

Fluid Flow Measurement

ME240

Fall 2010

What is fluid flow measurement?

- Fluid flow measurement is the technique of measuring the flow velocity (or volume) of a fluid in a contained channel or pipe.
- Some techniques are only suited for certain types of fluids
 - Liquid
 - Gas
 - Characteristics
 - Contamination
 - Chemical properties.

Liquid vs Gas

- Most techniques can be used for either, however some are limited to only one or the other.
- We are going to limit our techniques to those that apply to closed pipes only

Velocity vs Volume vs Mass

- Most flow measurement techniques actually measure velocity of the fluid
- What we really want is volume or mass flow

Laminar Flow

- Occurs at low Reynolds numbers, where viscous forces are dominant, and is characterized by smooth, constant fluid motion
- At low flows in a pipe the flow is laminar, the particles of water flowing in straight lines.
- The particle velocity is greatest in the center and lowest at the walls.

Turbulent flow

- Occurs at high Reynolds numbers and is dominated by inertial forces, producing random eddies, vortices and other flow fluctuations.

Critical Flow

- The velocity at which the flow changes from laminar to turbulent.
- Generally characterized by Reynolds numbers between 2100 and 4000 for pipes.

Reynolds Number

- the Reynolds number is the ratio of inertial forces ($v_s \rho$) to viscous forces (μ/L)

$$Re = \frac{\rho v_s^2 / L}{\mu v_s / L^2} = \frac{\rho v_s L}{\mu} = \frac{v_s L}{\nu} = \frac{\text{Inertial forces}}{\text{Viscous forces}}$$

- * v_s - mean fluid velocity, [m s^{-1}]
- * L - characteristic length, [m^2] *For pipes : diameter*
- * μ - (absolute) dynamic fluid viscosity, [N s m^{-2}] or [Pa s]
- * ν - kinematic fluid viscosity: $\nu = \mu / \rho$, [$\text{m}^2 \text{s}^{-1}$]
- * ρ - fluid density, [kg m^{-3}].

Volume Flow Rate

- Integral of velocity distribution over the cross section of the pipe.

$$Q = \int_A V(x, y) dA$$

Measurement Devices

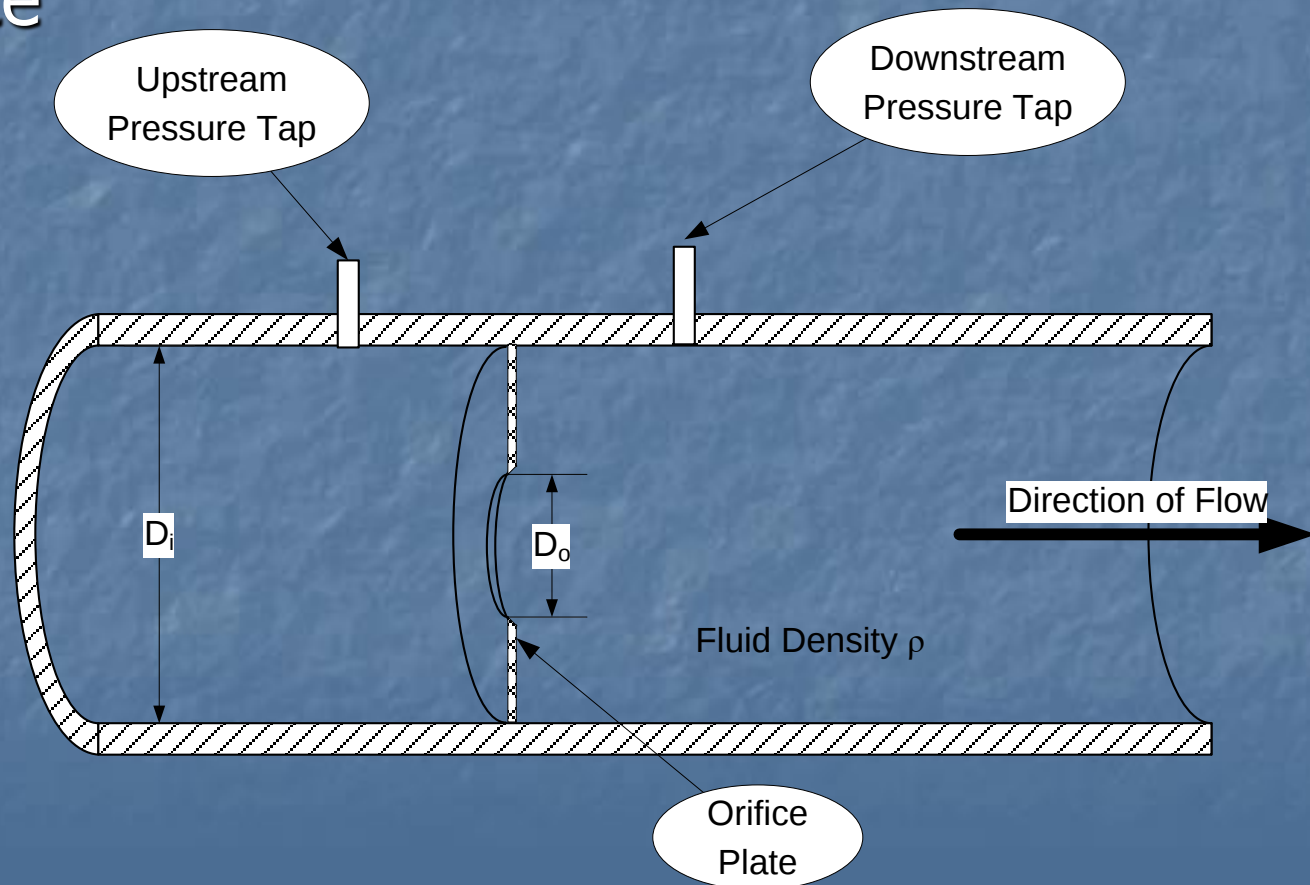
- Flowmeters measure
 - Volume flow rate (Q)
 - Average Velocity (V)
- Velocity probes measure
 - Point Velocity $V(x,y)$
 - Can be integrated to get total volume flow rate (Q)

Orifice Flowmeter

- Most basic obstruction flow meter
- Consists of a plate with a hole, inserted into the pipe
- Measure the pressure drop across the plate to determine the flow.

Obstruction Meters

■ Orifice



Calculation of Flow

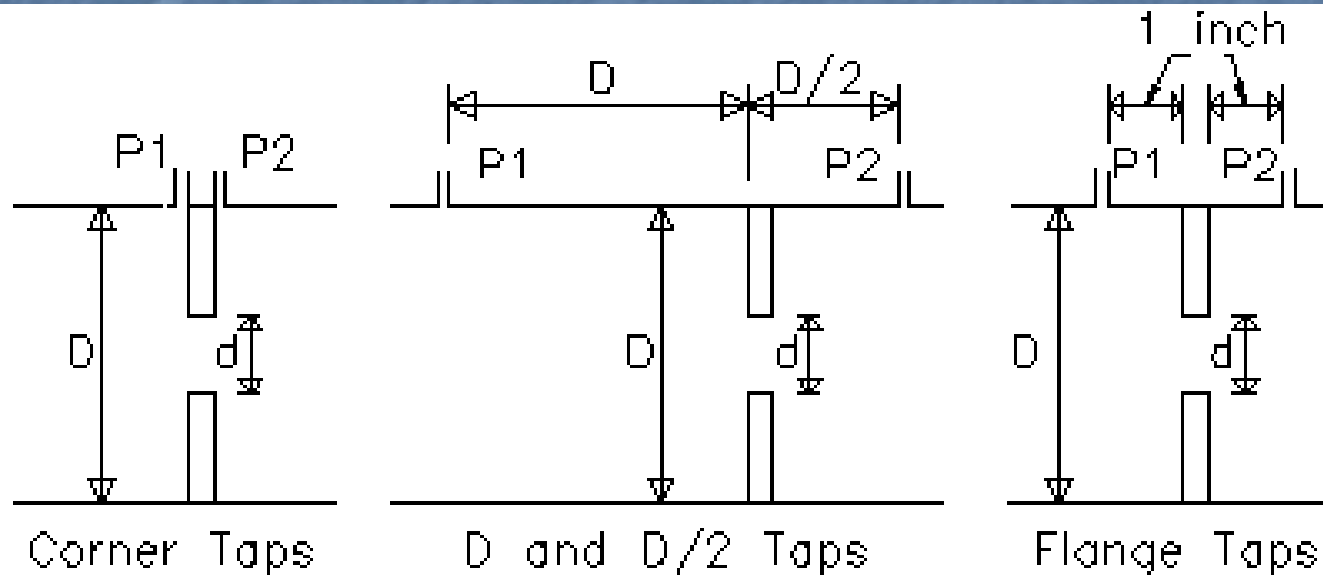
- Q = Flow rate (Volumetric)
- C_f = Discharge coefficient
- A_0 = Area of Orifice
- Δp = Pressure across orifice
- ρ = Density of fluid

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

- Incompressible only

Orifice Flowmeter

- Pressure taps follow three basic forms



—→ Flow Direction for all Orifice types

Orifice discharge coefficient

$$\begin{aligned}
 C = & 0.5961 + 0.0261 \beta^2 - 0.216 \beta^8 + 0.000521 \left(\frac{10^6 \beta}{\text{Re}_D} \right)^{0.7} \\
 & + \left(0.0188 + 0.0063 \left(\frac{19000 \beta}{\text{Re}_D} \right)^{0.8} \right) \left(\frac{10^6}{\text{Re}_D} \right)^{0.3} \beta^{3.5} \\
 & + \left(0.043 + 0.08 e^{-10 L_1} - 0.123 e^{-7 L_1} \right) \left(1 - 0.11 \left(\frac{19000 \beta}{\text{Re}_D} \right)^{0.8} \right) \frac{\beta^4}{1 - \beta^4} \\
 & - 0.031 \left(\frac{2 L_2}{1 - \beta} - 0.8 \left(\frac{2 L_2}{1 - \beta} \right)^{1.1} \right) \beta^{1.3}
 \end{aligned}$$

If $D < 0.07112 \text{ m}$ (2.8 inch), then add the following (where D is in meters):

$$+ 0.011(0.75 - \beta) \left(2.8 - \frac{D}{0.0254} \right)$$

Calculation for compressible fluids

$$Q_m = \frac{e C A_{throat} \sqrt{2 \rho \Delta p}}{\sqrt{1 - \beta^4}} \quad Q_a = \frac{Q_m}{\rho} \quad Q_s = Q_a \frac{P_1 T_{std}}{P_{std} T}$$

$$\rho = \frac{P_1}{R T} \quad e = 1 - (0.41 + 0.35 \beta^4) \frac{\Delta P}{K P_1} \quad \beta = \frac{d}{D}$$

$$Re_D = \frac{V_{pipe} D}{\nu} \quad Re_d = \frac{V_{throat} d}{\nu} \quad \nu = \frac{\mu}{\rho}$$

$$w = \frac{\sqrt{1 - \beta^4} - C \beta^2}{\sqrt{1 - \beta^4} + C \beta^2} \Delta P \quad K_m = \frac{2w}{\rho V_{pipe}^2} \quad V_{pipe} = \frac{Q_a}{A_{pipe}}$$

$$V_{throat} = \frac{Q_a}{A_{throat}} \quad A_{pipe} = \frac{\pi}{4} D^2 \quad A_{throat} = \frac{\pi}{4} d^2$$

Where

A_{pipe} = Pipe Area [L^2], A_{throat} = Throat Area [L^2], C = Discharge Coefficient

d = Throat Diameter [L], D = Pipe Diameter [L], e = Gas Expansibility

k = Equivalent Roughness of Pipe Material [L]

K = Gas Isentropic Exponent, K_m = Minor Loss Coefficient

M = Mass Flowrate [M/T]

P_1 = Upstream Absolute Pressure [F/L^2], P_2 = Downstream Absolute Pressure [F/L^2]

ΔP = Differential Pressure [F/L^2] = $P_1 - P_2$

P_{std} = Standard Absolute Pressure = 14.73 psia = 1.016×10^5 N/m²

Q_a = Actual Volumetric Flowrate [L^3/T]

Q_s = Volumetric Flowrate at Standard Pressure and Temperature [L^3/T]

R = Gas Constant (used to compute gas density) = 8312/ W N-m/kg-K

Re_d = Reynolds Number based on d , Re_D = Reynolds Number based on D

T = Gas Temperature [t] (converted automatically to absolute)

T_{std} = Standard Absolute Temperature = 520 °R = 288.9 K

V_{pipe} = Gas Velocity in Pipe [L/T], V_{throat} = Gas Velocity in Throat [L/T]

w = Static Pressure Loss [F/L^2], W = Molecular Weight of Gas [gram/mole]

β = Ratio d/D , ρ = Gas Density [M/L^3], μ = Gas Dynamic Viscosity [$F-T/L^2$]

ν = Gas Kinematic Viscosity [L^2/T]



