Instrumentation

Flow Measurement

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Flow Measurement

The *volumetric flow* rate (also known as volume flow rate, rate of fluid flow or volume velocity) is the volume of fluid which passes per unit time; usually represented by the symbol *Q*

$$Q = \mathbf{v} \cdot \mathbf{A}$$

Flow velocity

Cross-sectional area/surface

In physics and engineering, *mass flow* rate is the mass of a substance which passes per unit of time.

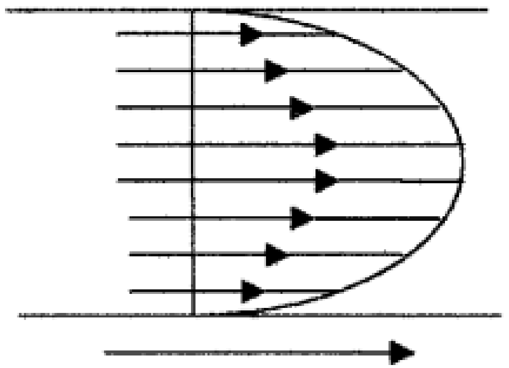
$$\boldsymbol{Q_m} = \boldsymbol{Q} \times \boldsymbol{\rho}$$

Volumetric flow

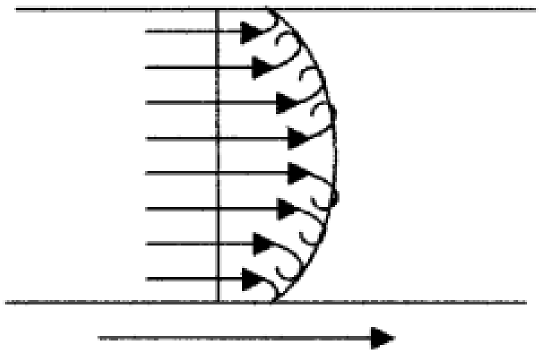
Density

Flow Measurement

Laminar flow of a liquid occurs when its average velocity is comparatively low and the fluid particles tend to move smoothly in layers



Turbulent flow occurs when the flow velocity is high and the particles no longer flow smoothly in layers and turbulence or a rolling effect occurs.

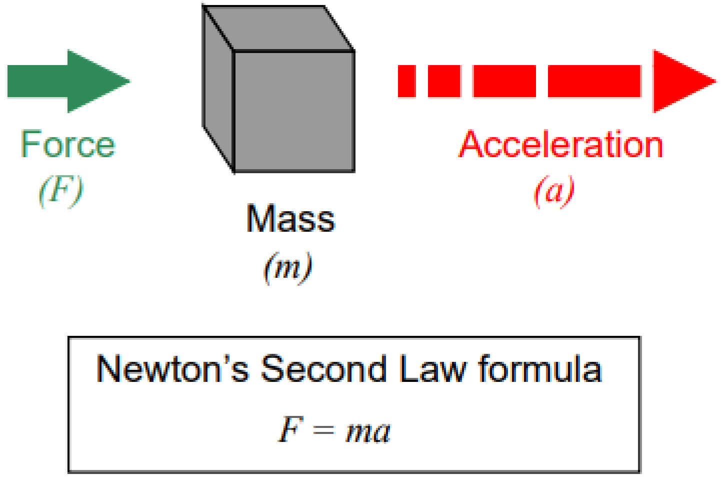


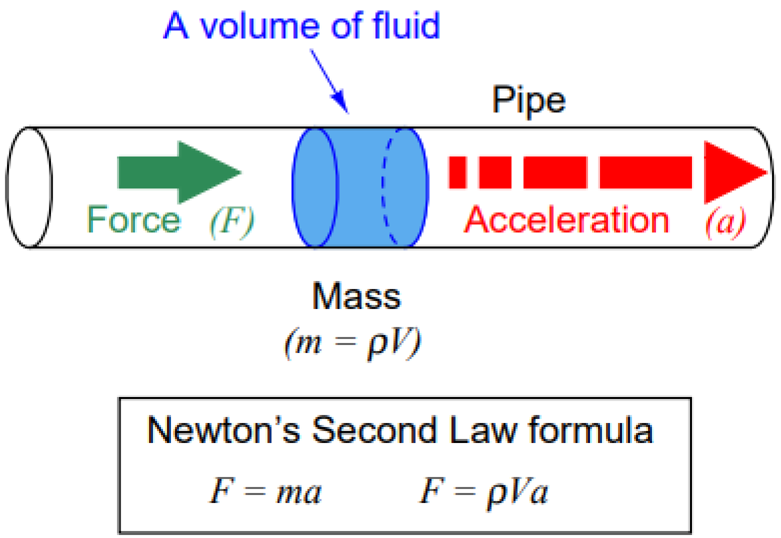
Reynold Number: $R = \frac{VD\rho}{\mu}$

where V = average fluid velocity
D = diameter of the pipe
ρ = density of the liquid
μ = absolute viscosity

$If\ \ R \leq 2000 \rightarrow Laminar$
$If\ 2000 < R \leq 5000 \rightarrow Mixture$
$If\ \ R > 5000 \rightarrow Turbulent$

Pressure Based Flowmeter

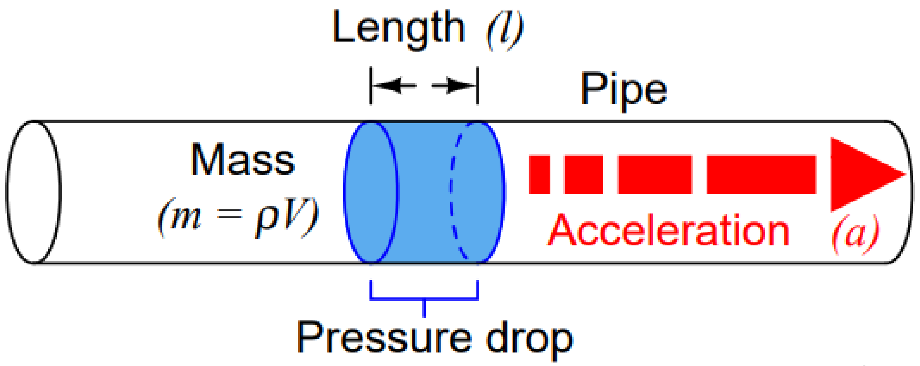




$$F = \rho V a$$

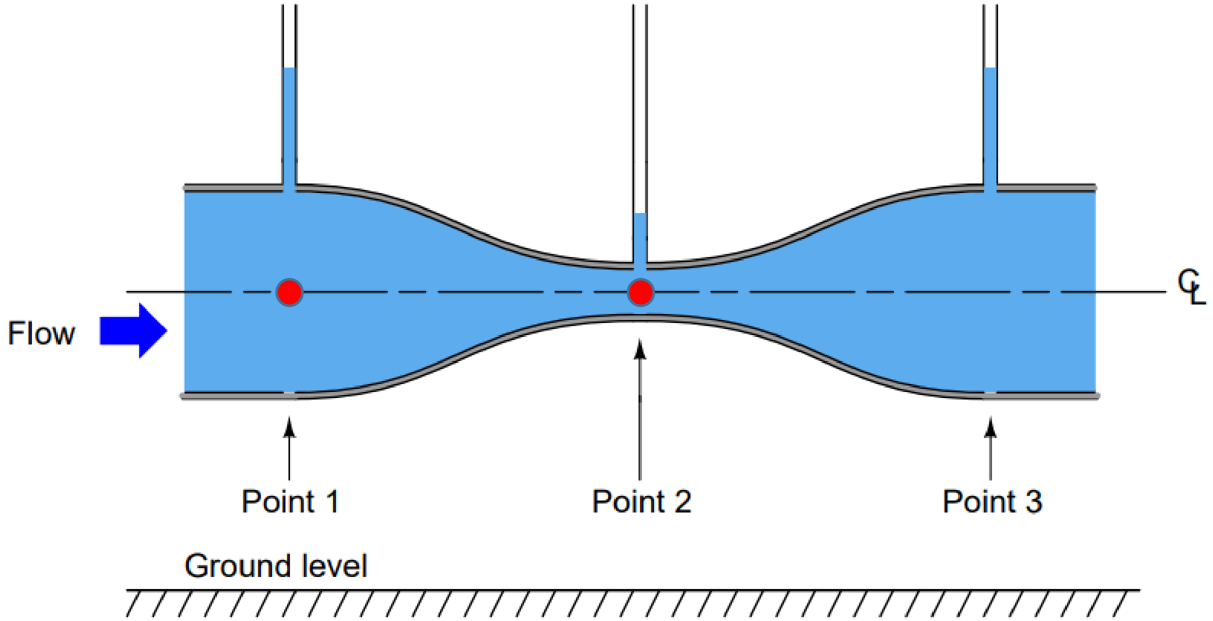
$$\frac{F}{A} = \rho \frac{V}{A} a$$

$$P = \rho \frac{V}{A} a$$



$$P = \rho l a$$

Venturi tubes and basic principles



Bernoulli’s Equation:

$$mgh_1 + \frac{1}{2}mv_1^2 + P_1V = mgh_2 + \frac{1}{2}mv_2^2 + P_2V$$

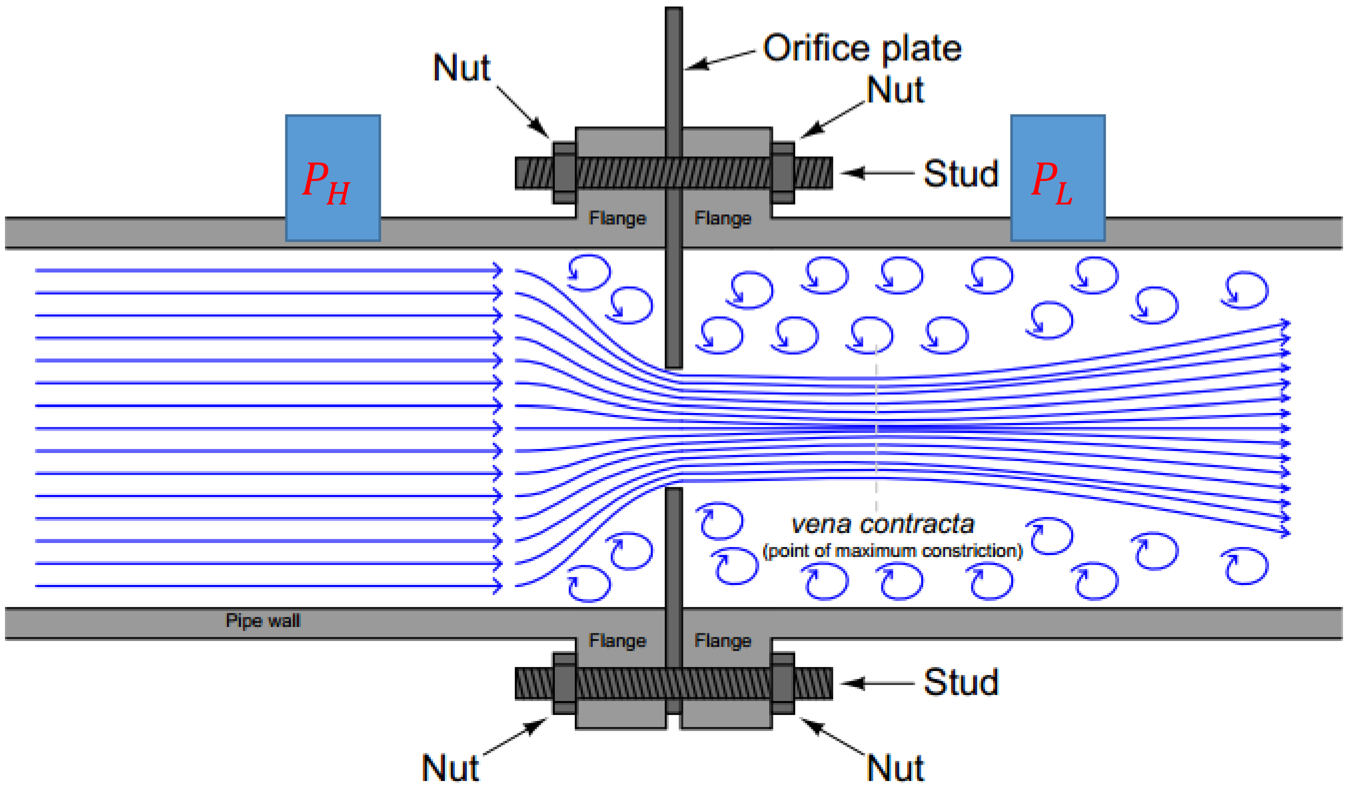
$$\rho gh_1 + \frac{1}{2}\rho v_1^2 + P_1 = \rho gh_2 + \frac{1}{2}\rho v_2^2 + P_2$$

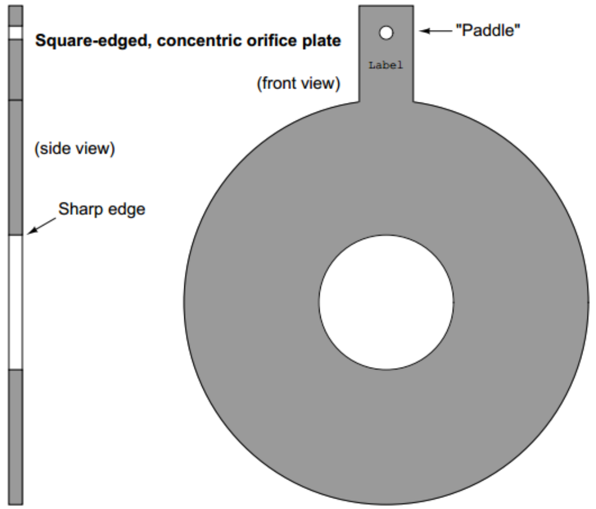
$$h_1 = h_2 \rightarrow \frac{\rho}{2}(v_2^2 - v_1^2) = P_1 - P_2$$

