in the liquid (density, temperature) – Measures average velocity across pipe (best for turbulentflow) – Liquid only – Particles and bubbles can attenuate signal – best for clean liquids
Ultrasonic Doppler	+ Noninvasive + Often clamp onto outside of pipe – Usually require some small particulates or bubbles in liquid – Liquid only – Accuracy no better than 2% – Poor spatial resolution – Mean values only – Susceptible to installation errors
Positive Displacement	+ Rugged + Accuracy as good as ±0.2 - 2% + Typical 100:1 turndown, with good accuracy even and lowest flows + Inexpensive + Can handle high pressures + Gas or liquid – Need clean supply to avoid fouling – High pressure loss – Bubbles in liquid will cause errors – Can block lines if jammed – Induce flow pulsations
Thermal Mass	+ Gas or liquid – Requires clean fluids so careful filtering (and subsequent pressure loss) are often needed

Flowmeter Summary

Type	Pros and Cons (and comments)
Coriolis Mass	+ Good accuracy- typical 0.4 to 1.0% uncertainty + Up to 100:1 turndown ratio + Gas or liquid + Not directly sensitive to viscosity, density, or temperature so applicable to sanitary, cryogenic, and corrosive liquids and gases/vapors in pipes smaller than 6-12 inches, including the water, wastewater, mining, mineral processing, power, pulp and paper, petroleum, chemical, and petrochemical industries. + Relative insensitivity to density allows applications where physical properties of the fluid are not well known. + Accuracy is not dependent on piping geometry, and no inlet/outlet flow conditioning is required. + A wide range of meter sizes is available to accommodate flows ranging from fractions of a pound per hour to many tons per minute. + Wetted parts consist of simple metal tubing and have no moving parts in the flow. Measuring slurry and extremely viscous materials such as peanut butter is as easy as measuring water. – Operation at low flow rates can degrade accuracy so run at upper end of flow range. Note that high viscosity fluids increase the pressure drop across the flowmeter. – For liquid flows, make sure that the flowmeter is completely full of liquid. Be especially careful when measuring gas/vapor flow with Coriolis mass flowmeters. – Pay special attention to installation because pipe vibration can cause operational problems. – More limited turndown (and lower accuracy) for gases than liquids. – High pressure drop: best accuracy when meter size must provides adequate velocity through the tubes to allow for measurement of the relatively small Coriolis force. This can cause substantial differential pressures across the meter.

Questions?