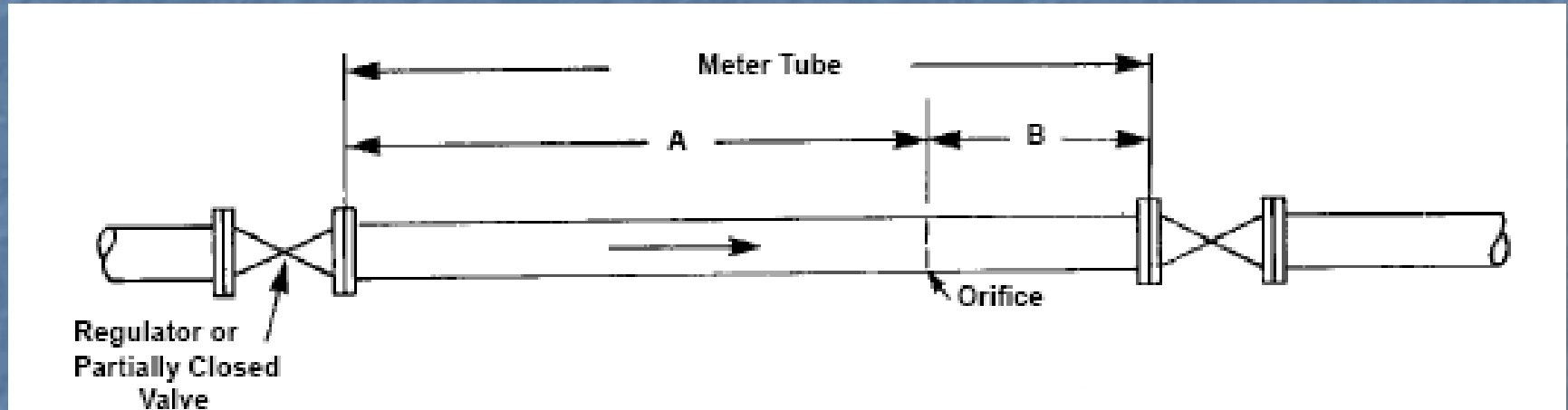
$$C_f$$

- Calculation is difficult
- Better to experimentally determine
- Numbers published for standard sizes and configurations

Characteristics of Orifice Plate

- Simple, no moving parts
- High pressure drop (20 to 40%)
- Can be eroded by liquids with particulates or contaminants
- Reasonably inexpensive
- Accuracy is based on the accuracy of the pressure drop measurement.
- Turndown ratios as high as 15:1

Application downstream of Valve



4" orifice in a 8" pipe

Ratio of Pipe to Orifice diameter is .5

.5 ratio

Apx 25 pipe
diameters

➤ $25 \times 8'' = 200''$

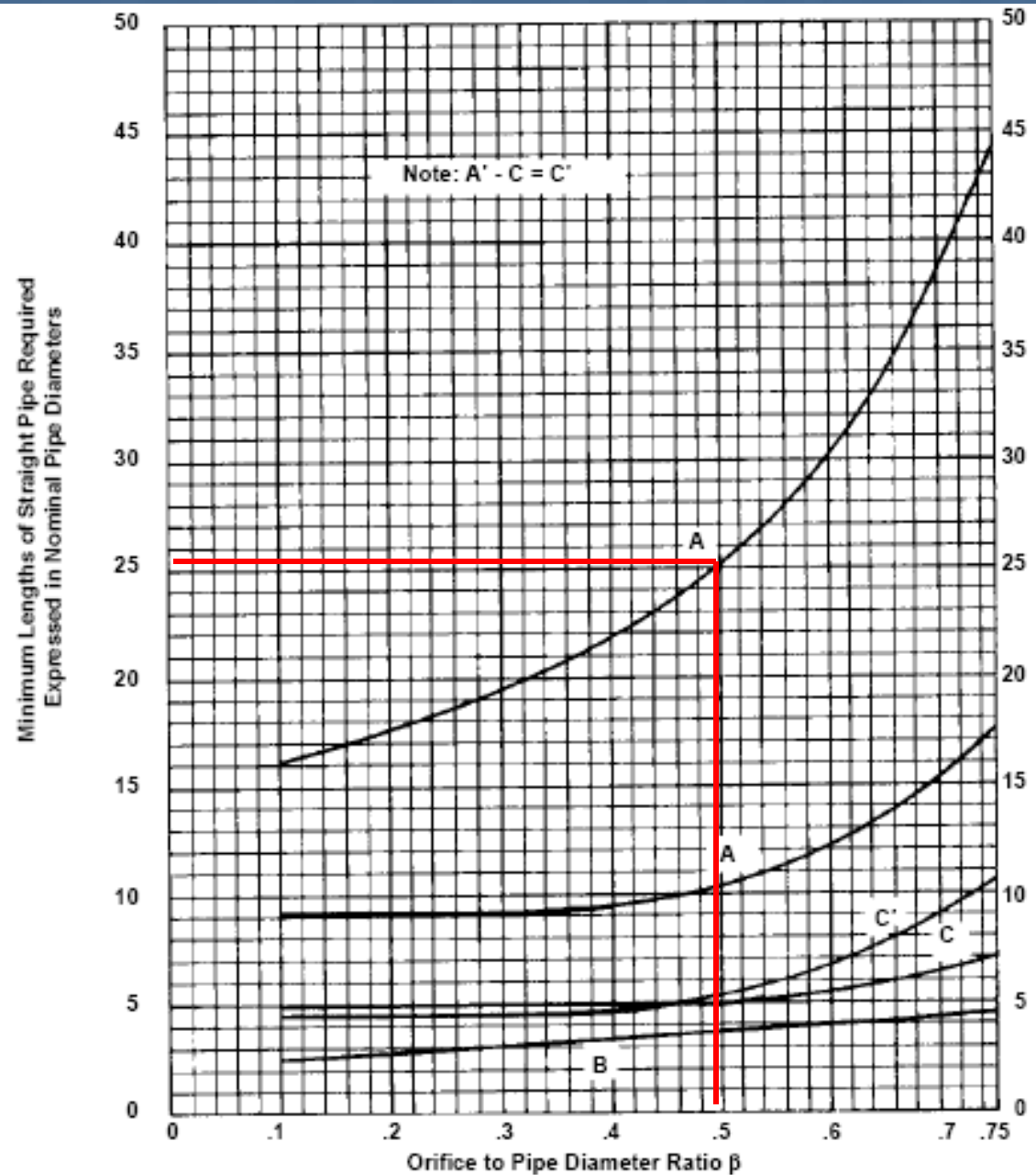
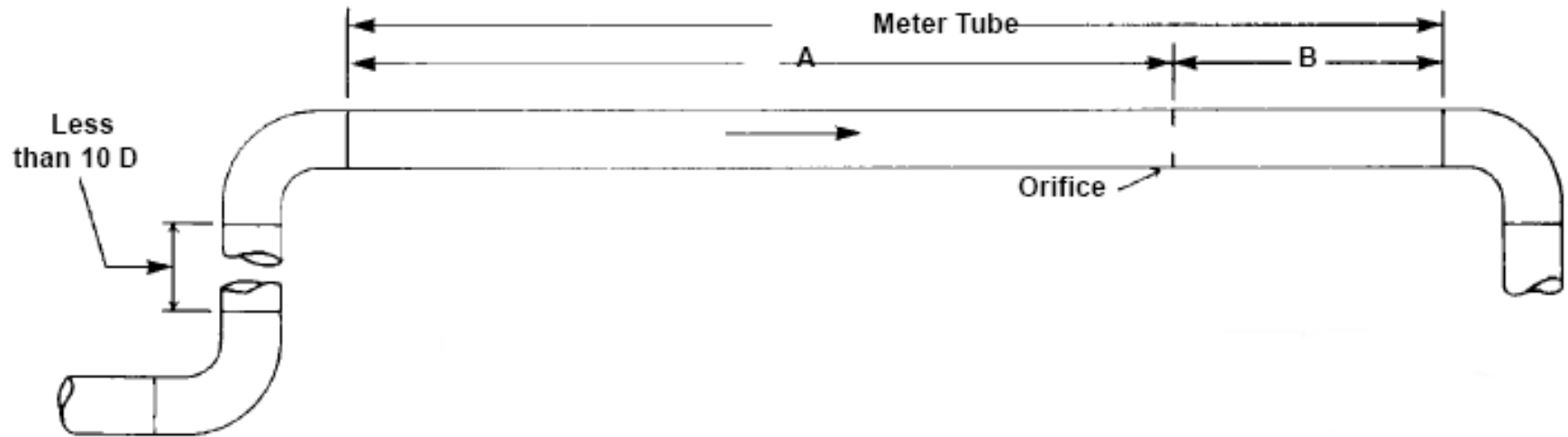
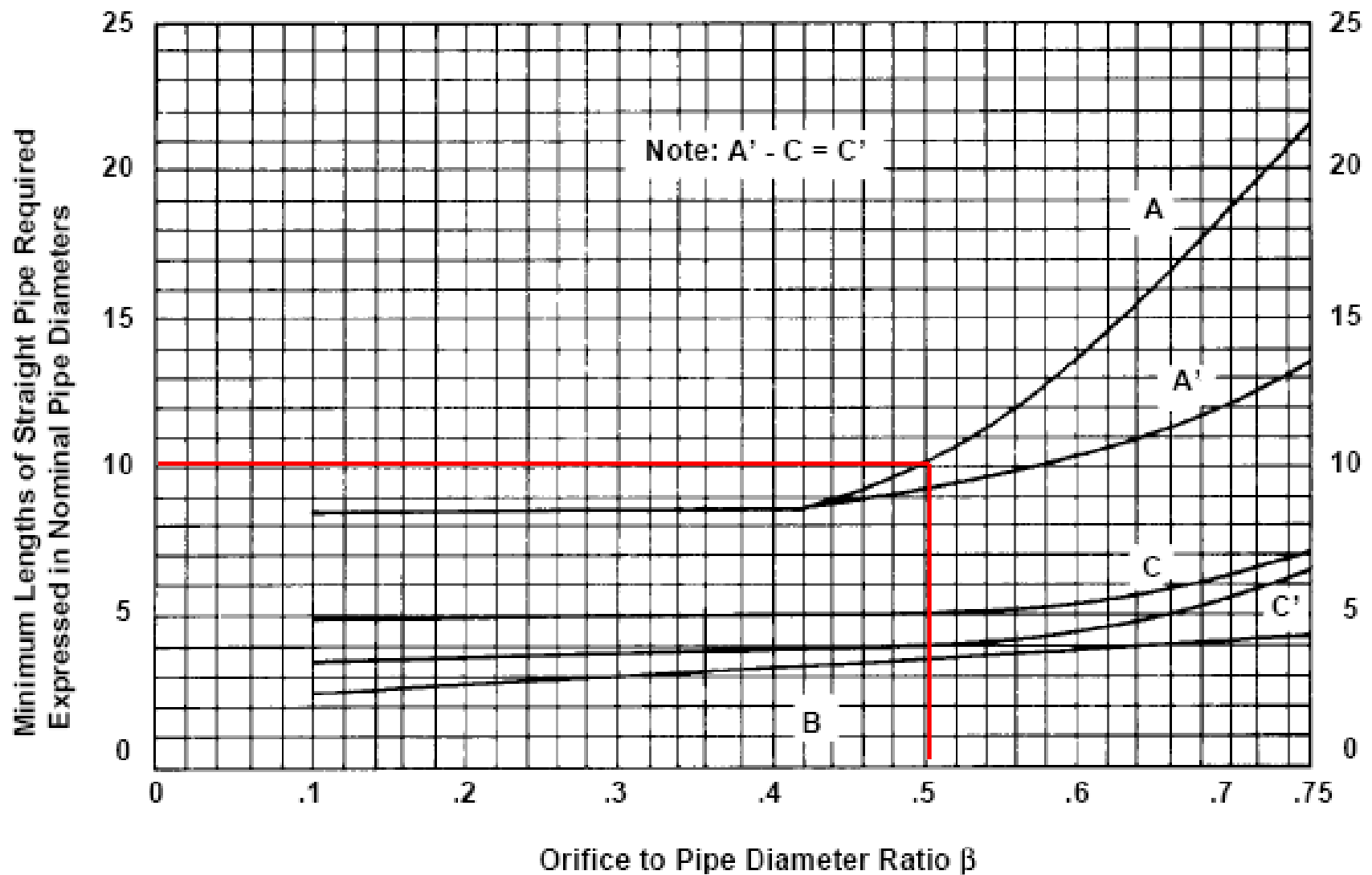


FIGURE 1. Partly Closed Valve Upstream of Meter Tube

Different geometry





- Same diameter ratio now = $10 * 8 = 80''$

The calculation

CALCULATED DATA (Calculation performed at normal conditions. DP in H₂O at 68 °F)

Orifice Bore Size:	4.000	inch	Bore Reynolds Number (Normal):	894278.832	
DP at Min. Flow:	16.379	in H ₂ O at 68 °F	Pipe Reynolds Number (Normal):	448514.484	
DP at Normal Flow:	29.117	in H ₂ O at 68 °F	Gas Expansion Factor:	0.99538888	
DP at Max. Flow:	45.496	in H ₂ O at 68 °F	Permanent Pressure Loss:		
URV (DP at Full Scale):	45.496	in H ₂ O at 68 °F	at Normal Flow:	21.2294996	in H ₂ O at 68 °F
Drain/Vent Corr. Factor:	1		at Max Flow:	33.1710931	in H ₂ O at 68 °F
Beta:	0.50119		Velocity at Max. Flow:	46.6687791	ft/sec
Discharge Coefficient	0.60366		Minimum Accurate Flow:	2111.34891	lb/hr