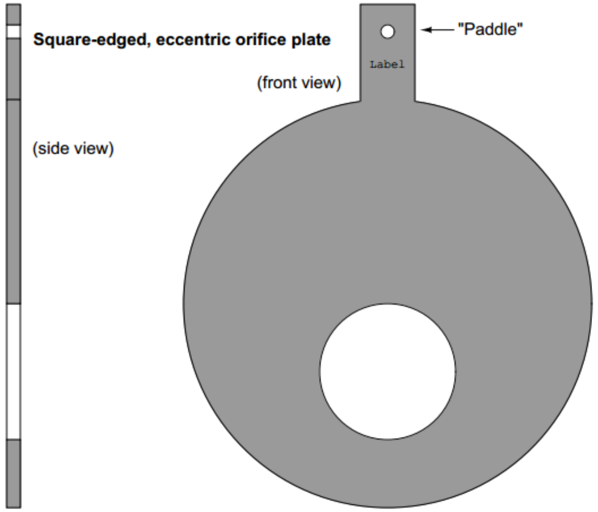
$$Q_1 = Q_2 \rightarrow A_1v_1 = A_2v_2 \rightarrow v_1 = \left(\frac{A_2}{A_1}\right)v_2 \rightarrow$$

$$v_2 = \sqrt{2}\frac{1}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}}\sqrt{\frac{P_1 - P_2}{\rho}} \xrightarrow{\times A_2} Q = \sqrt{2}\frac{A_2}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}}\sqrt{\frac{P_1 - P_2}{\rho}} \rightarrow \boldsymbol{Q = k\sqrt{\frac{P_1 - P_2}{\rho}}}$$

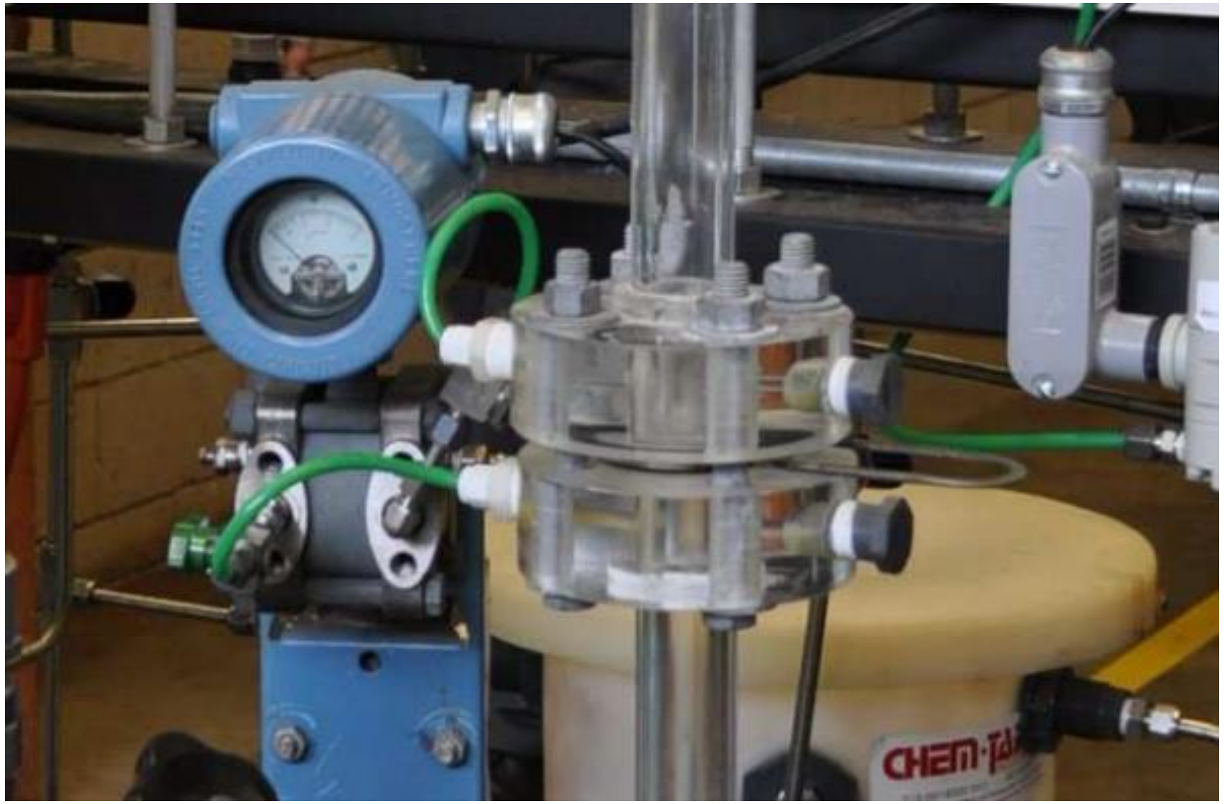
Orifice plates



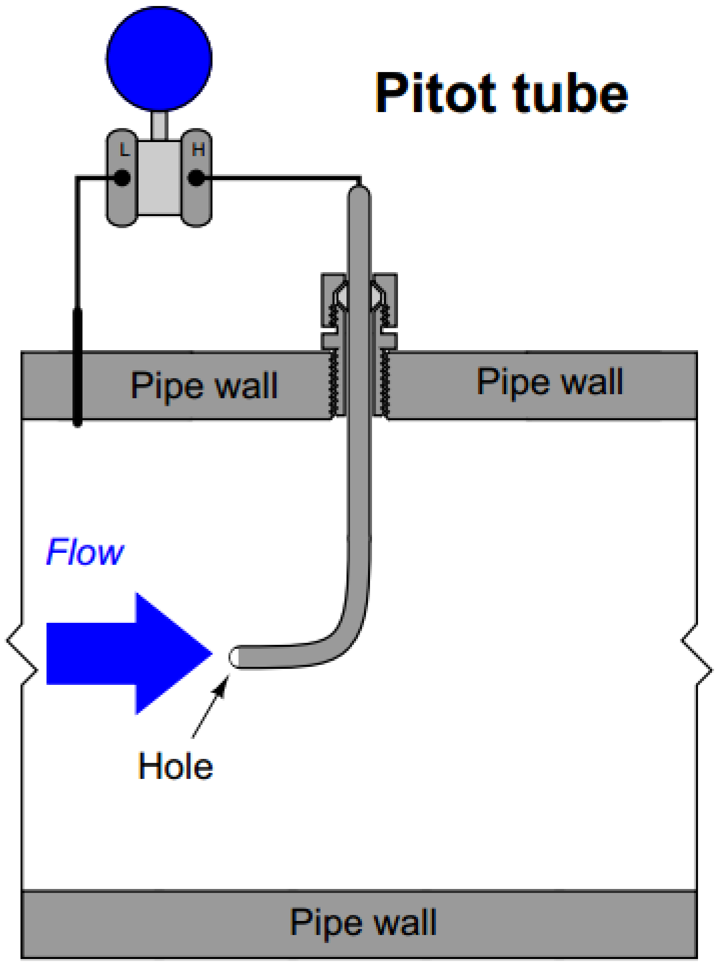




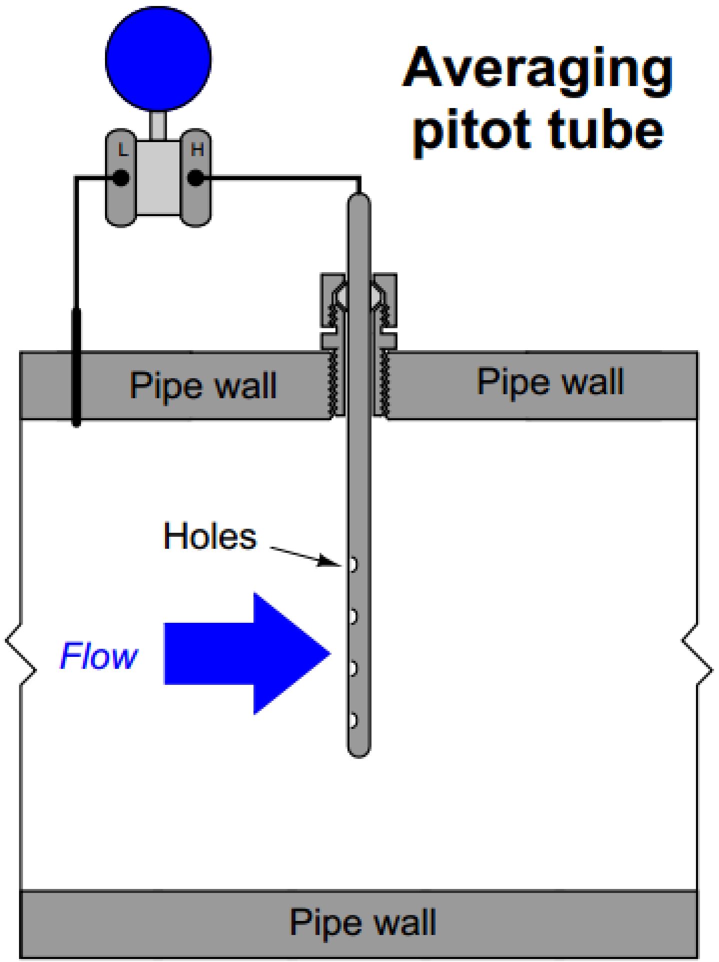
Orifice plates



Pitot tube

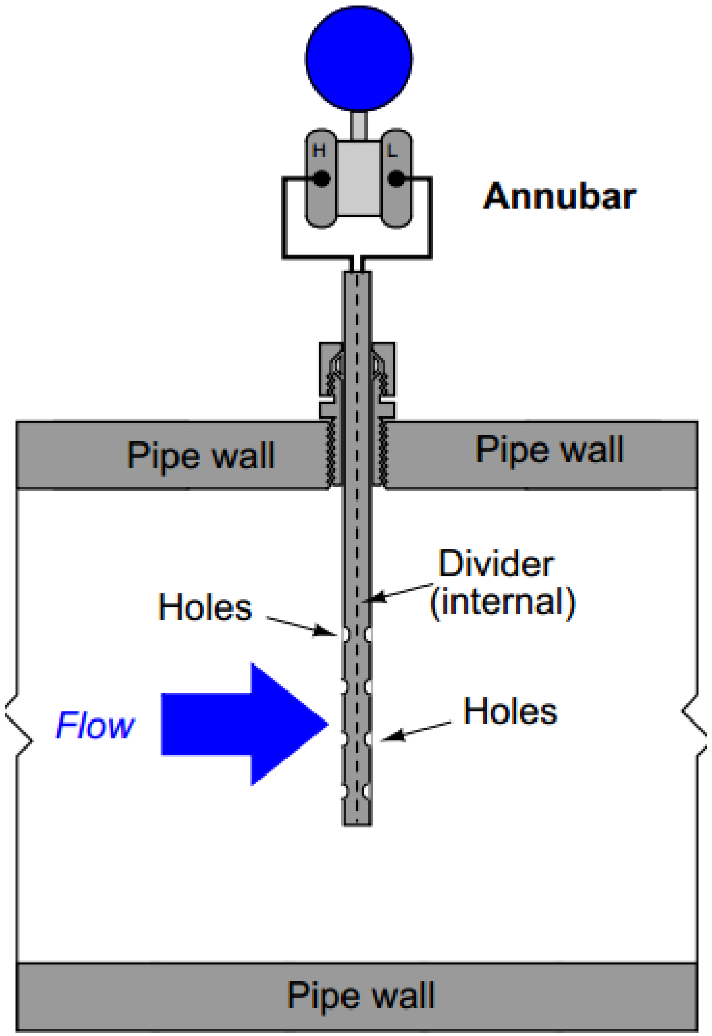


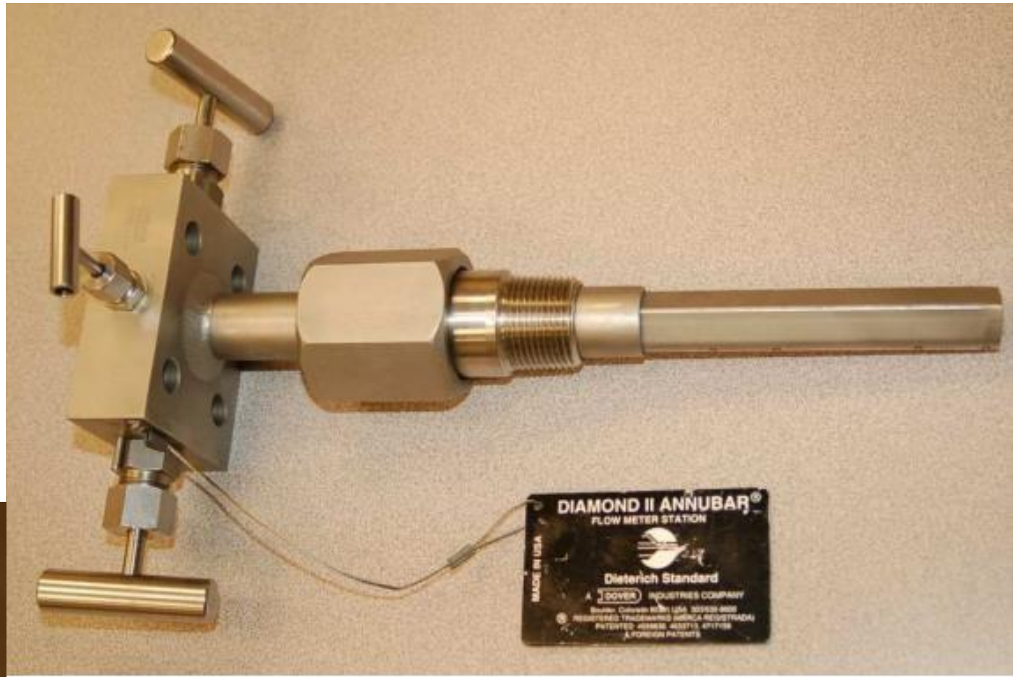
Pitot tube
L
H
Pipe wall
Pipe wall
Flow
Hole
Pipe wall