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

$$\Delta P = 30 \text{ in Hg}$$

$$\rho = 64.5 \text{ lbm/ft}^3$$

$$A_0 = .5233 \text{ ft}^2$$

$$C_f = 0.60366$$

$$Q = 2.46 \text{ FT}^3/\text{s}$$

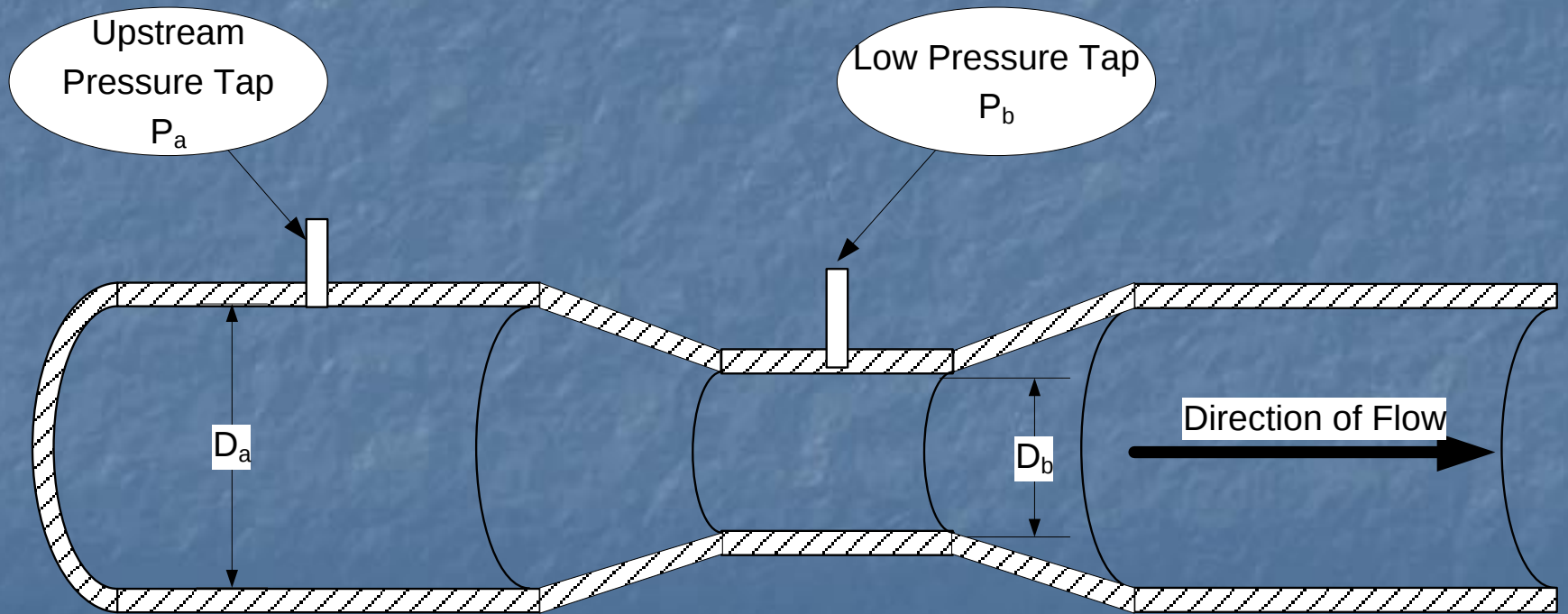
$$1104 \text{ GPM}$$

$$V_{\text{pipe}} = 7 \text{ ft/s}$$

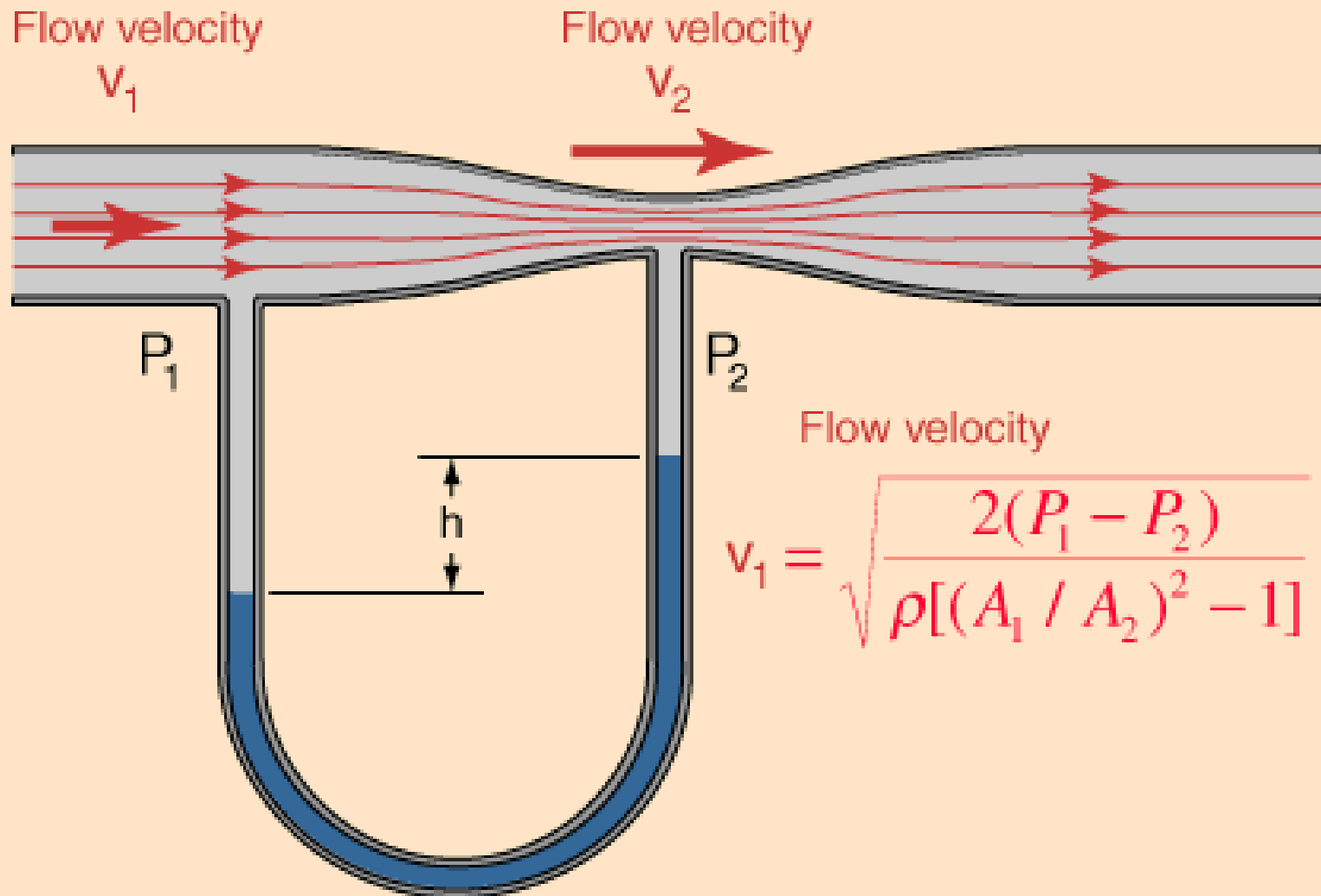
$$V_{\text{orifice}} = 14 \text{ ft/s}$$

$$\text{ReD} = 462000$$

Venturi Meters



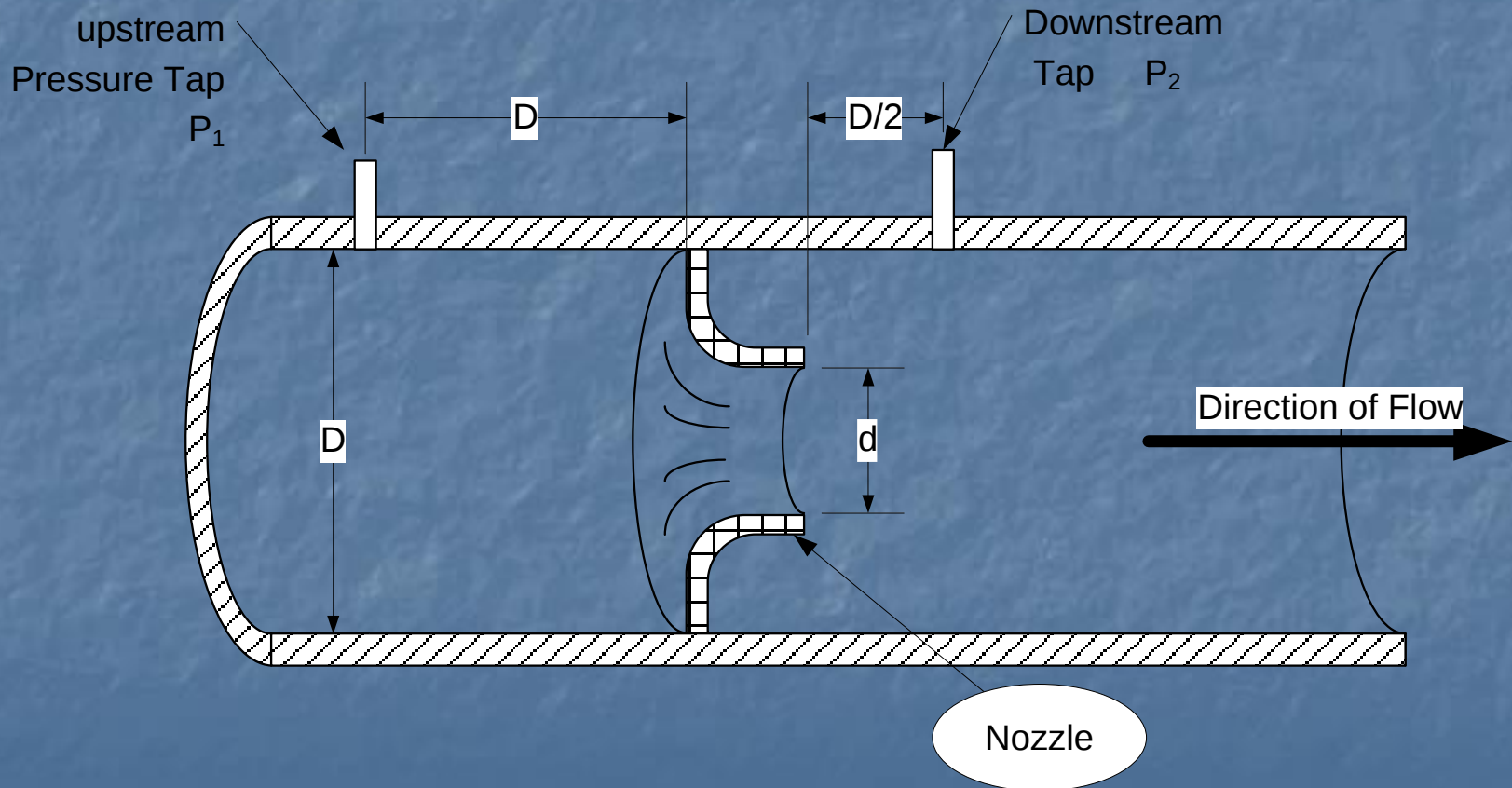
Venturi Flowmeter



Venturi Characteristics

- Lower Pressure drop than orifice plate
- Lower pressure differential
- Useable In large flow systems (waste treatment plants)
- More easily tolerate “dirty” fluids
- Generally an 8:1 turndown is max useable range

Nozzle Meters



Nozzle



Nozzle Characteristics

- A cross between a venturi and orifice.
- Only about 40% of pressure drop of orifice
- Can have extremely high turndown (60:1)

Laminar flow element

- Low obstruction meter
- Most commonly used with gasses
- Element with many small passages to create laminar flow
- 20:1 turndown
- Accuracy within 1/2%
- .00019 to 2500 SCFM

Flow rate calculation

$$Q = \frac{(P_1 - P_2)\pi r^4}{8\eta L}$$

Where:

Q = Volumetric Flow Rate

P_1 = Static pressure at the inlet

P_2 = Static pressure at the outlet

r = Hydraulic Radius of the restriction

η = (eta) absolute viscosity of the fluid

L = Length of the restriction

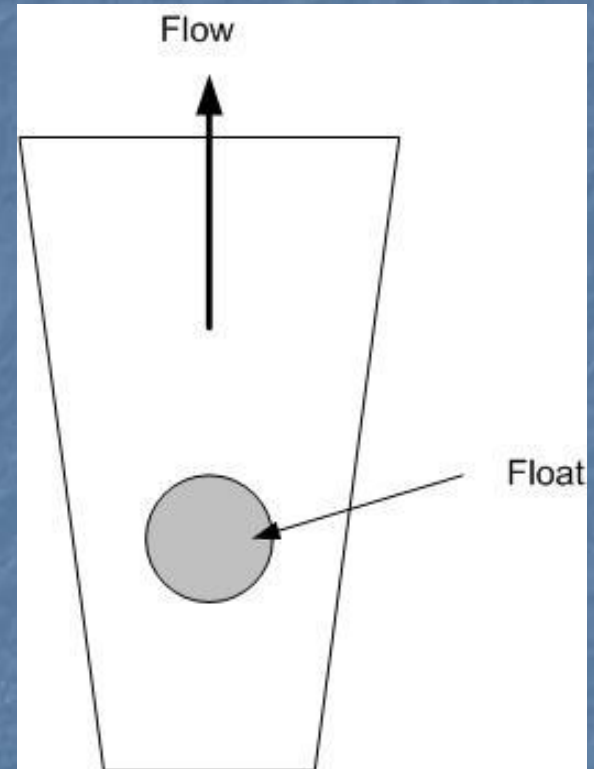
Variable Area

- There are two primary styles
 - Rotameter
 - Spring balanced float (Piston type)