Averaging pitot tube
L
H
Pipe wall
Pipe wall
Holes
Flow
Pipe wall

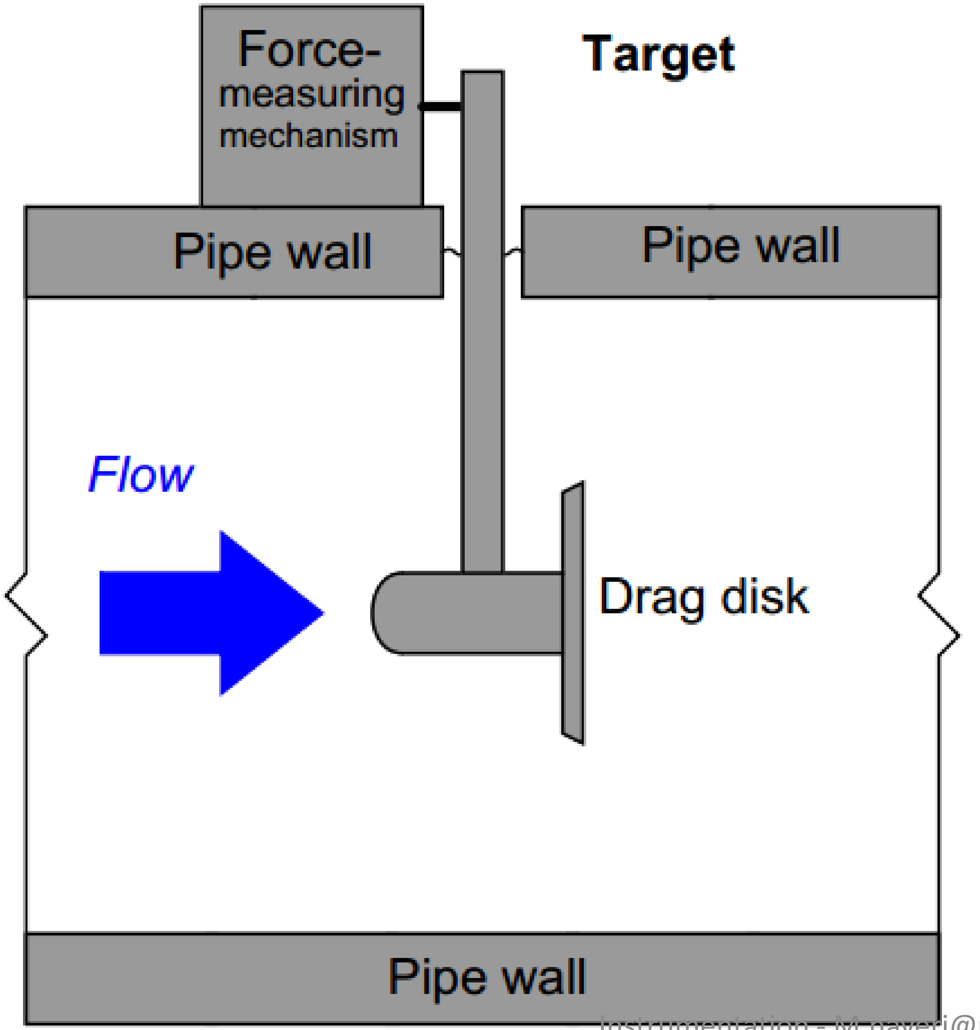
Pitot tube


Annubar
H
L
Pipe wall
Pipe wall
Divider
(internal)
Holes
Flow
Holes
Pipe wall


DIAMOND II ANNUBAR®
FLOW METER STATION
Dieterich Standard

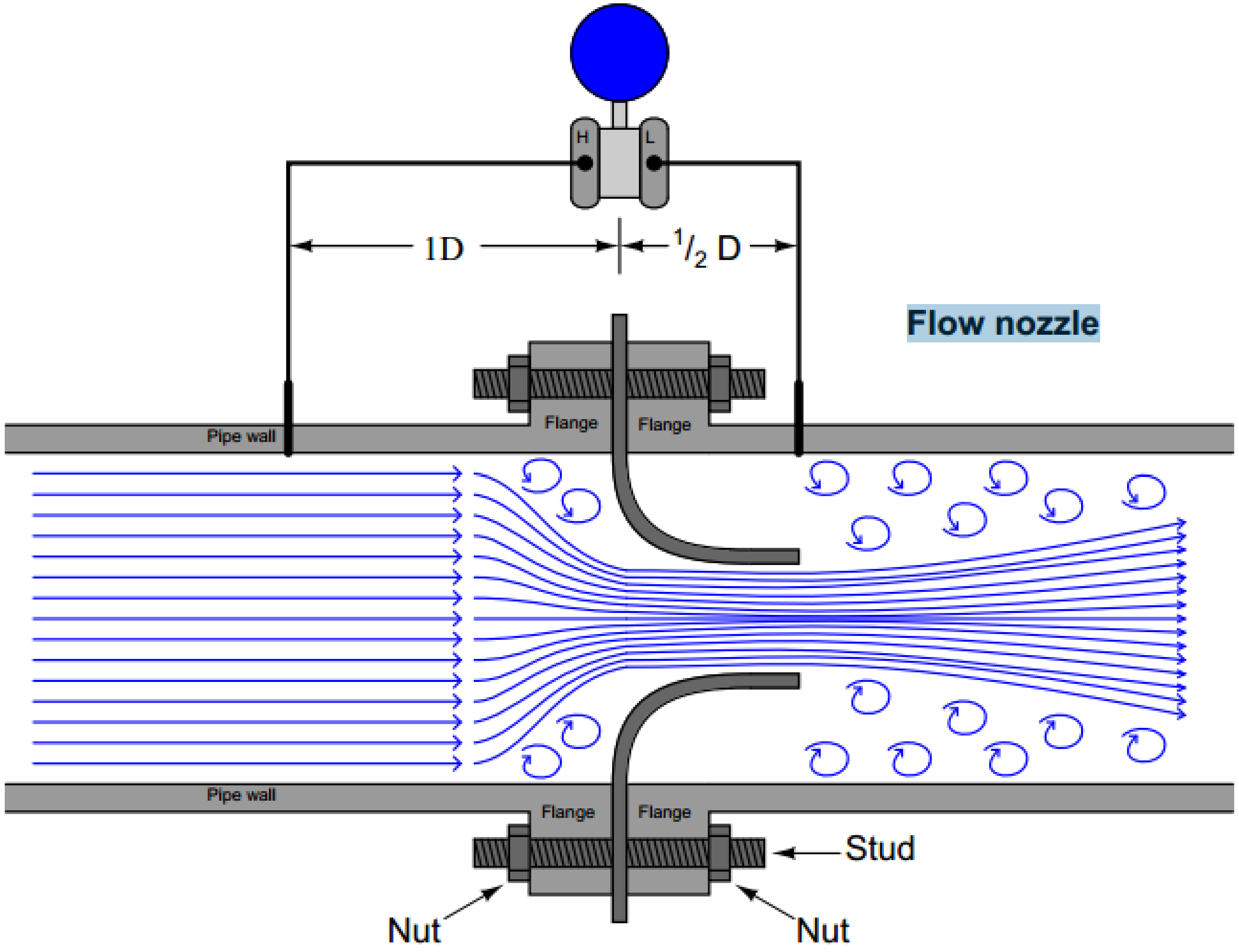
Pitot tube

Drag disk

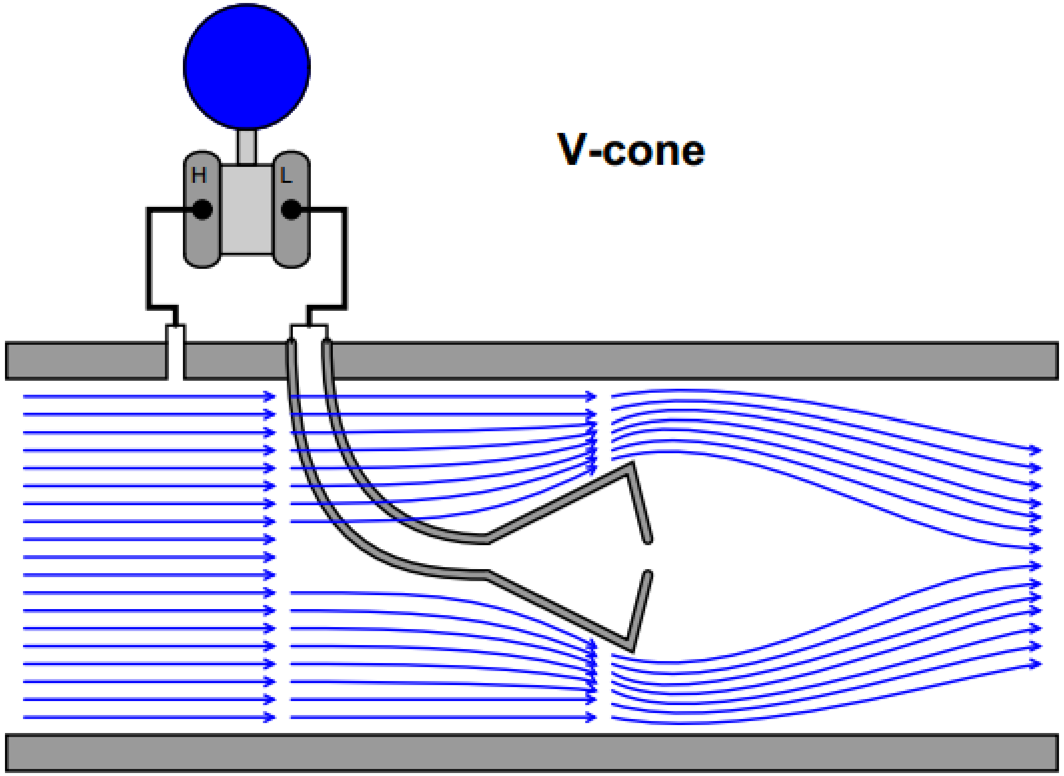

Force-
measuring
mechanism
Target
Pipe wall
Pipe wall
Flow
Drag disk
Pipe wall


FOXBORO
BCIT

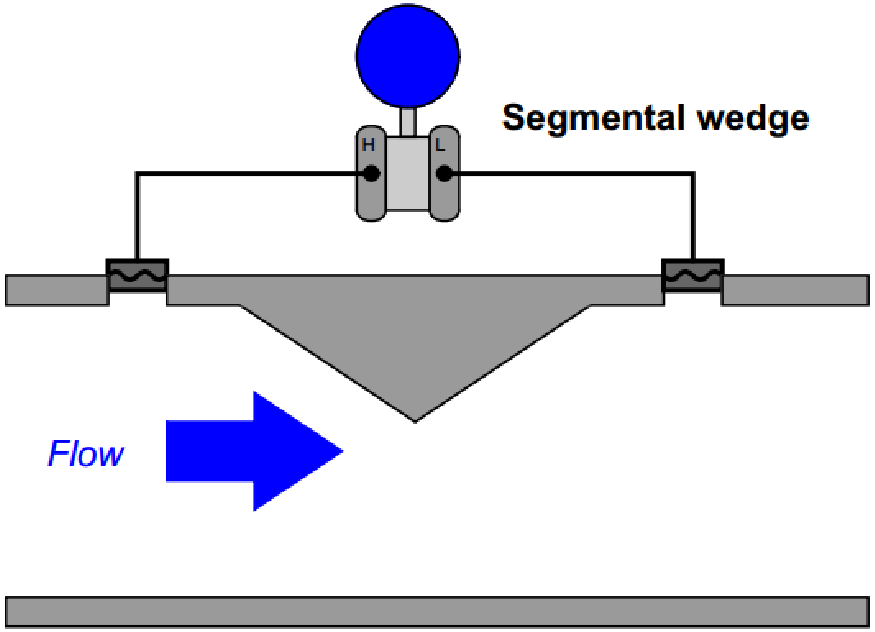
Flow nozzle


H
L
1D
$^1/_2$ D
Flow nozzle
Pipe wall
Flange
Flange
Pipe wall
Flange
Flange
Stud
Nut
Nut