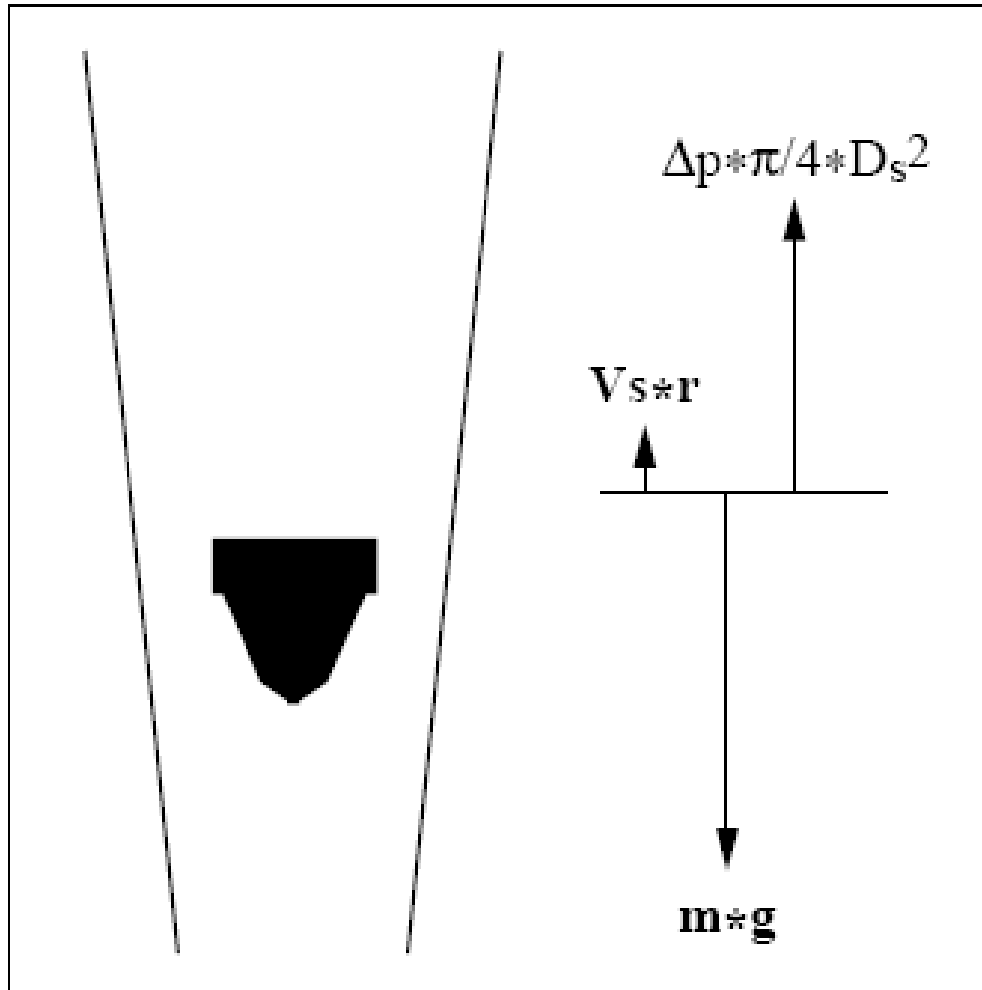


Rotameter

- Tapered tube with a float
- Mounted vertical
- Gravity pulls the float down
- Flow pushes the float up
- Area for water to flow around the float changes with height.



Rotameter flow



Force Equation

$$\Delta p * \pi / 4 * D_s^2 = m * g - V_s * r$$

Δp = pressure loss at the float

D_s = diameter of the float

m = mass of the float

g = acceleration in the earth field

V_s = Volume of the float

ρ = Density of the fluid

qv = Volume flow

p_s = Density of the float

Flow Equation

$$qv = D_s / p * \sqrt{m * g * (1 - p / p_s)}$$

Rotameter characteristics

- Differential pressure across the meter is always nearly constant
- Poor for opaque or “dirty” fluids
- Not good for high temperatures
- Limited in size to <200GPM (250 SCFM Air)
- VERY good at small flows
 - .025GPM
 - 5 ml/min air
- Turndown ratio roughly 10:1
- MUST be vertical
- Can be used with either liquids or gasses (Mass of the float differs)

Rotameter characteristics

- Density correction required
- Can be fitted with magnets on the float for use as switching elements
- Reading accuracy varies greatly with the temperature of the fluid
- Good for visual indications only, can't really feed them to a computer

Spring float type

- Special case of Rotameter with float working against a spring instead of gravity.
- Can be placed in any direction
- Not as accurate as a rotameter.
- Easily gummed up



Paddlewheel and Turbine

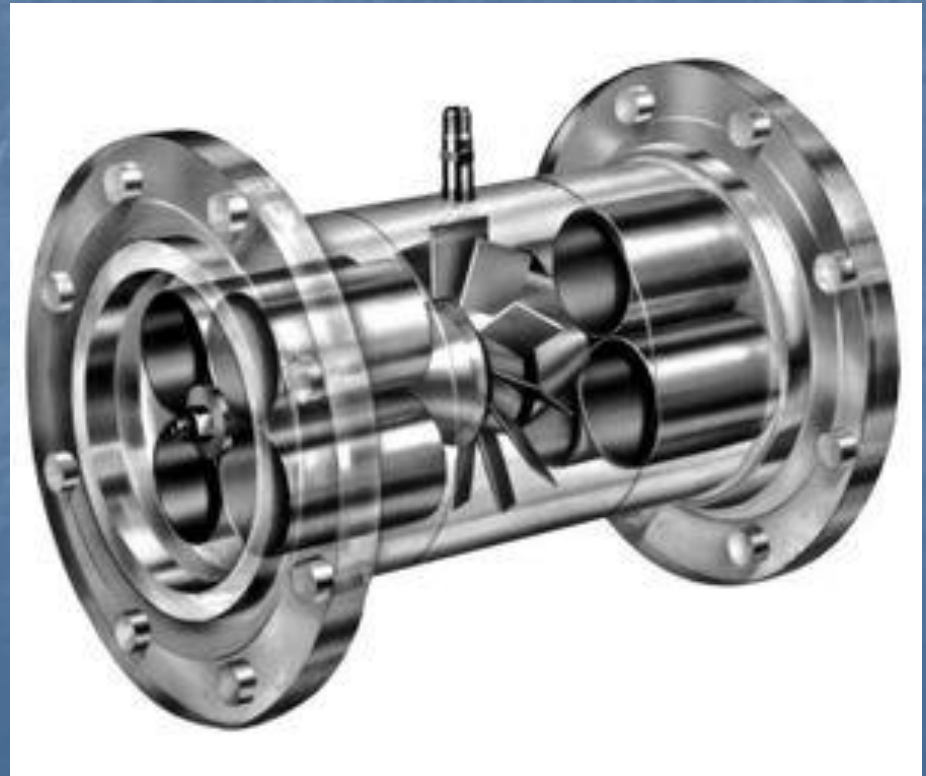
- This class of meters are constructed of a rotating element, turned by the moving fluid. Velocity of the fluid is based on the frequency of the vanes passing the pickup.

Turbine

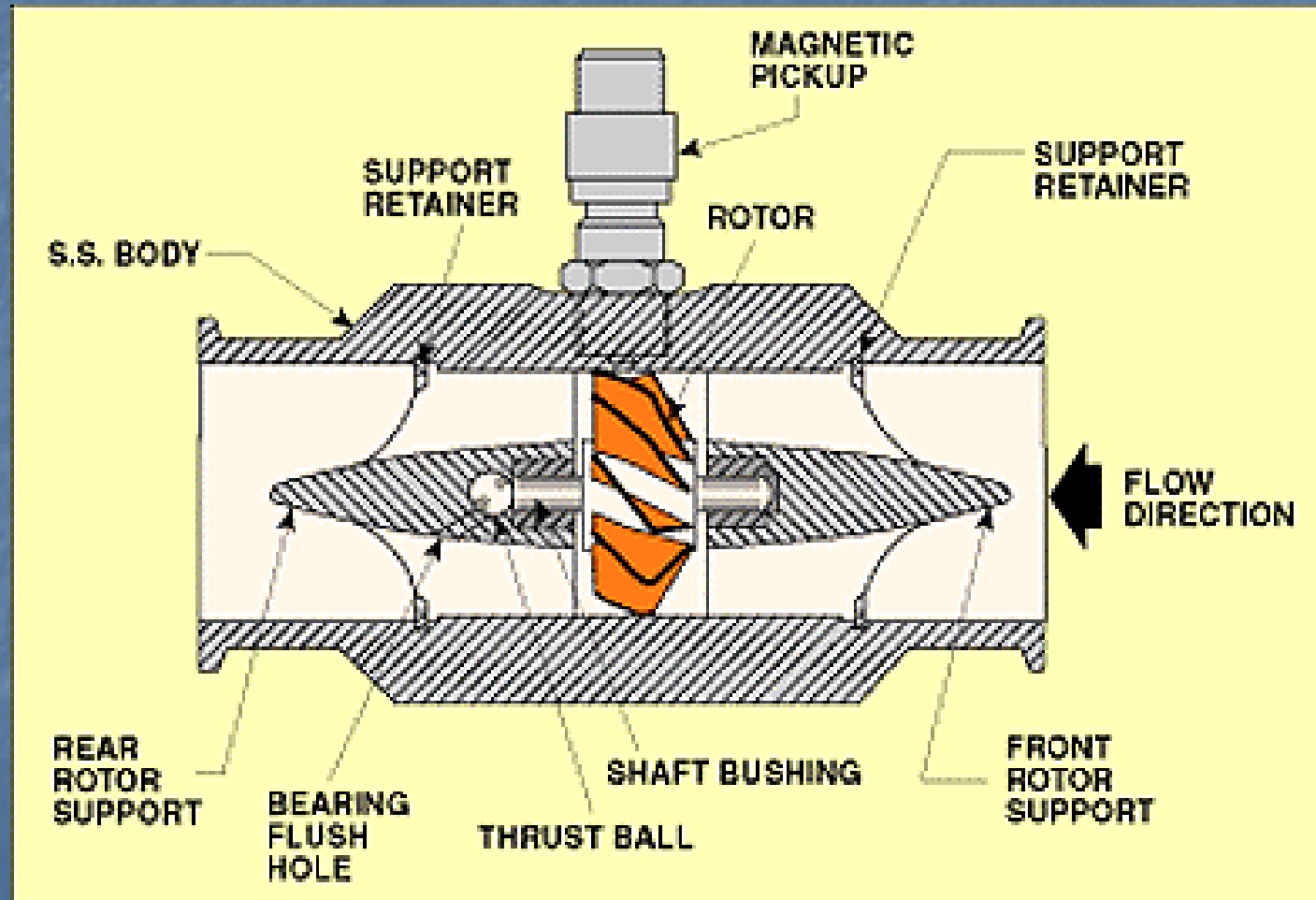


Turbine characteristics

- Typically inserted in the full stream
 - The full flow runs through the housing and over the turbine
- Turbine element suspended on central shaft.
- VERY high quality bearings



Turbine Flowmeter cross section

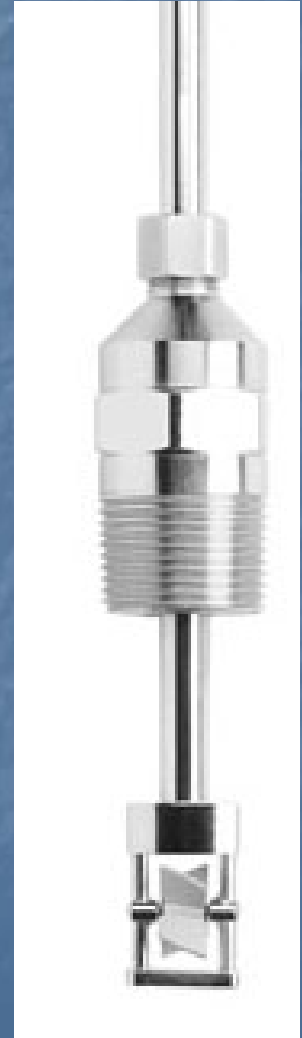


Turbine characteristics

- Highly accurate
- Turndown typically 100:1 in clean fluids
- Work equally well in gases and liquids
- Good for wide range of flows
 - .03 to 50,000 GPM
 - .09 to 15,000 CFM
- Can be made to operate in extremely high pressures (up to 60,000 PSI)