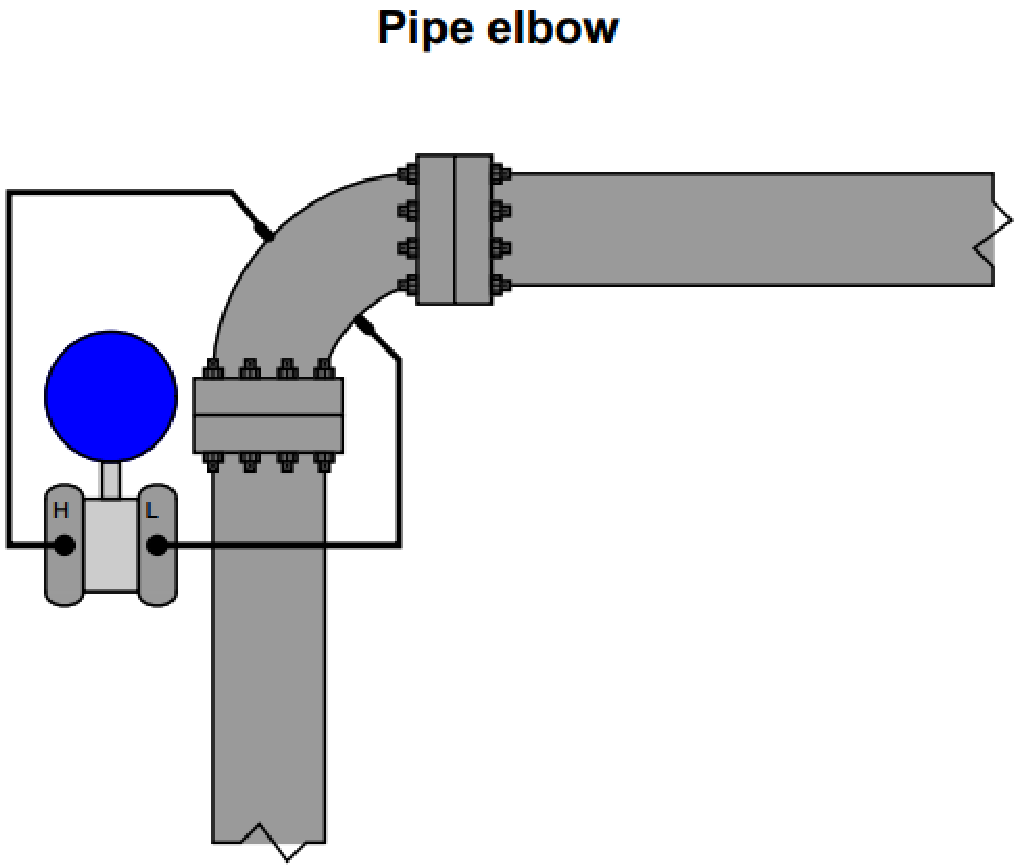
V-cone

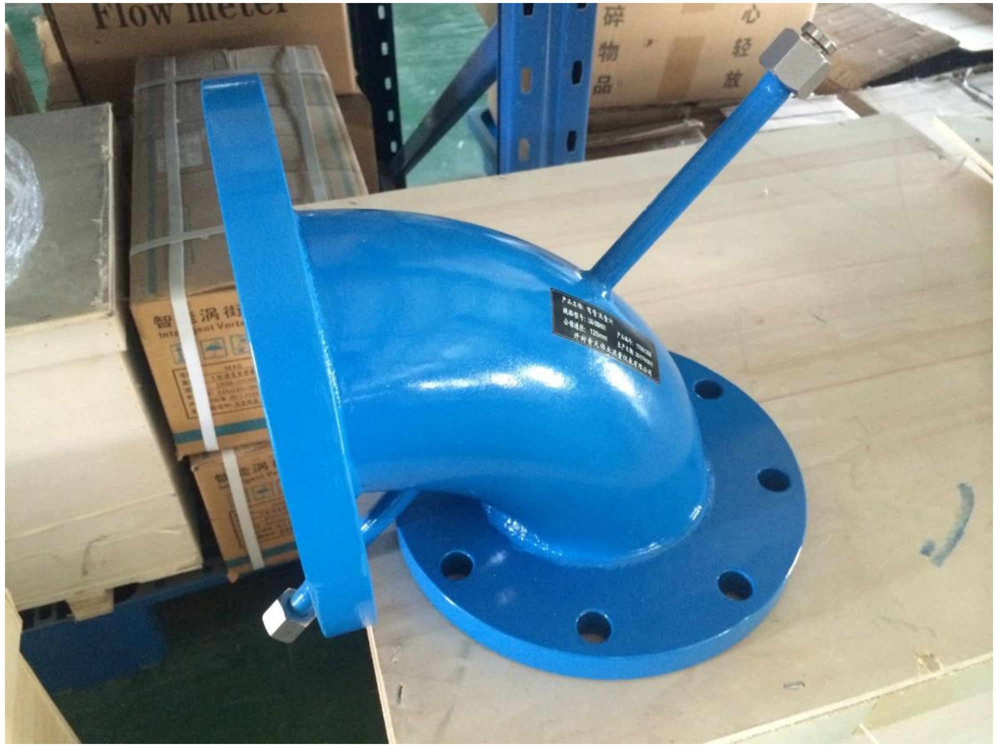


Segmental wedge

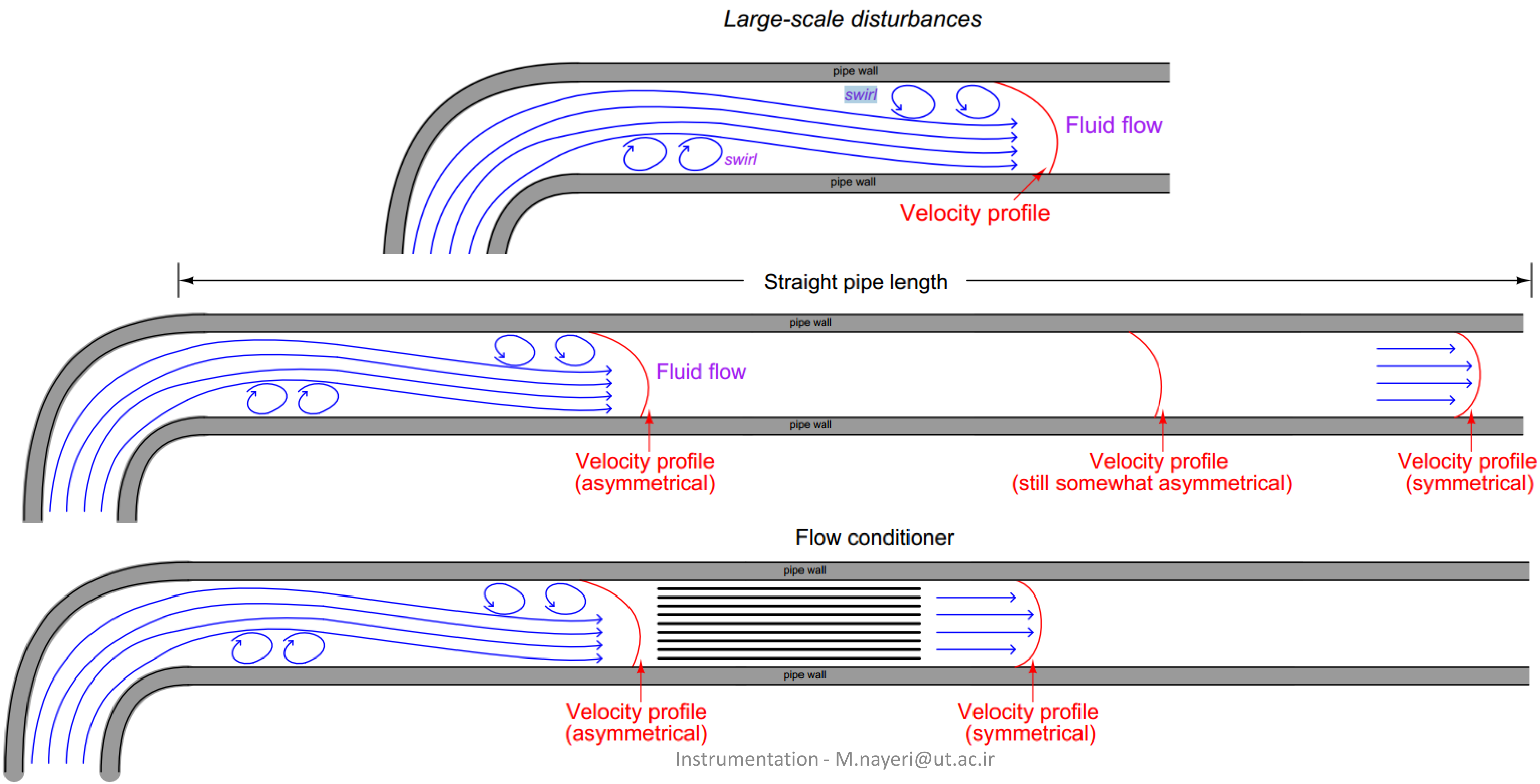


Pipe elbow

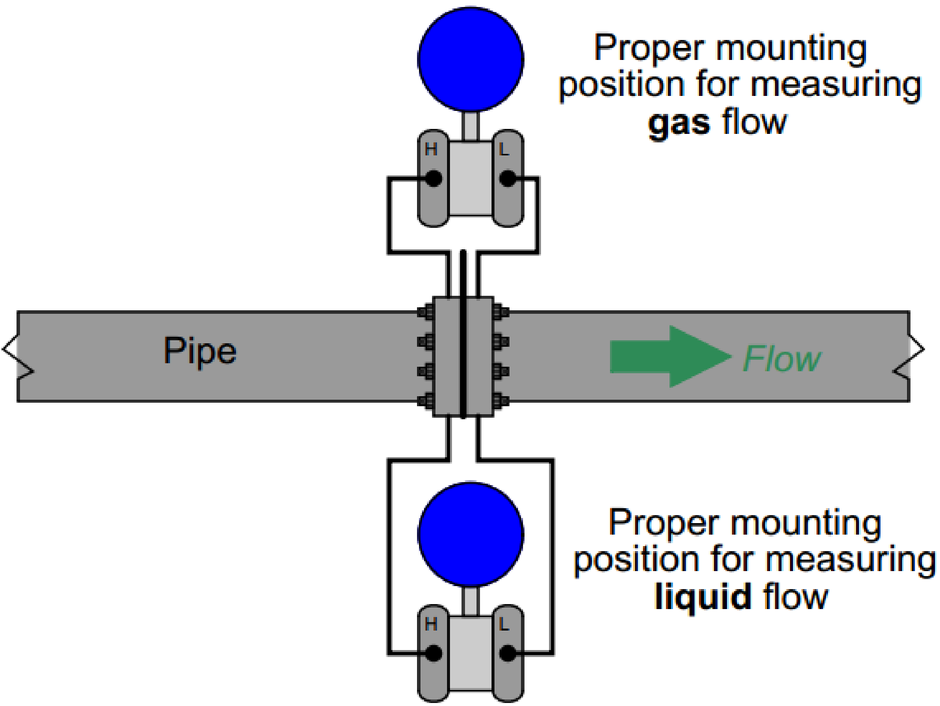


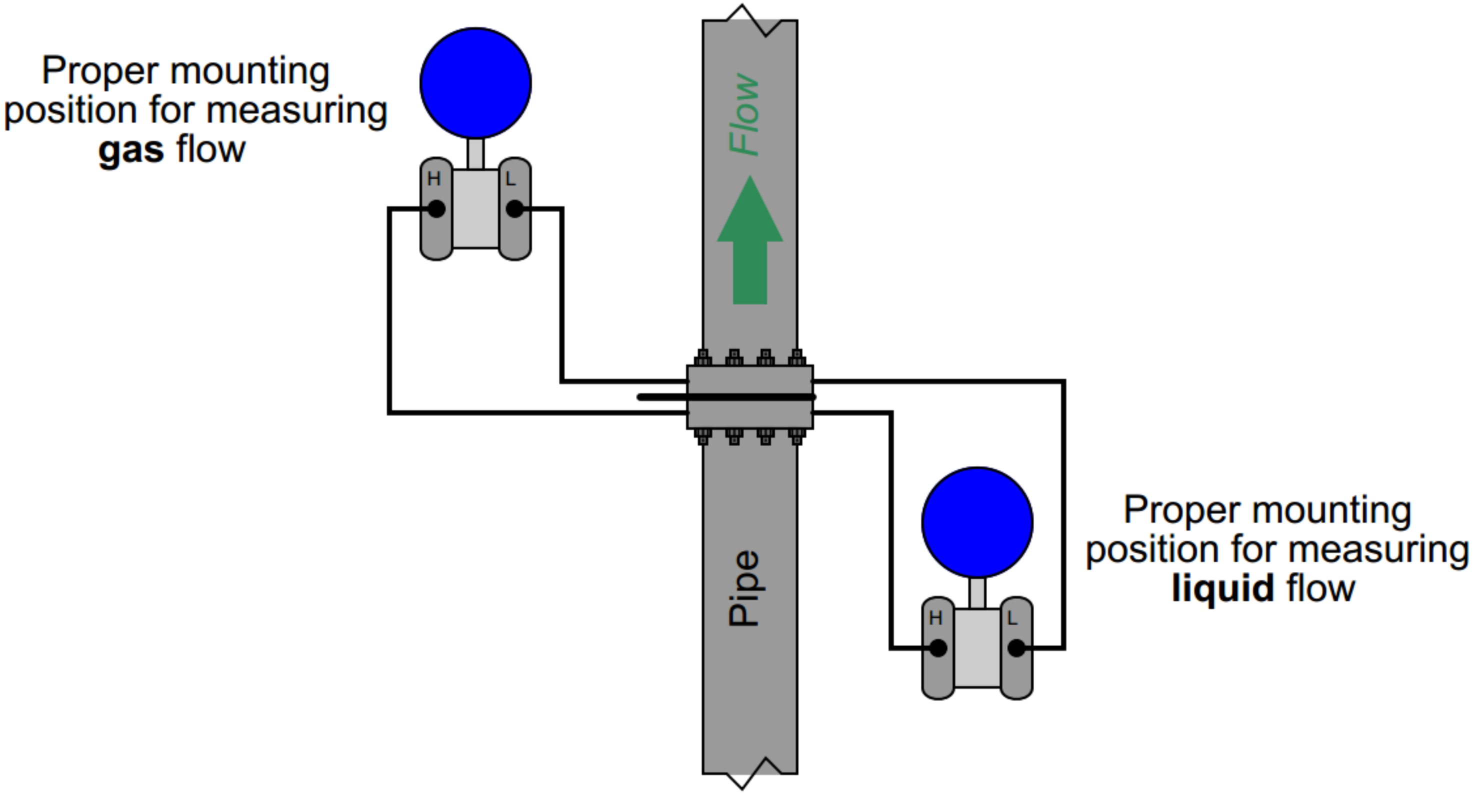


Installation



Installation





High-accuracy flow measurement

- Energy losses due to turbulence and viscosity
- Energy losses due to friction against the pipe and element surfaces
- Unstable location of *vena contracta* with changes in flow
- Uneven velocity profiles caused by irregularities in the pipe
- Fluid compressibility
- Thermal expansion (or contraction) of the element and piping
- Non-ideal pressure tap location(s)
- Excessive turbulence caused by rough internal pipe surfaces

$$C = \frac{\text{True flow}}{\text{Theoretical flow}} \qquad Y = \frac{C_{gas}}{C_{liquid}} \qquad Y = \frac{\left(\frac{\text{True gas flow}}{\text{Theoretical gas flow}}\right)}{\left(\frac{\text{True liquid flow}}{\text{Theoretical liquid flow}}\right)}$$

High-accuracy flow measurement

The American Gas Association (AGA) provides a formula for calculating volumetric flow of any gas using orifice plates

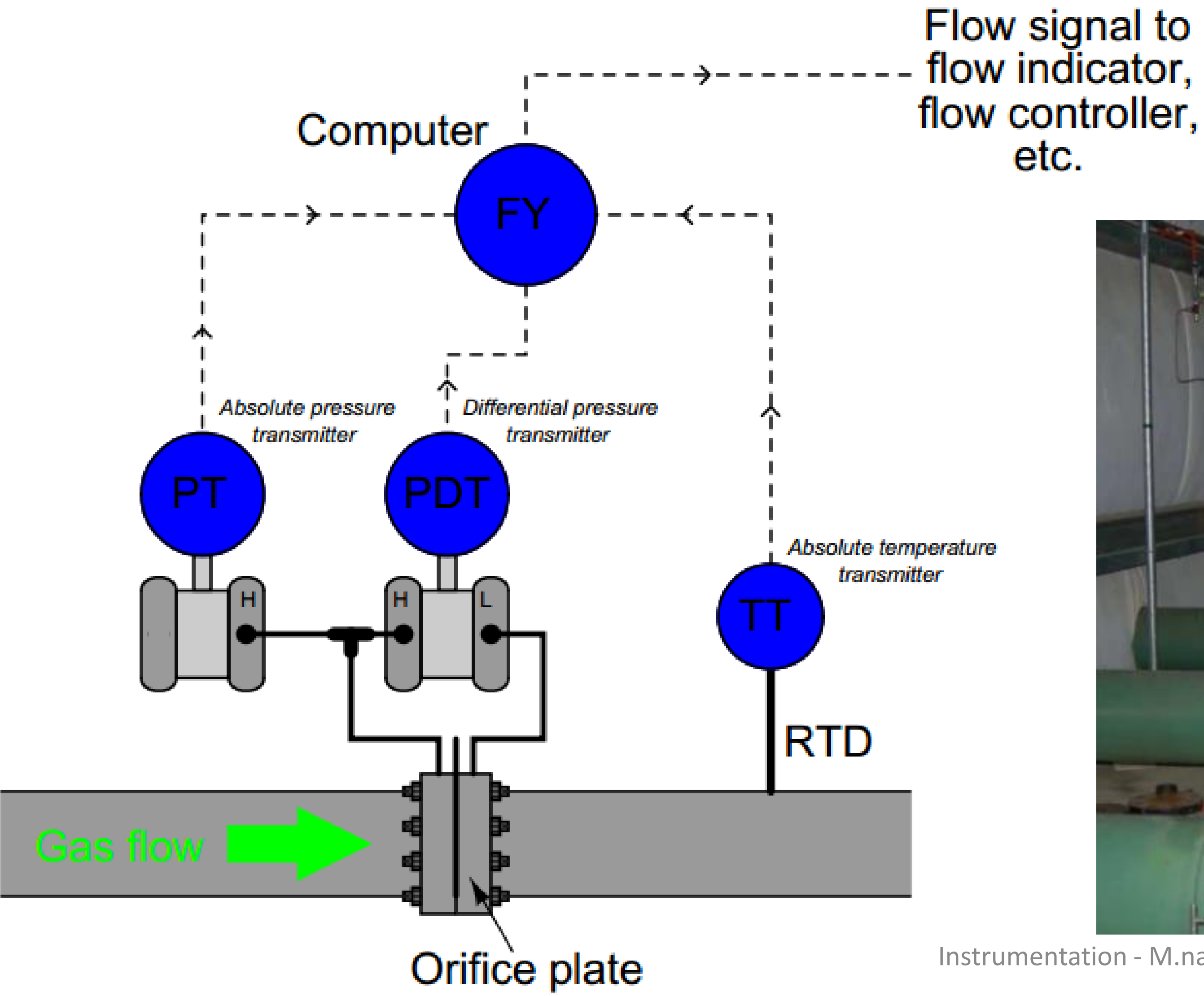
$$Q = N \frac{C Y A_2}{\sqrt{1 - \left(\frac{A_2}{A_1}\right)^2}} \sqrt{\frac{Z_s P_1 (P_1 - P_2)}{G_f Z_{f1} T}}$$

$$Q = k \sqrt{\frac{P_1 - P_2}{\rho}}$$

Where,

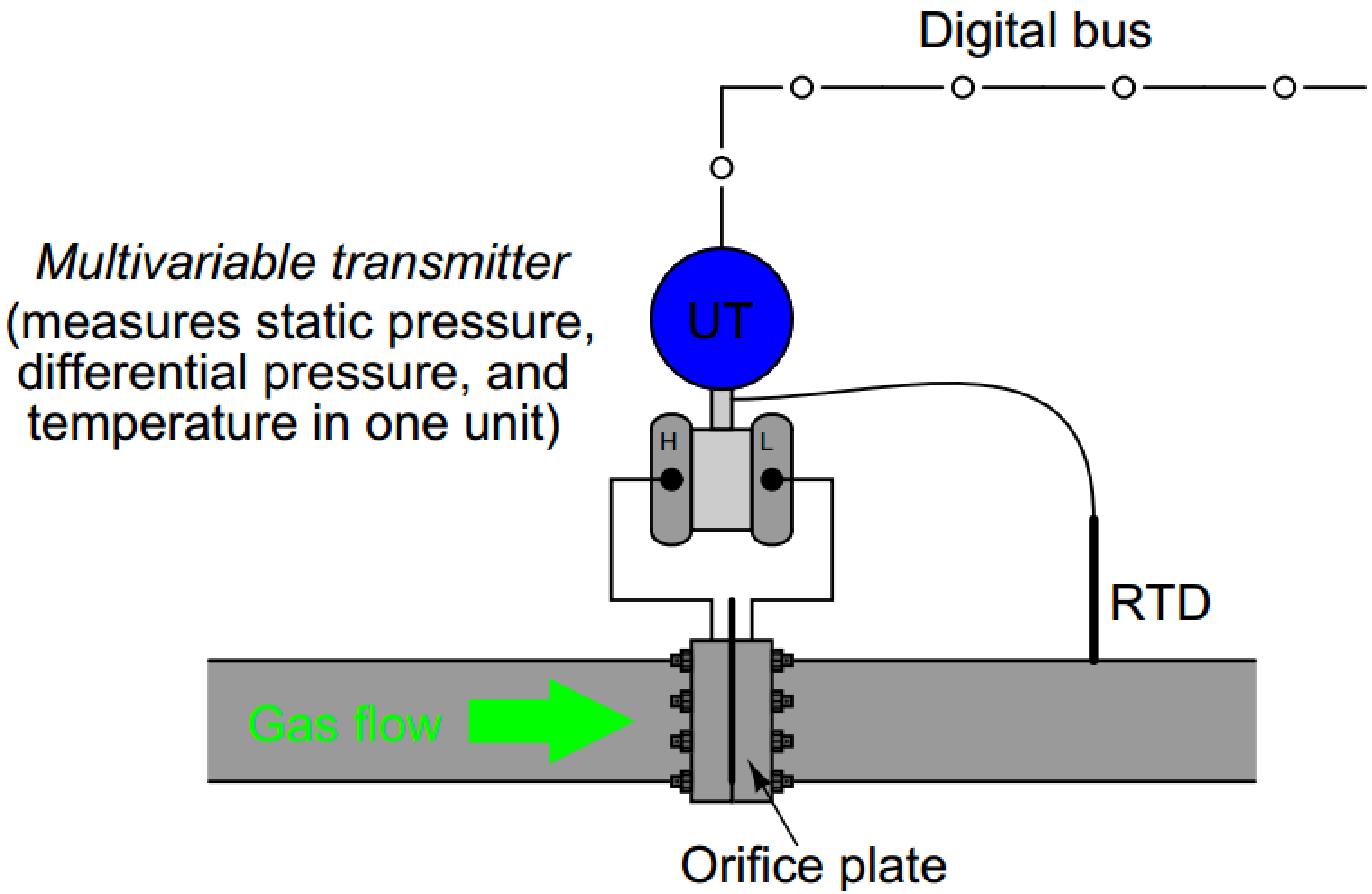
Q = Volumetric flow rate (SCFM = standard cubic feet per minute)
N = Unit conversion factor
C = Discharge coefficient (accounts for energy losses, Reynolds number corrections, pressure tap locations, etc.)
Y = Gas expansion factor
A_1 = Cross-sectional area of mouth
A_2 = Cross-sectional area of throat
Z_s = Compressibility factor of gas under standard conditions
Z_{f1} = Compressibility factor of gas under flowing conditions, upstream
G_f = Specific gravity of gas (density compared to ambient air)
T = Absolute temperature of gas
P_1 = Upstream pressure (absolute)
P_2 = Downstream pressure (absolute)

High-accuracy flow measurement

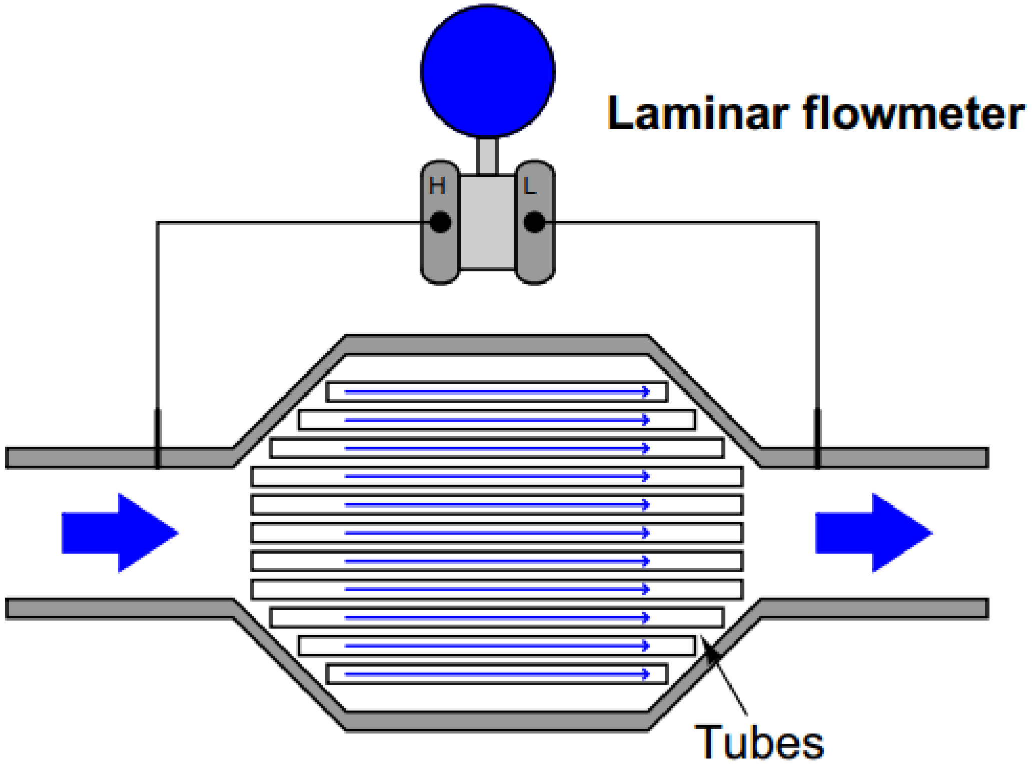


High-accuracy flow measurement

An alternative to multiple instruments (differential pressure, absolute pressure, and temperature) installed on each meter run is to use a single multi-variable transmitter capable of measuring gas temperature as well as both static and differential pressures. This approach enjoys the advantage of simpler installation over the multi-instrument approach.