Insertion Turbine characteristics

- There are partial insertion types

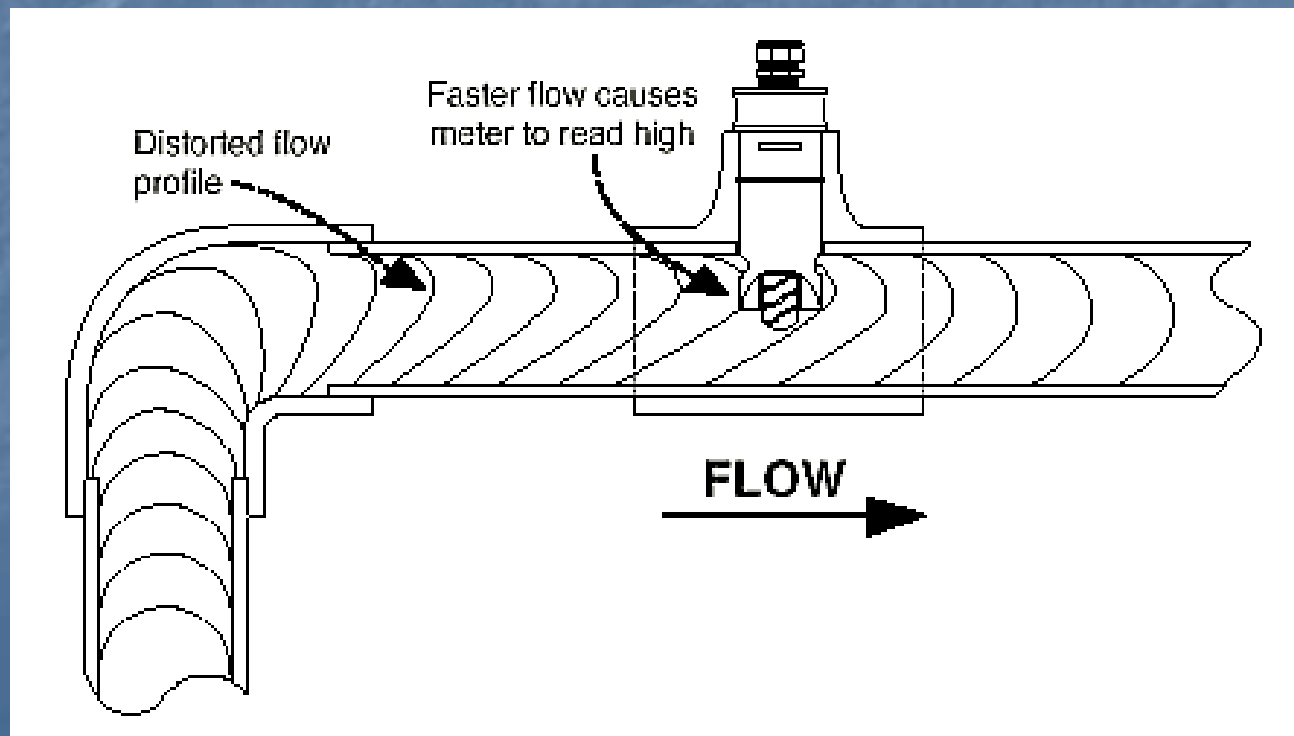


Insertion Turbine characteristics

- less accurate than full flow models
 - Typically $\pm 1\%$
- Flow Range: 0.2 - 30 ft/sec
- Note that these are **VELOCITY** transducers, **NOT VOLUME!!!**
- Turndown ratios typically 35:1

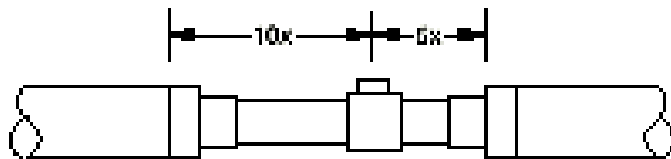
Insertion Turbine characteristics

- Measure velocity only at one point, so insertion point is critical

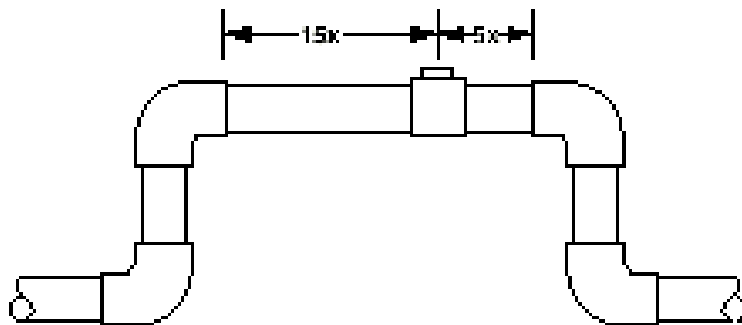


Insertion Turbine placement

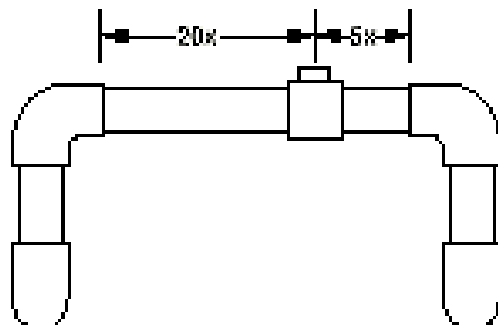
Reduced Pipe



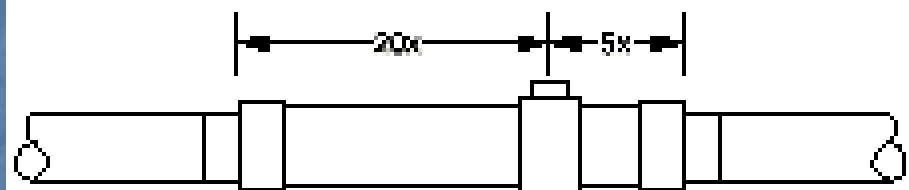
Two Elbows, in plane



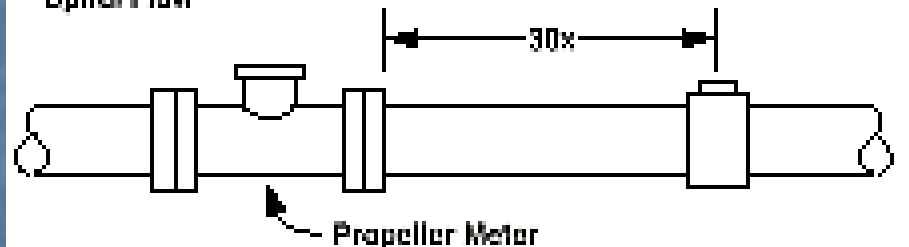
Two Elbows, out of plane



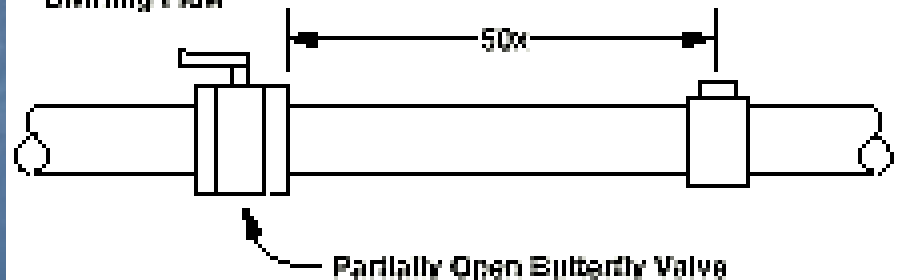
Expanded Pipe



Spiral Flow

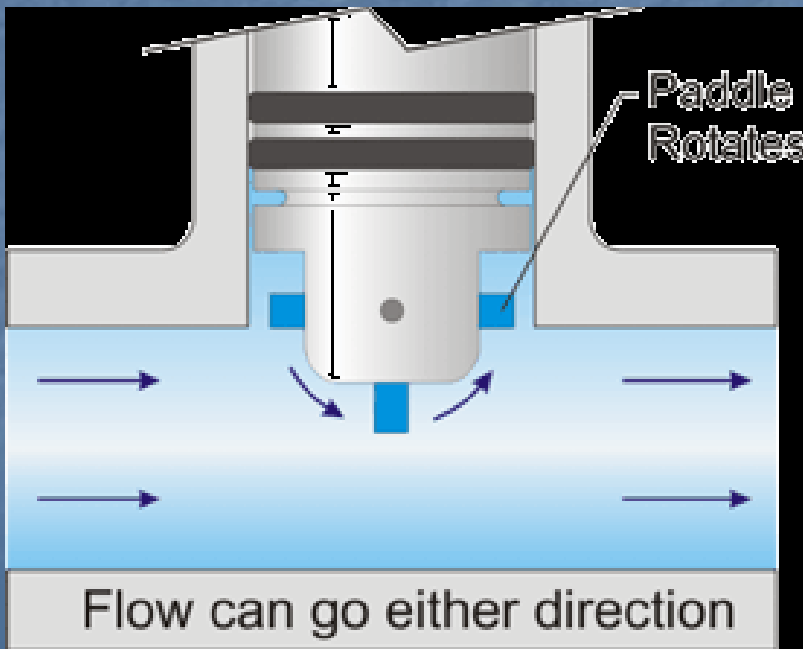


Swirling Flow



Paddle Wheel Flowmeter

- Similar to an insertion turbine meter except uses perpendicular paddle



Paddlewheel characteristics

- Velocity transducer
- Usually made of plastic
- Easy to install
- Typically around 1% accuracy or higher
- Work well with high viscosity fluids
- Not appropriate for low velocity air flows

Paddlewheel characteristics

- Need fully developed laminar flow to be accurate
 - Reynolds numbers lower than 4000 over entire flow range
- Accuracy suffers greatly below 1 f/s (some will work as low as .3 f/s)
- Typically inserted in pipes 1/2" to 8" dia.
- Turndown typically 20:1 but can be as high as 60:1 on high end units

Paddlewheel characteristics

- Shaft is exposed to fluid, so maintenance can be a problem in caustic or dirty fluids
- Since it is an insertion type, the meter can't be bypassed for maintenance.
- Installation similar to insertion turbine meter

Positive Displacement

- Insert into the flow so full flow passes through meter.
- Measures positive volume
- Piston
- Sliding Vane
- Multi rotor
- Nutating disk