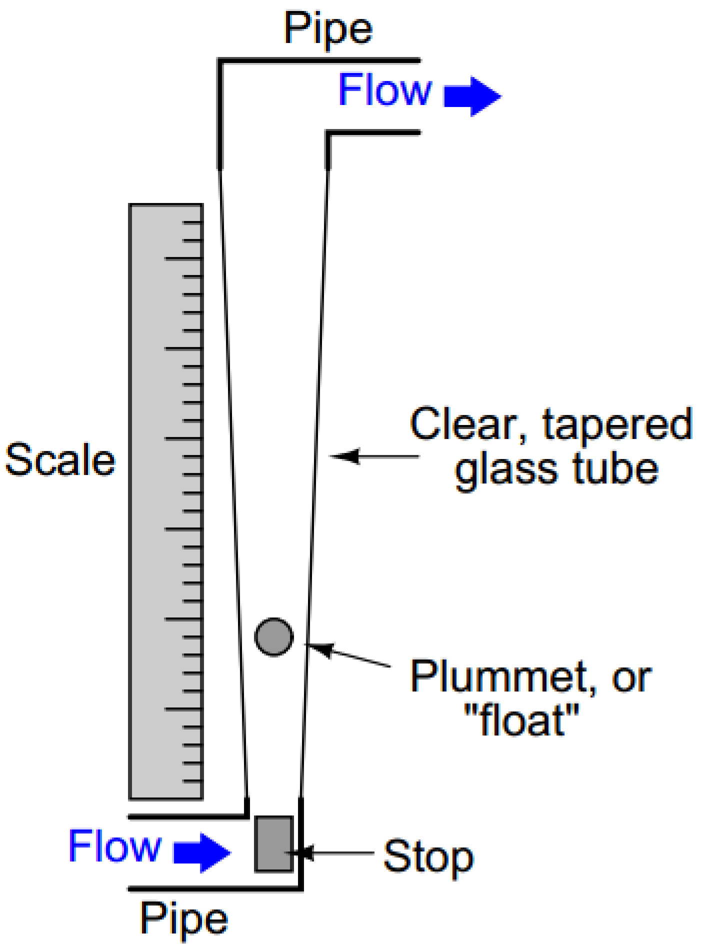
Laminar flow meters

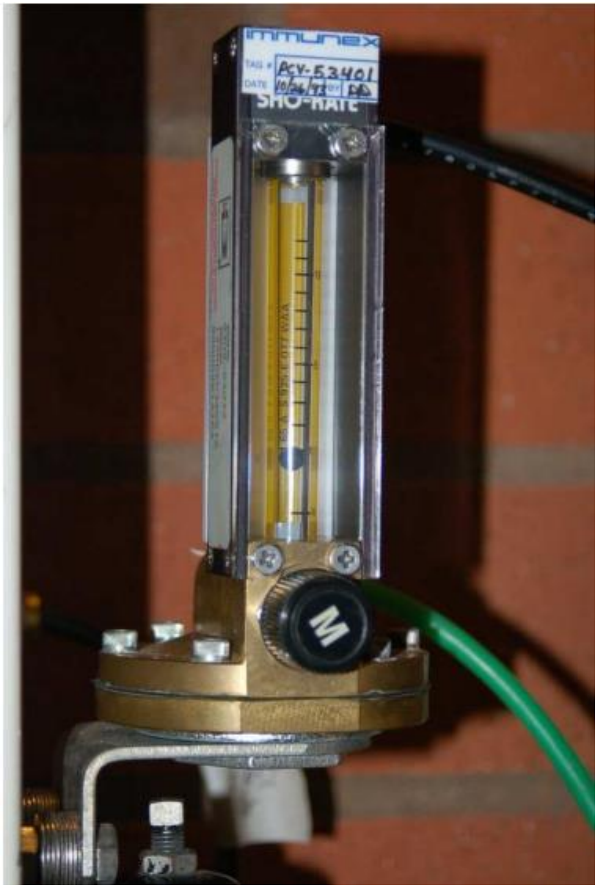


$$Q = k\left(\frac{\Delta P D^4}{\mu L}\right)$$

Q = Flow rate
ΔP = Pressure dropped across a length of pipe
D = Pipe diameter
μ = Fluid viscosity
L = Pipe length
k = Coefficient accounting for units of measurement

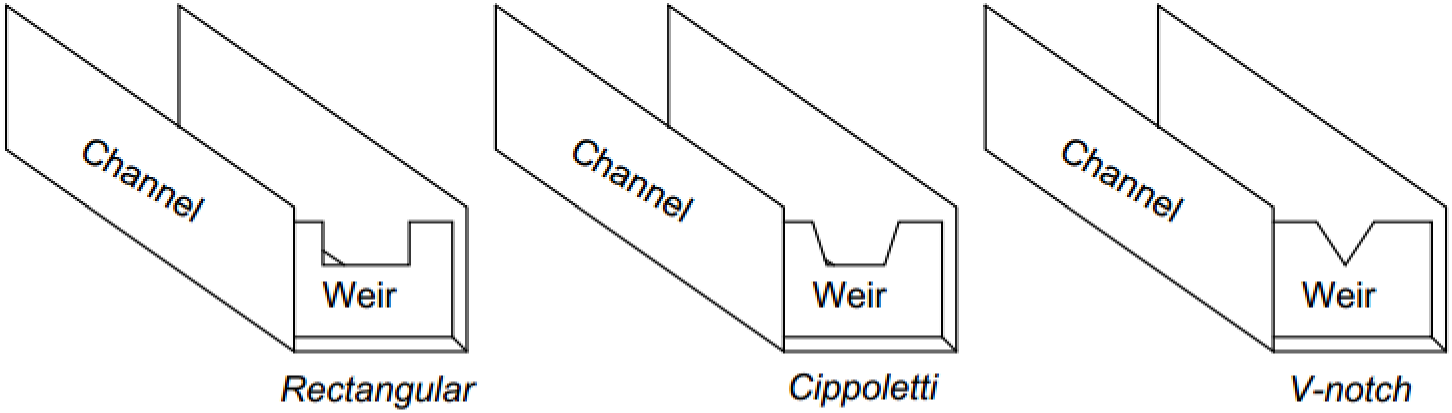
Rotameters





$F = P\,A$

Weirs

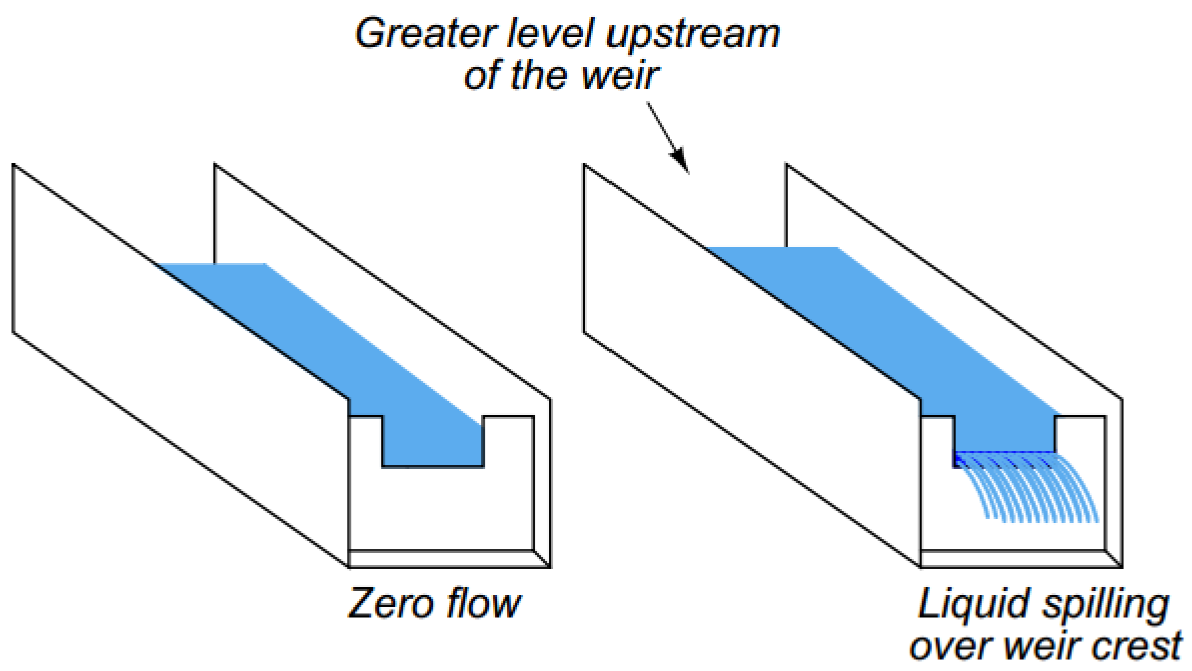


$$Q = 3.33(L - 0.2H)H^{1.5}$$

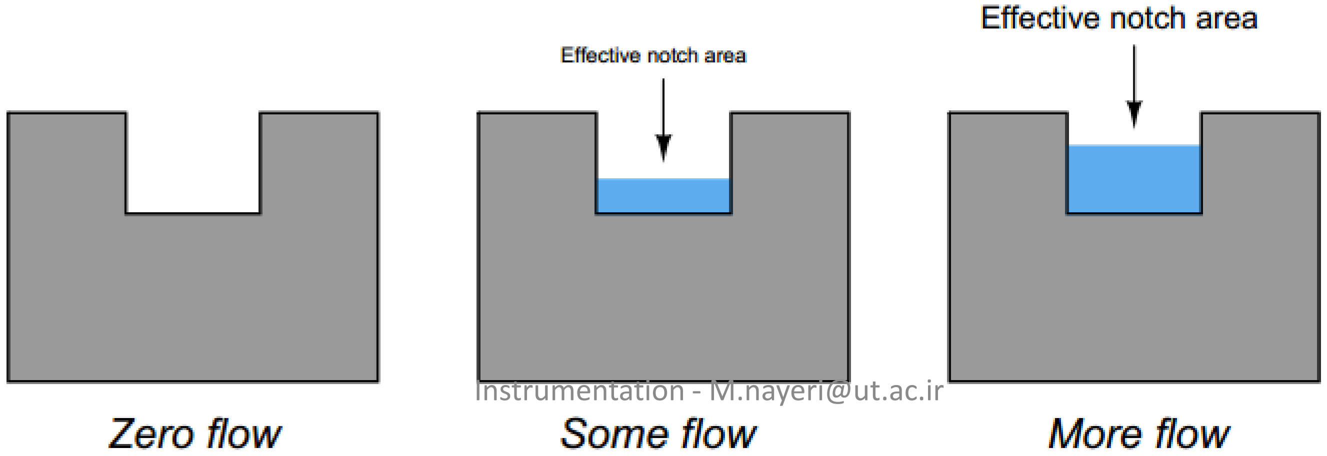
$$Q = 3.367LH^{1.5}$$

$$Q = 2.48\left(\tan\frac{\theta}{2}\right)H^{2.5}$$

Weirs

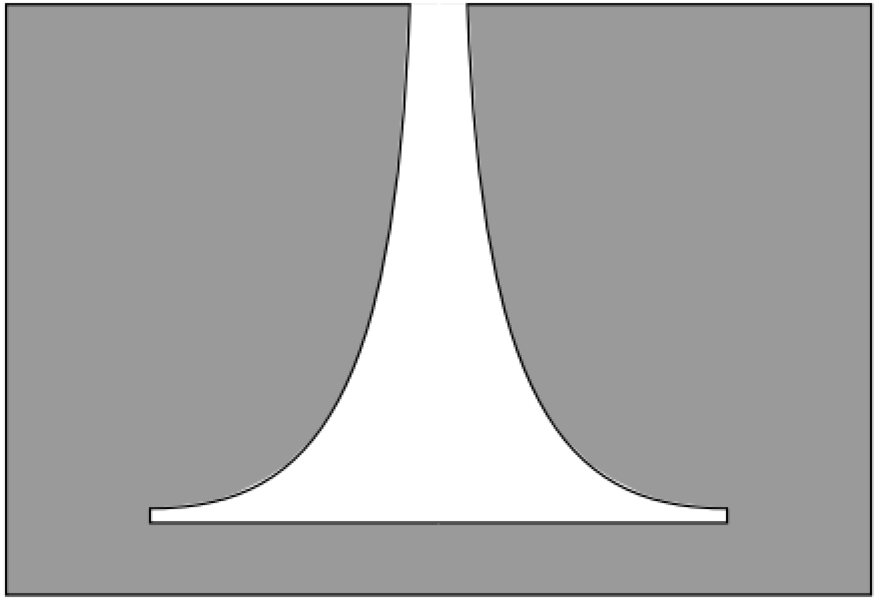


Greater level upstream of the weir
Zero flow
Liquid spilling over weir crest



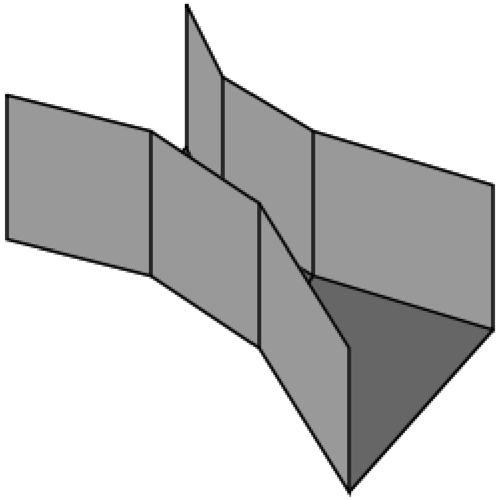
Effective notch area
Effective notch area
Zero flow
Some flow
More flow

Weirs



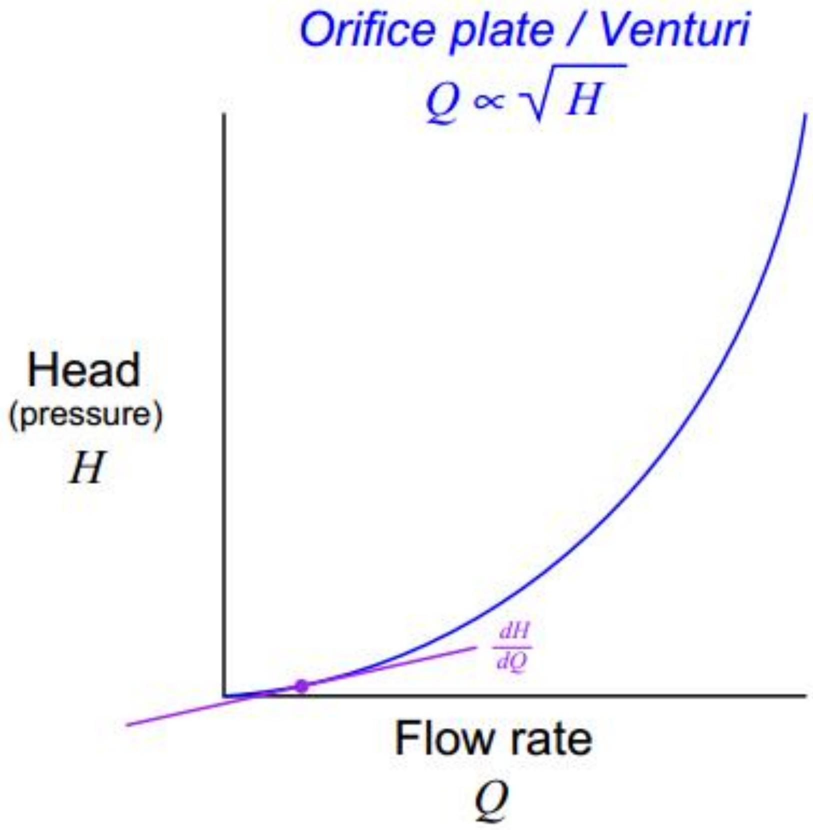
Proportional weir, which is designed to have a **linear relationship between head and flow rate.**

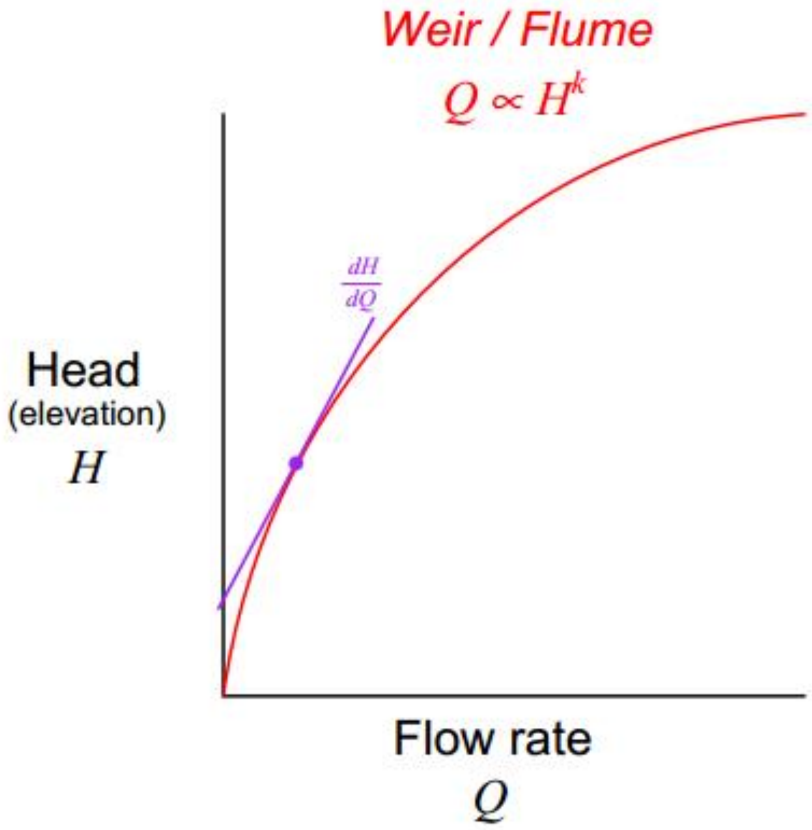
Flumes



Flumes are generally **less accurate** than weirs, but they do enjoy the advantage of being inherently **self-cleaning**.