Piston meter configurations

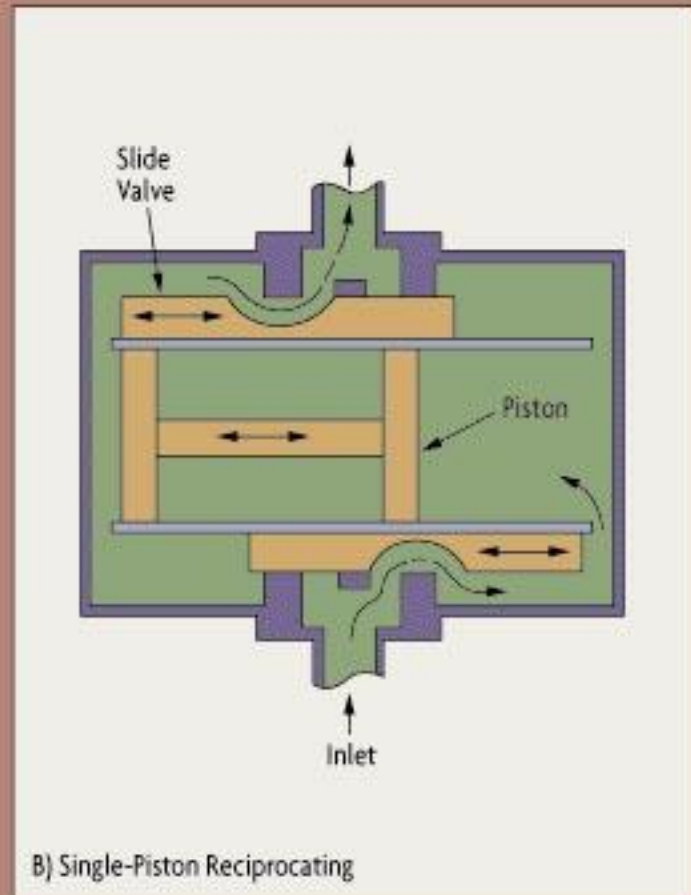
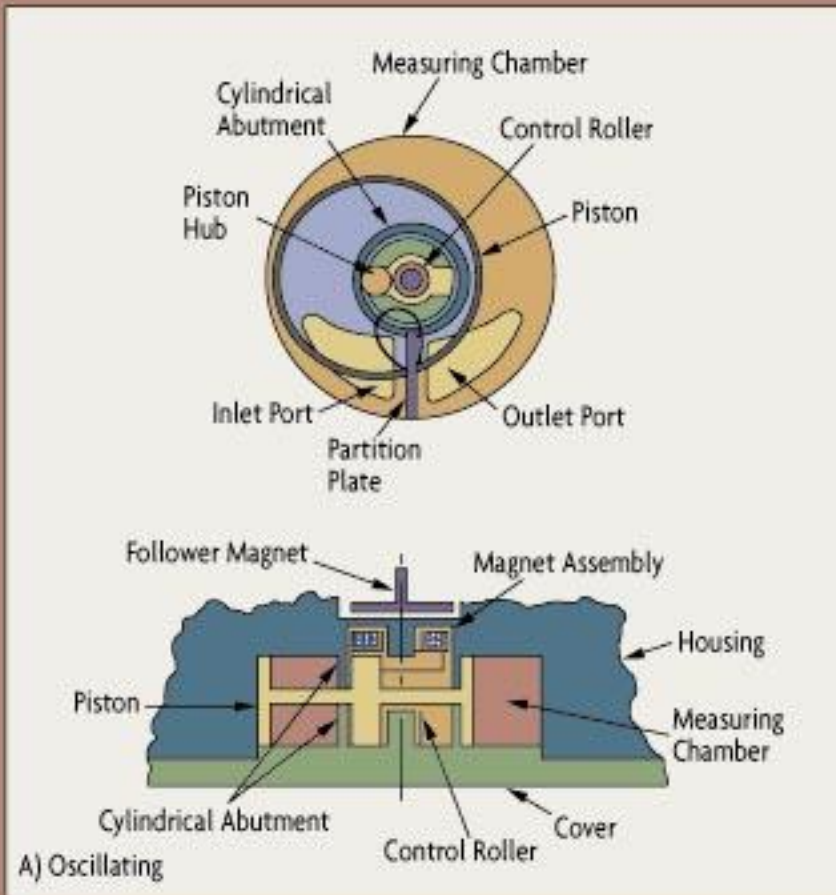
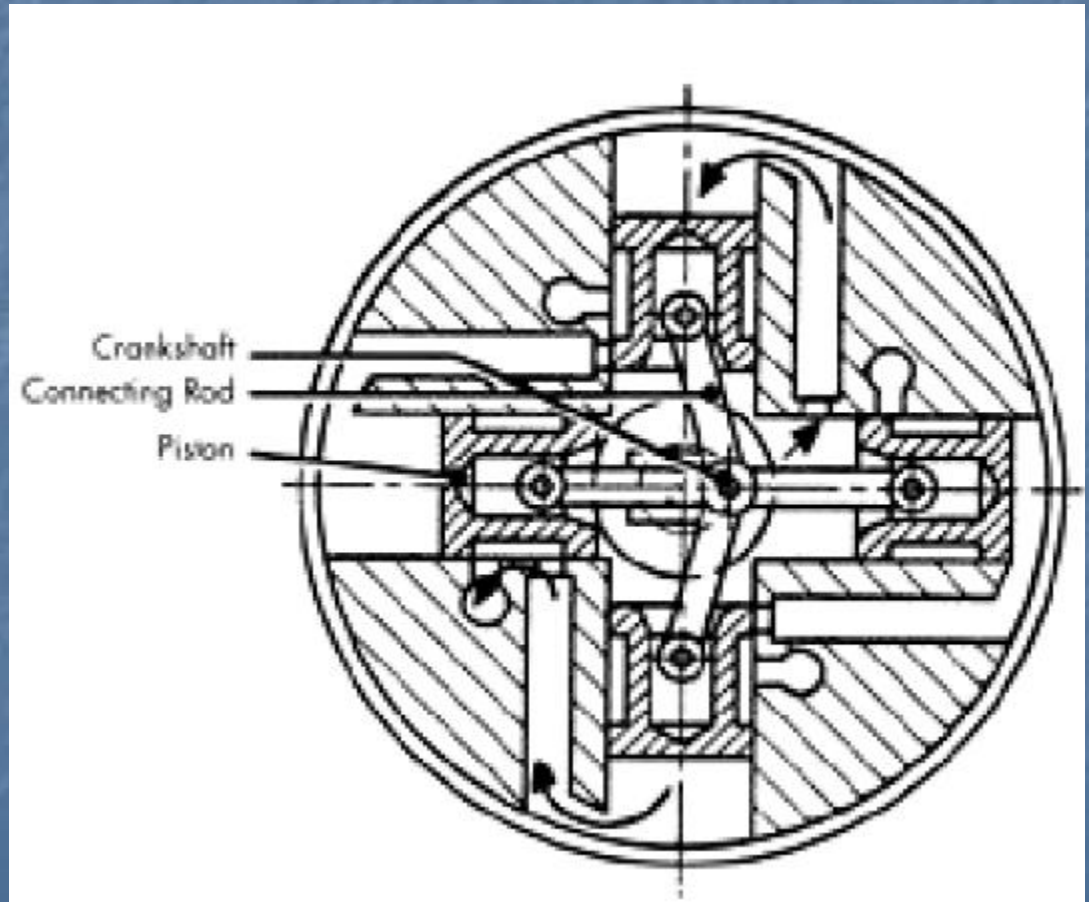


Figure 3-2: Piston Meter Designs

Piston meter configurations

- Good for extremely low flows
- As low as 1 liter per hour

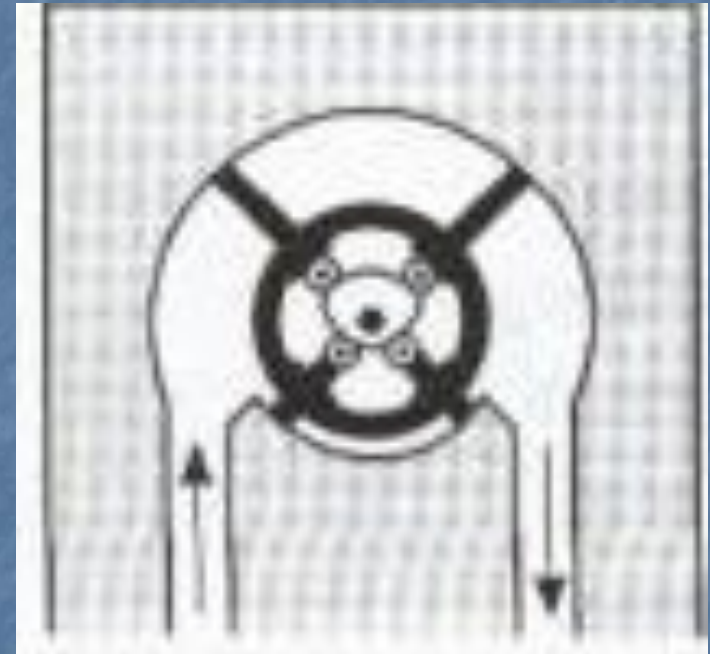


Piston meter characteristics

- Can provide rate and total volume (mass)
- Generally designed for low flows
 - 0.006 to 400 GPM
- Fluid Viscosity $\leq 4,000$ centipoise
- 1000:1 Turndown for high viscosity fluids
- Functional for gasses as well as liquids
- High accuracy (as good as 0.1%)

Sliding Vane Flowmeter

- Cavity and off center "core"
- As core rotates, vanes slide in and out to maintain contact with sides of cavity.



Sliding vane flowmeter characteristics

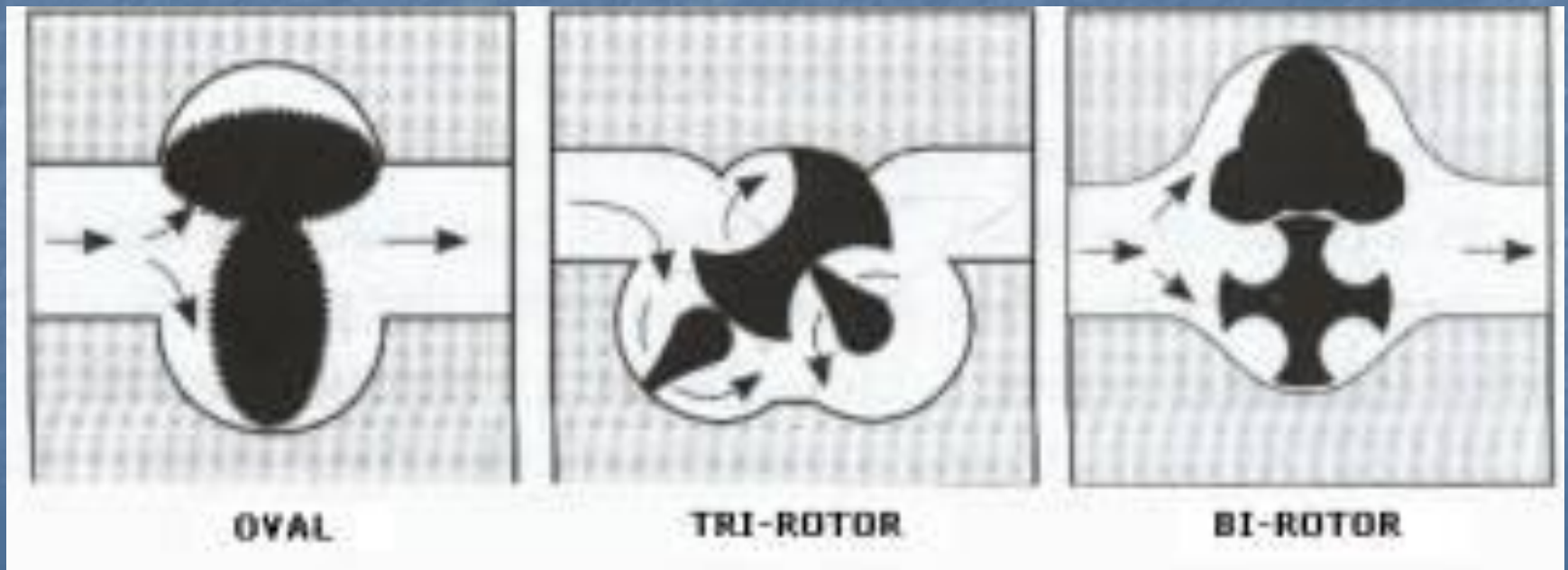
- Flows up to 3500 GPM as low as .25 GPM
- 20:1 turndown typical
- Best with liquids
 - Can work with gasses, but less turndown and lower accuracy
- Fairly high friction
- Always some leakage around vane seals

Sliding vane flowmeter characteristics

- Limited in temperatures to around 200°C
 - As low as -20°C
- Operating pressures up to 1000 PSI
- Accuracy as good as .3%

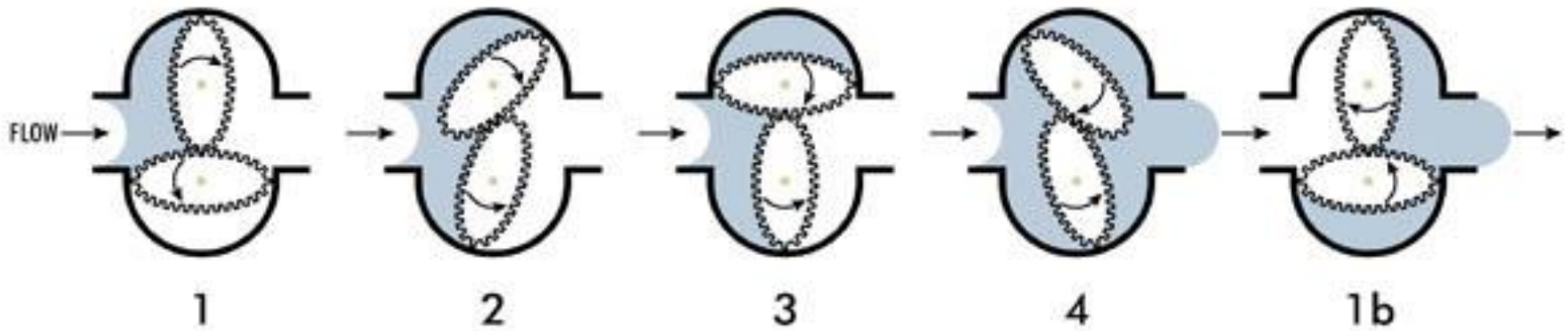
Multi Rotor meter

- Similar to rotary pumps, but in reverse



Oval gear flowmeter

POSITIVE DISPLACEMENT

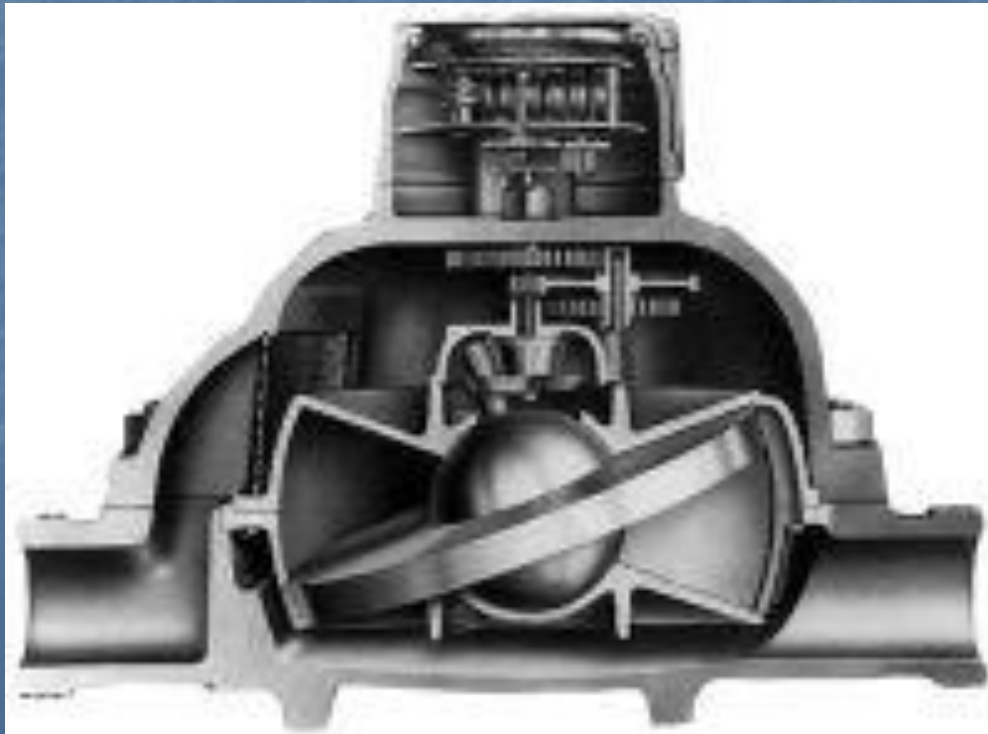


Multi rotor flowmeter characteristics

- Measure positive volume flow of liquids
 - Water, Hydrocarbon liquids, cryogenics
- Not suited for abrasive or dirty fluids
- Flow rates 10 to 17,000 GPM
- Up to 400°F, 3000 PSI
- Viscosity 1 to 25,000 centipoise.
- 50:1 turndown ratio

Nutating disk

- “Original” water meters
- Wobbling disk and cavity



Nutating Disk Meter

- Position of the disk divides the chamber into compartments containing an exact volume.
- Liquid pressure drives the disc to wobble and a roller cam causes the nutating disc to make a complete cycle.

Disk meter characteristics

- Due to its design the unit is very rugged and tolerant of foreign products.
- 1/2" to 4" pipe sizes
- 0.2 gpm to 400 gpm
- pressure ratings of up to 1400 psig
- operating temperatures up to 400° F (204° C)
- Don't care how developed the flow is, so they can be placed in virtually any location.

Disk flowmeter characteristics

- Continuous flow rate 60-80% of the maximum flow
- If the process fluid viscosity is greater than 10 centipoise and the flowrate is above 20% of rated capacity, accuracy of 0.1% AR can be obtained.

Fluidic Flowmeters

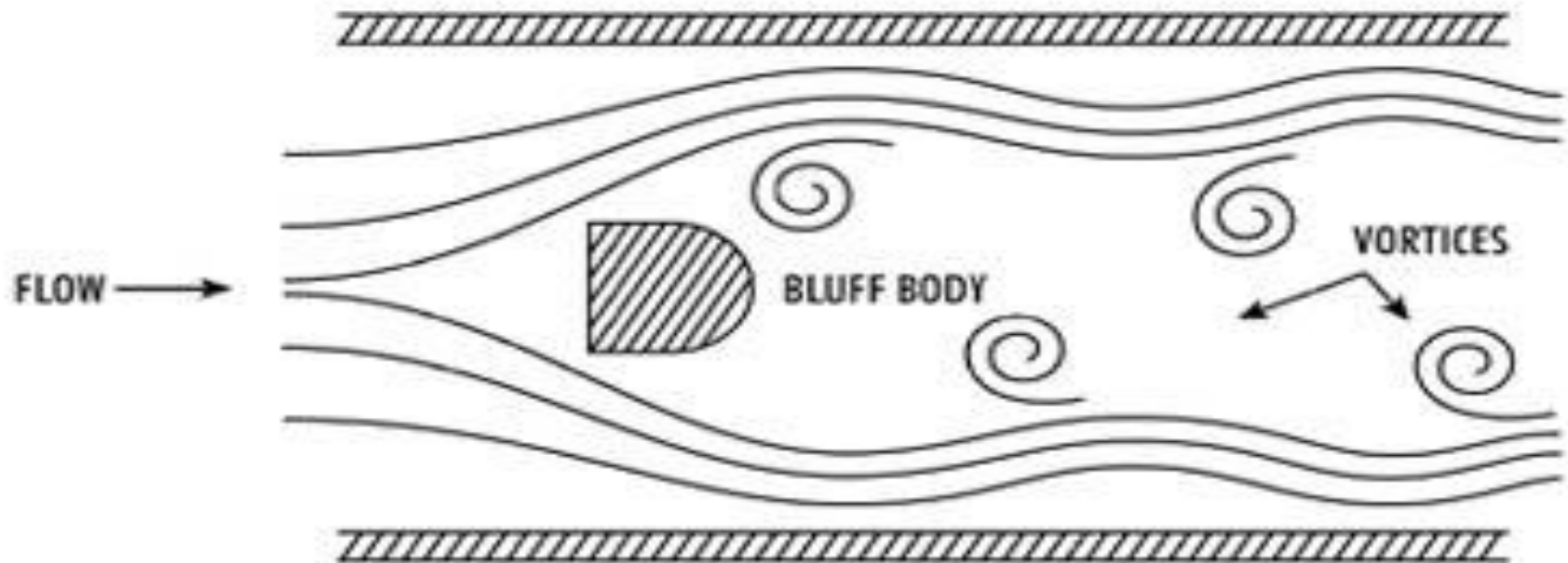
- Fluidic flowmeters are flowmeters that generate oscillations as a result of flow
- Vortex Shedding
- Coanda Effect
- Vortex Precession

Vortex Shedding

Vortex shedding flowmeters alternately generate vortices on both sides of a bluff body located in the flow stream. The number of vortices formed can be related to the flow rate.

Vortex Shedding

VORTEX SHEDDING



Vortex Shedding Characteristics

- The frequency of vortex shedding is the same as the vibrating frequency of the of the obstruction
- The vortex trail is call the von Karman vortex street or Karman street after von Karman's 1912 mathematical description of the phenomenon.

Vortex Shedding Characteristics

- Suitable for
 - Gasses
 - Clean or dirty
 - Liquids
 - Clean only
 - Steam
 - Saturated and superheated

Vortex Shedding Characteristics

- 1/2" to 48" pipe models
 - Insertion and inline models
- 10:1 turndown
- Reynolds numbers $10^2 \sim 10^7$
- Output 4-20 mA or digital pulse

Coanda Effect

Coanda Effect flowmeters channel the flow stream in the flowmeter so as to utilize the phenomenon that causes a fluid to attach itself to a surface. Feedback passages are used to alternately attach the fluid to each surface. Oscillating flows through the feedback passages can be related to the flow rate.

Coanda Effect

- A variety of electronic and mechanical techniques can be used to sense the feedback flow oscillations.
- The frequency of feedback flow changes is used to generate a flow measurement signal.
- Linear with respect to volumetric flow rate

Coanda Effect meter

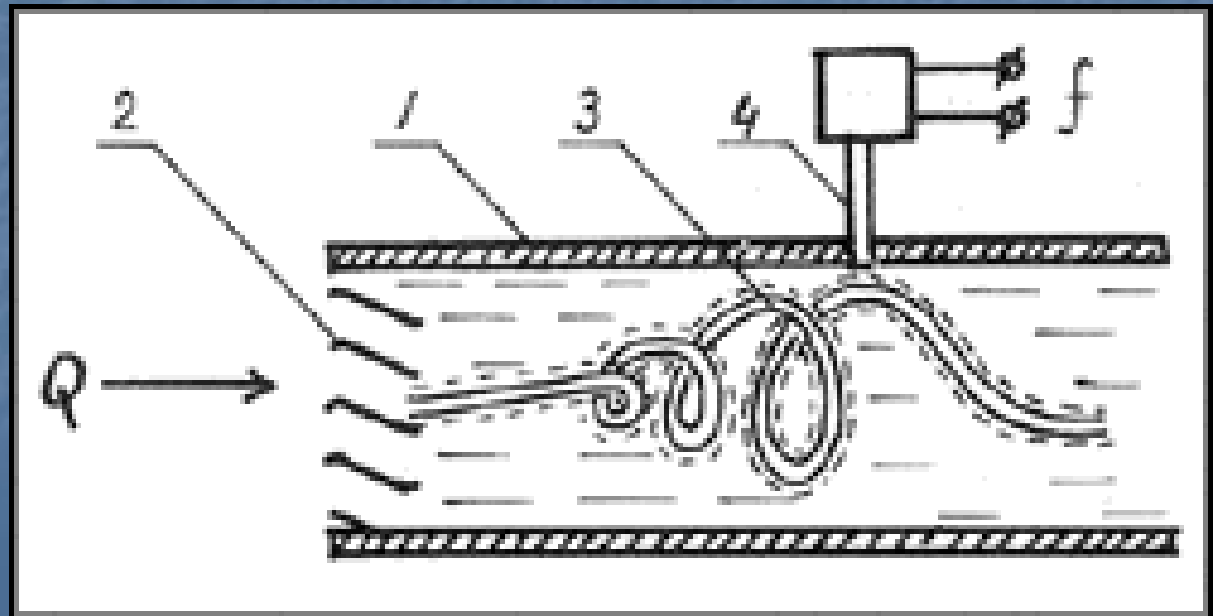
- Reynolds Numbers: 3000 to 1,000,000
- Accuracy 1%
- Turndown ratio 15:1

Vortex precession

Vortex precession flowmeters use inlet vanes to rotate the fluid to form a vortex center (similar to a cyclone) that rotates around the inside of the pipe. The velocity of rotation of the vortex can be related to the flow rate.

Vortex (Swirl) precession

- A variety of transduction elements are used to detect such fluid oscillation (piezoceramic disk, hot-wire anemometer, etc.).



Vortex (Swirl) precession

- Good for liquids, gasses and steams
- High turndown 25:1
- Accuracy as good as $\frac{1}{2}\%$
- Output : 4-20 ma
- Operation from -55 to 280°C

Velocity meters

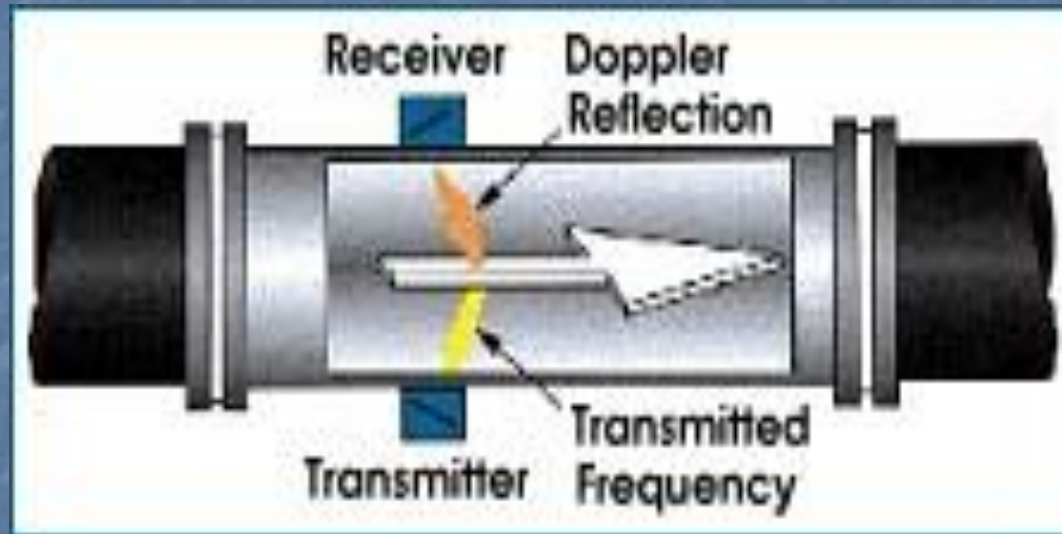
Averages over the
flow profile

- Ultrasonic
 - Doppler
 - Transit time
- Magnetic

Point Velocity only

- Pitot tube
- Hot wire / film

Ultrasonic Flowmeter



Doppler ultrasonic flowmeters operate on the Doppler effect, whereby the transmitted frequency is altered linearly by being reflected from particles and bubbles in the fluid.

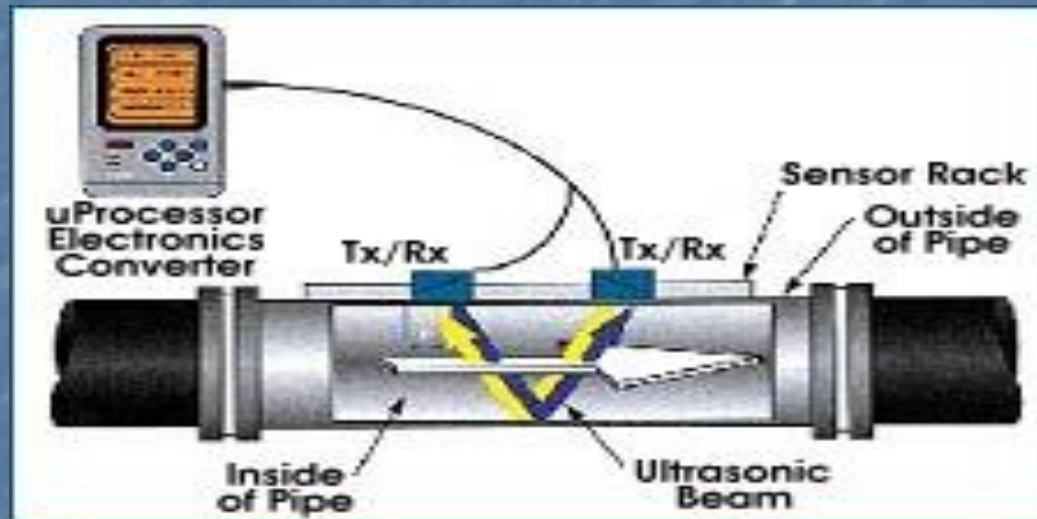
Ultrasonic flowmeter characteristics

- Function with medium and low viscosity liquids that contain sonically reflective materials such as solid particles or entrained air bubbles.
- 100:1 turndown is typical
- Accuracy to 1%

Ultrasonic flowmeter characteristics

- Pipe sizes from 0.25" to 120"
- 0.15 to 30 fps velocity ranges
- Pressure and temperature limited to pipe limits.
- Works best on metallic pipes, but can be used on plastic

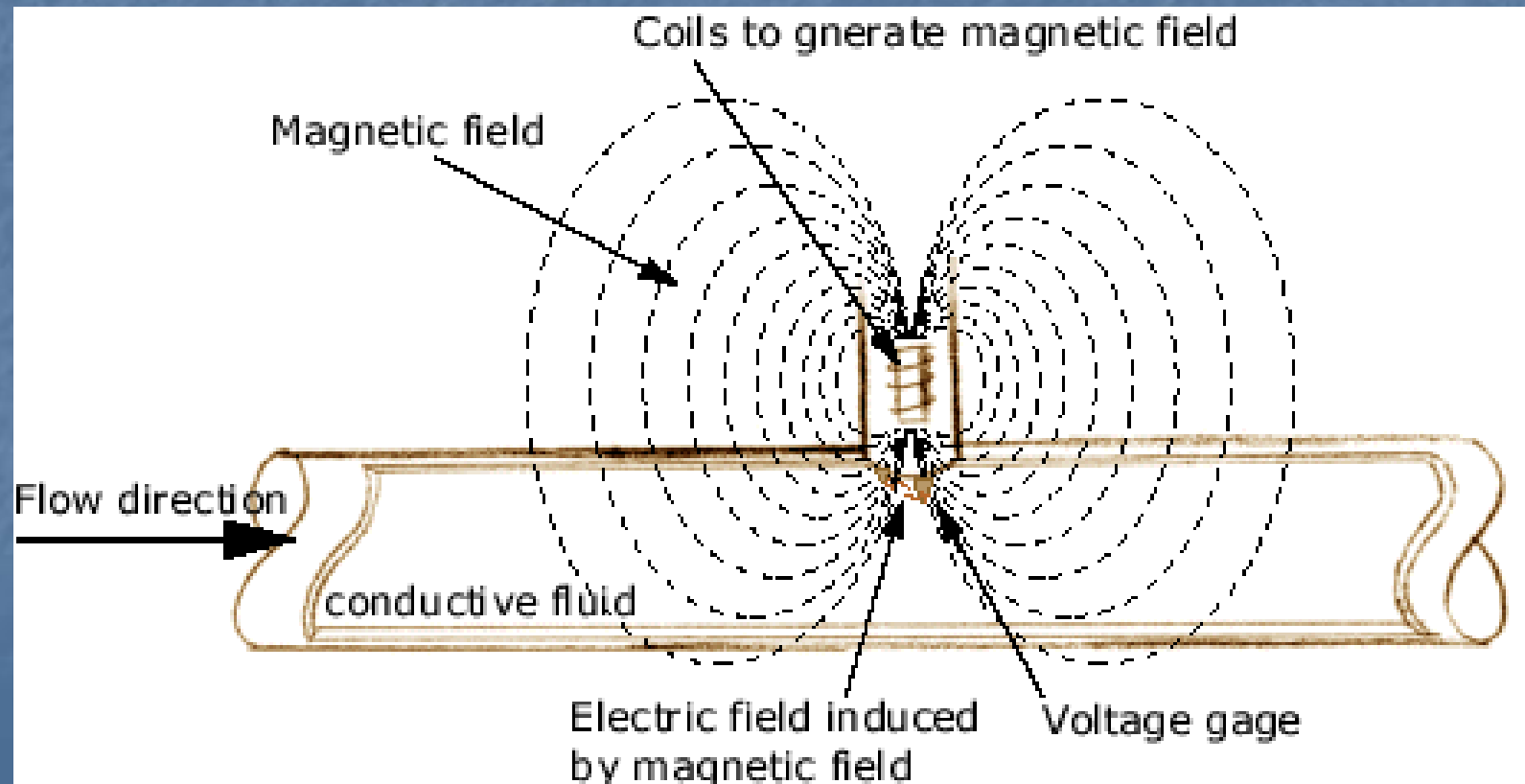
Transit time Ultrasonic



Transit-time meters measure the difference in travel time between pulses transmitted in the direction of, and against, the flow.

Magnetic flowmeter

- Based on Faraday's law



Magnetic flowmeter characteristics

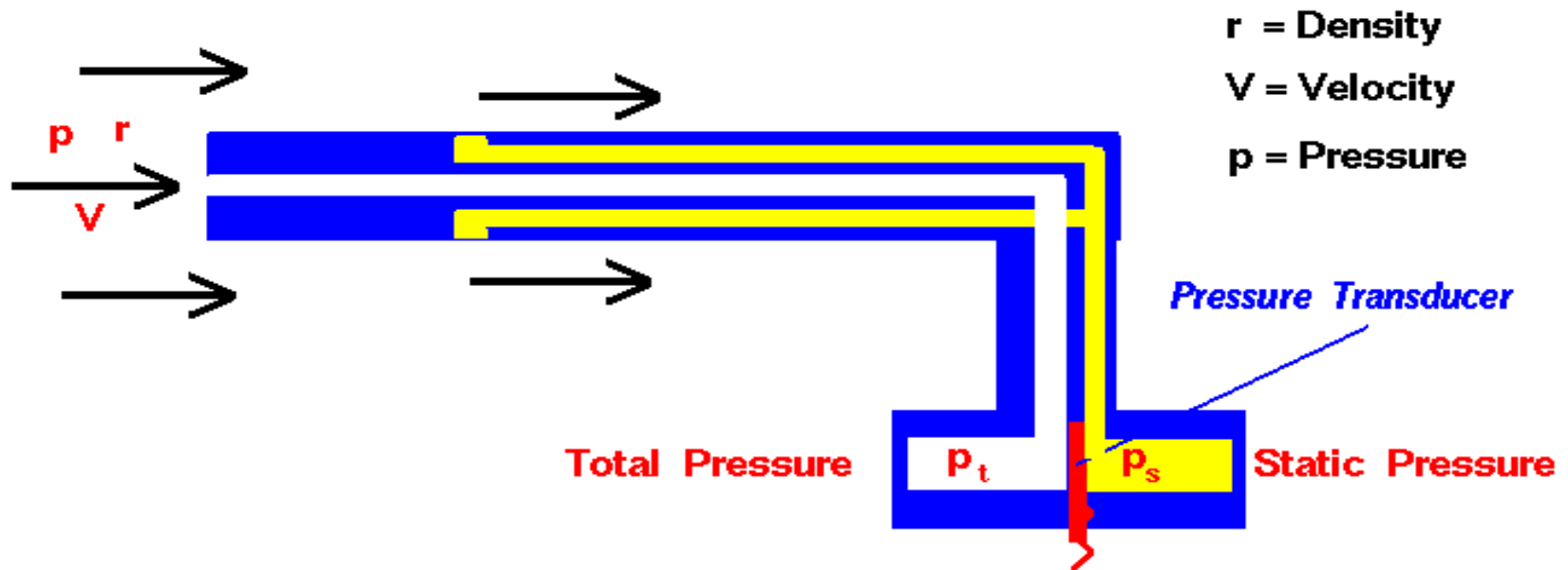
- Works with any conductive fluid
- 0.1 to 30 FPS
- Insertion type meter.
- Typical operation 105°C / 700PSI

Pitot Tube



Pitot-Static Tube Prandtl Tube

Glenn
Research
Center



Bernoulli's Equation:

static pressure + dynamic pressure = total pressure

$$\left(p_s + r \times \frac{V^2}{2} \right) = p_t$$

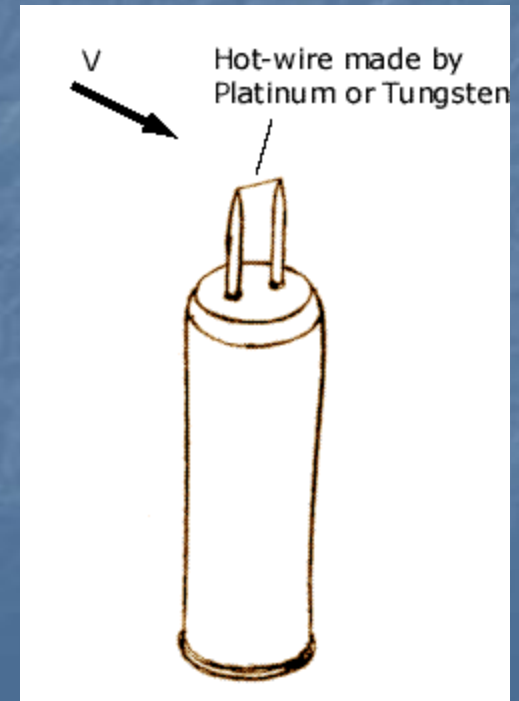
Solve for Velocity:

$$V^2 = \frac{2(p_t - p_s)}{r}$$

Measure difference in total and static pressure

Hotwire

- By measuring the change in wire temperature under constant current or the current required to maintain a constant wire temperature, the heat lost can be obtained. The heat lost can then be converted into a fluid velocity.

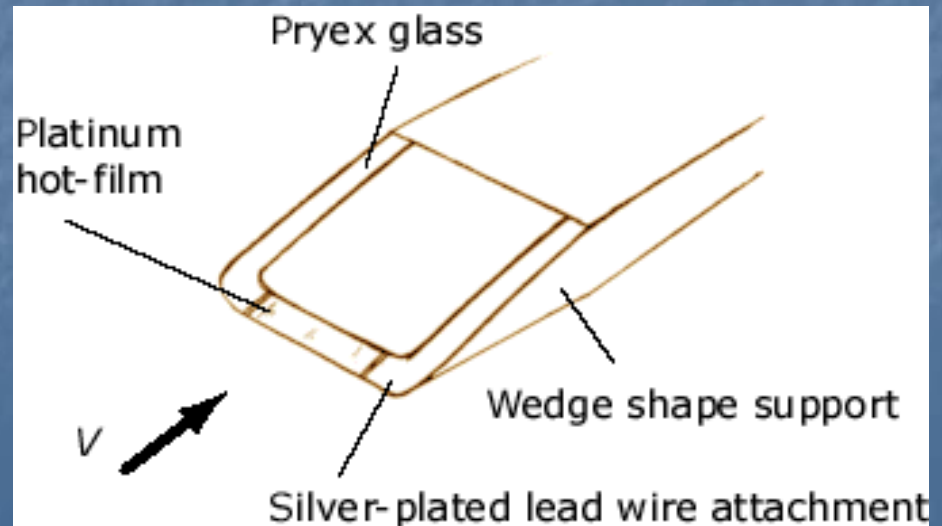


Hotwire characteristics

- Wire Diameter is small 4-10 μm
- Frequency response up to 17 kHz at 30 ft/s, 30 kHz at 100 ft/s, or 50 kHz at 300 ft/s.
- Only usable for Clean gasses

Hot film

- Another alternative is a pyrex glass wedge coated with a thin platinum hot-film at the edge tip



Hot film characteristics

- More rugged than the hot wire.
- Useable in liquids as well as gasses
- Needs to be recalibrated frequently
- \$\$\$\$\$\$\$\$\$\$

Mass Flow Meters

- Use a volume flow and adjust for density!

Others

- Laminar Flow element
- Critical Flow Orifice (choked flow)
- Calorimetric
- Coriolis
- Open channel



Application

- 20" pipe flowing sewage into a filtration plant

Solution

- Solids are a problem
- Large flow rate
- Low back pressure required
- Venturi meter

Application

- Flowing 0.2cc / min of light oil into a mixing kettle. Need a total volume for the process

Solution

- Total flow at a low rate screams positive displacement meter!
- Either a piston or multi-lobe meter

Application

- Take water flow measurements in an industrial plant Pipe sizes range from 2" to 8"
- Looking for at water usage by processes to determine where high water bill is coming from.

solution

- Need to be able to move around to multiple pipes
- Not a permanent, installation
- Ultrasonics are the ONLY thing that meets these requirements without making holes in pipes

A vertical stack of four images on the left side of the slide. From top to bottom: a blue clock face on a blue background, a red clock face on a red background, a green open book on a green background, and a blue open book on a blue background.

That's it!!!!

■ Homework

Posted on blackboard