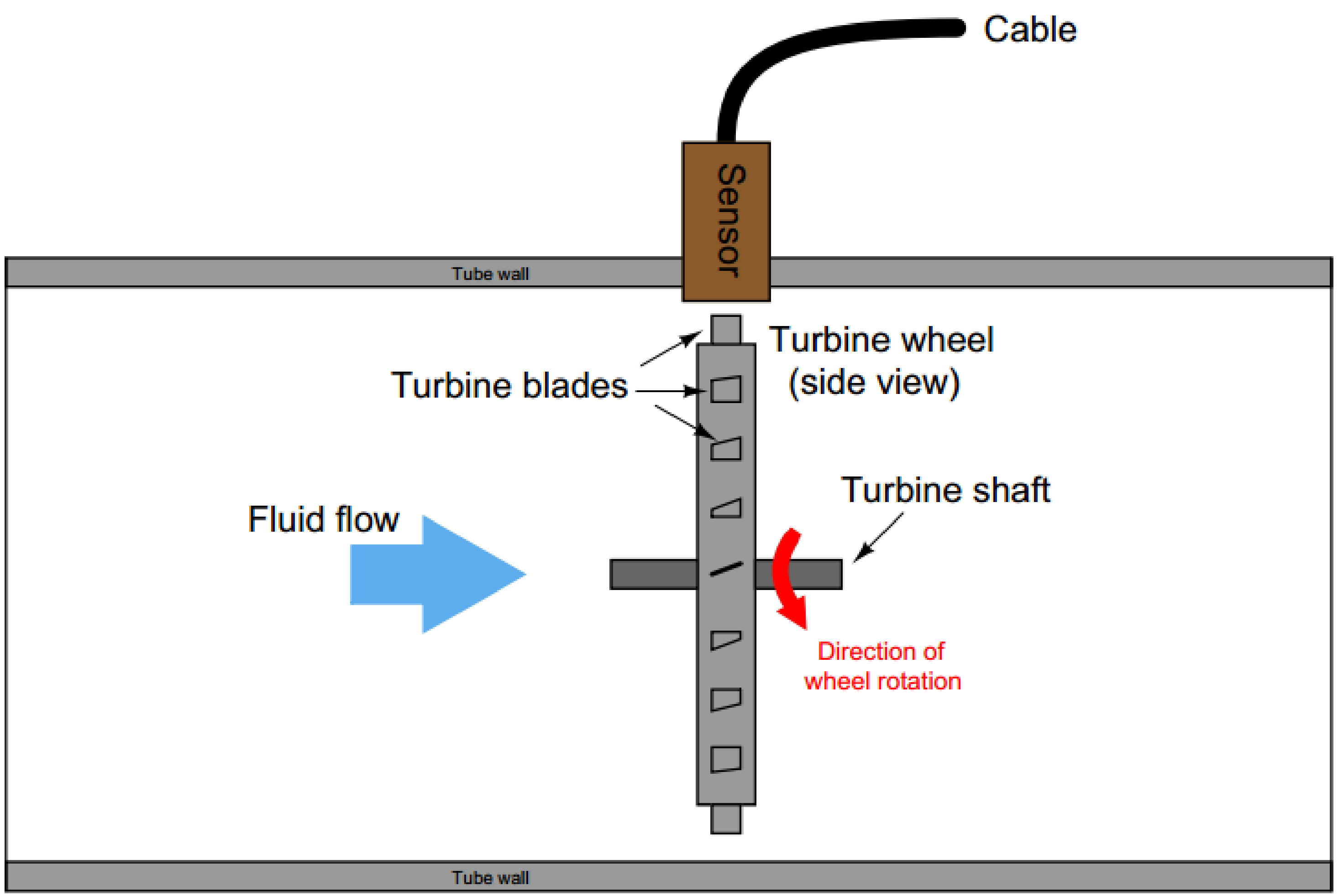
Weirs & Flumes

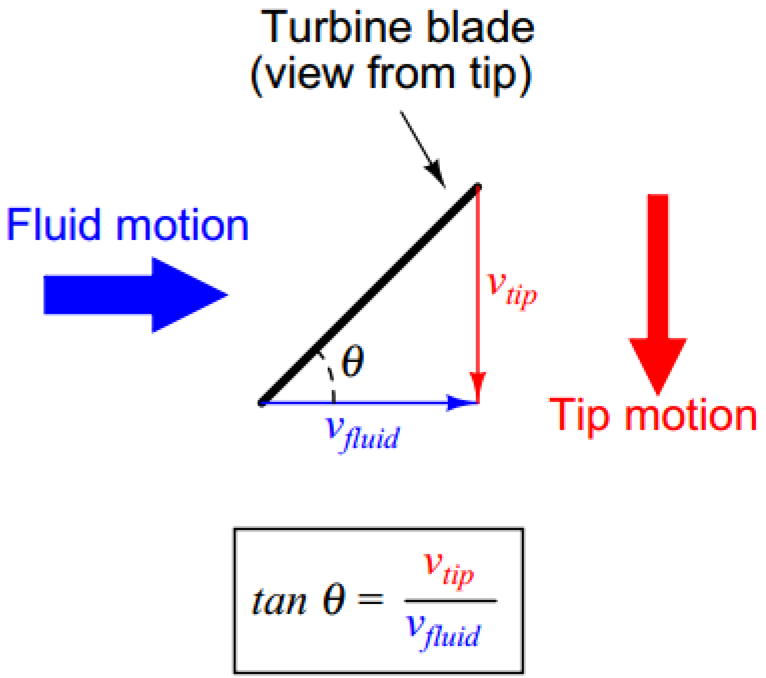




Flow Sensors

- **Turbine**

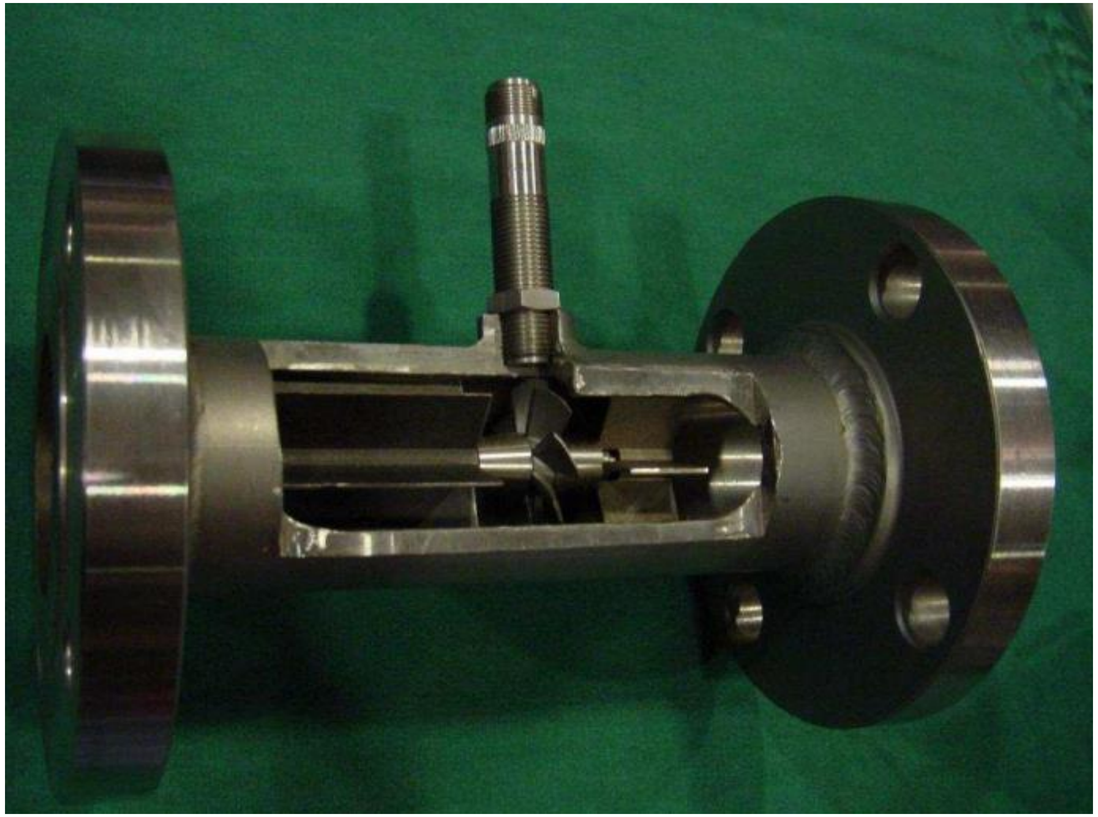




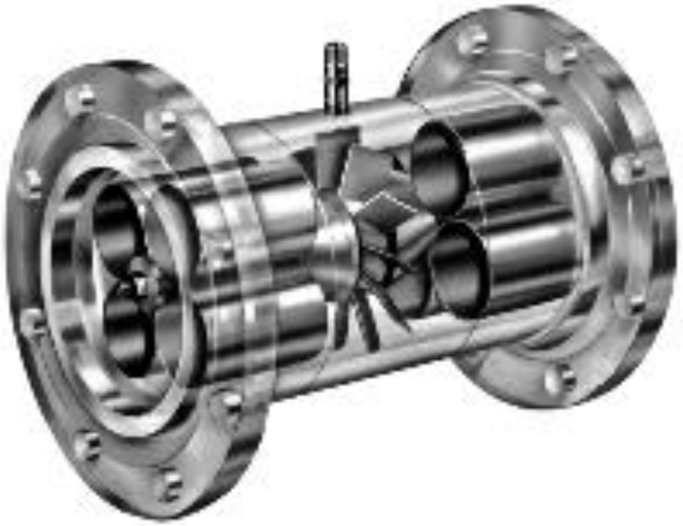
Flow Sensors

- **Turbine**

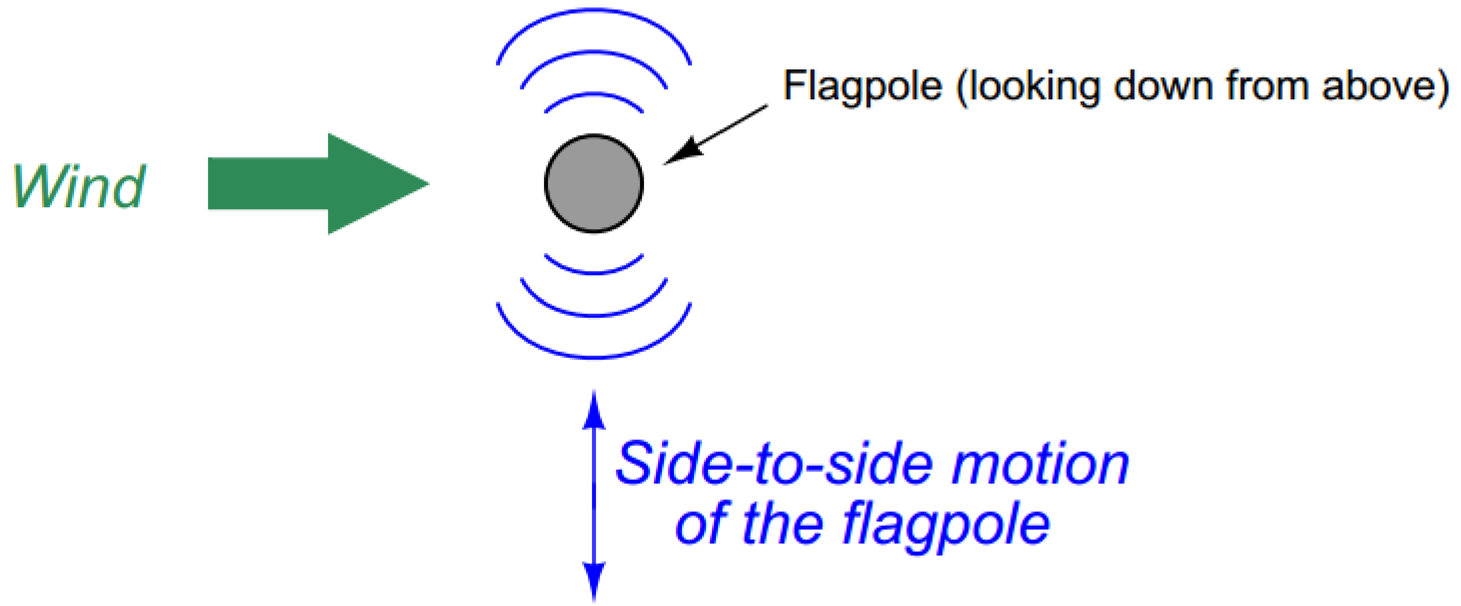
$$f = kQ$$



f = Frequency of output signal (Hz, equivalent to pulses per second)
Q = Volumetric flow rate (e.g. gallons per second)
k = "K" factor of the turbine element (e.g. pulses per gallon)

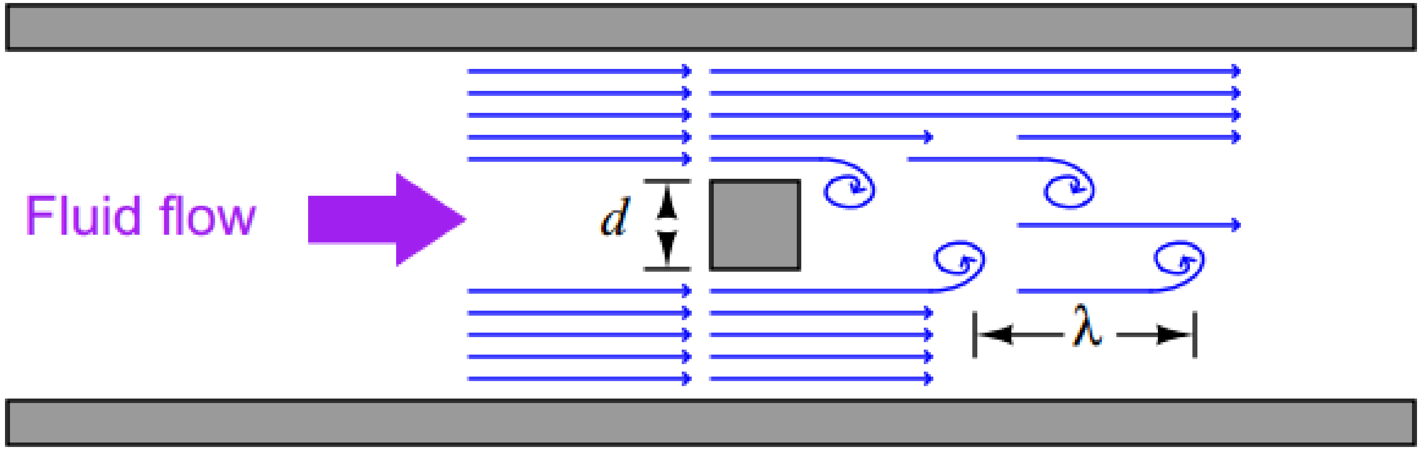


Vortex flowmeters



Vortex flowmeters

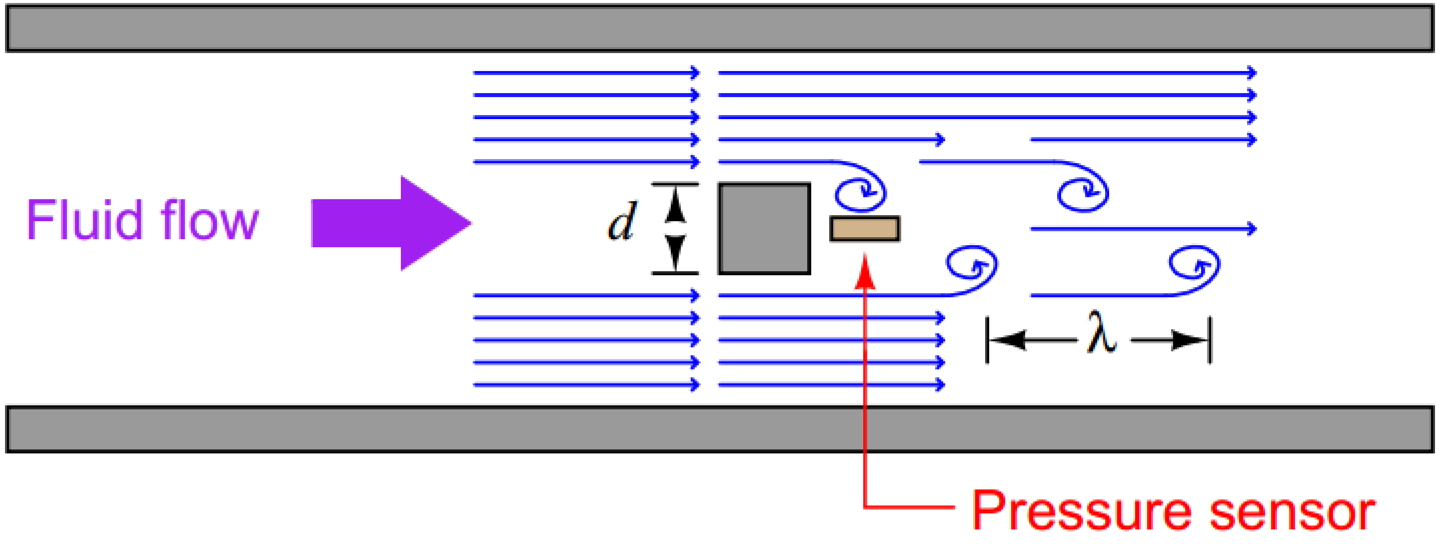
It was determined that the distance between **successive vortices** downstream of the stationary object is relatively constant, and directly **proportional to the width of the object**, for a **wide range of Reynolds number values**.



$$\lambda S = d \qquad \lambda \approx \frac{d}{0.17}$$

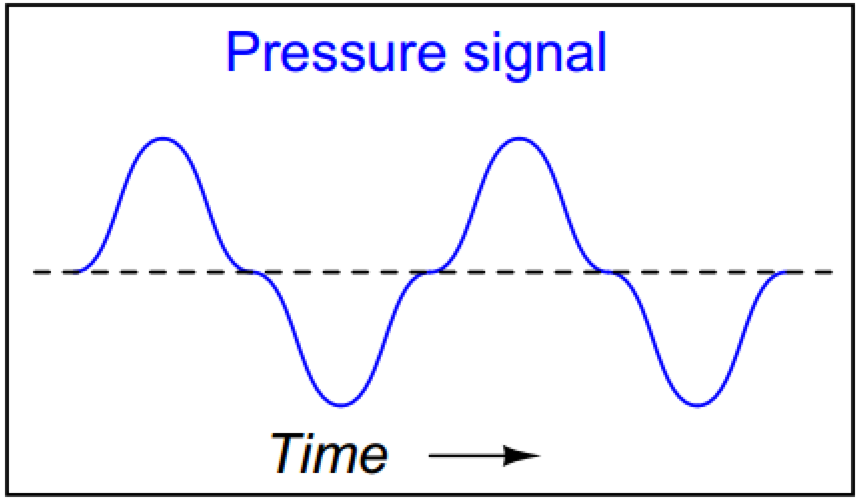
Strouhal number (S) approximately equal to 0.17

Vortex flowmeters



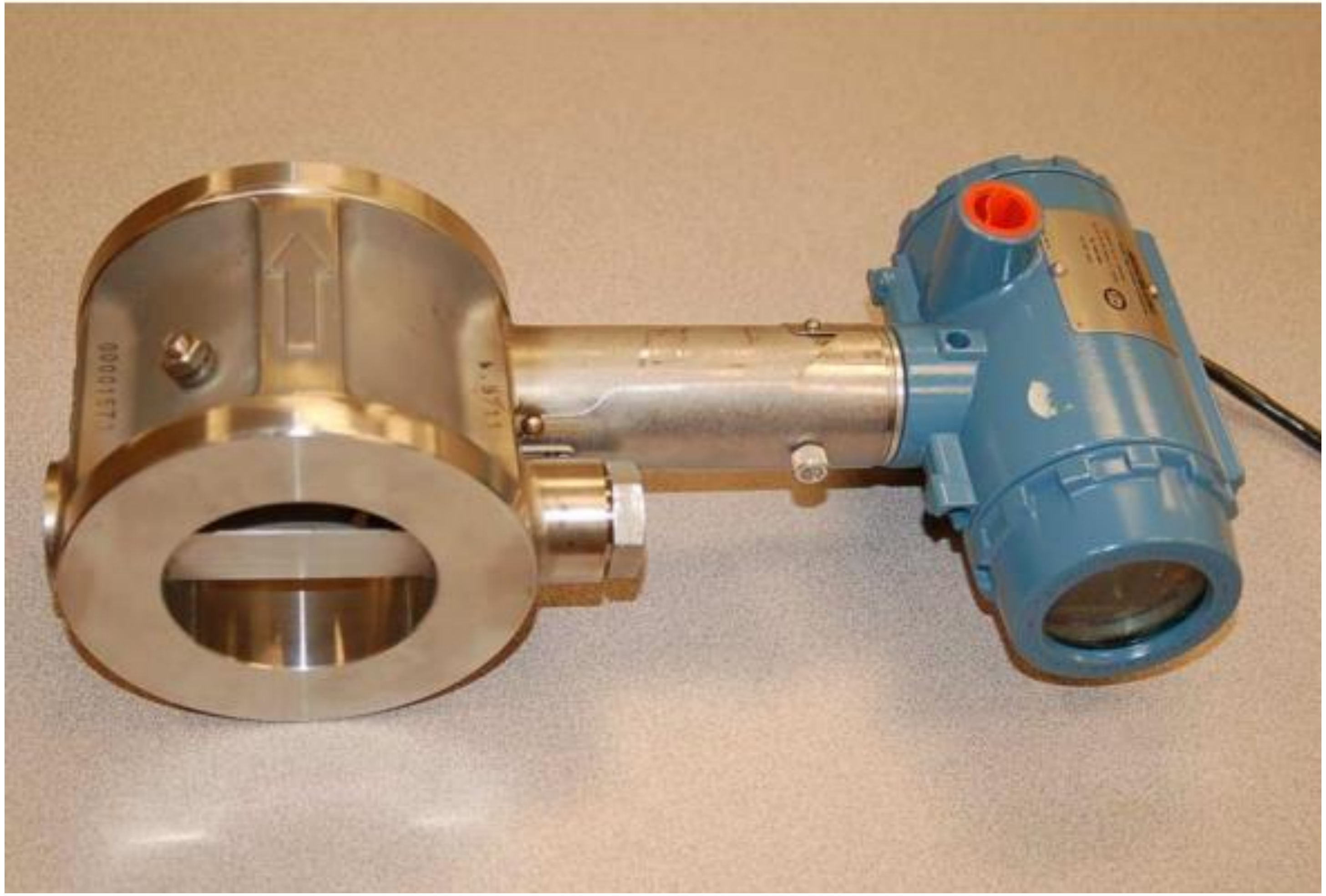
$$v = \lambda f$$

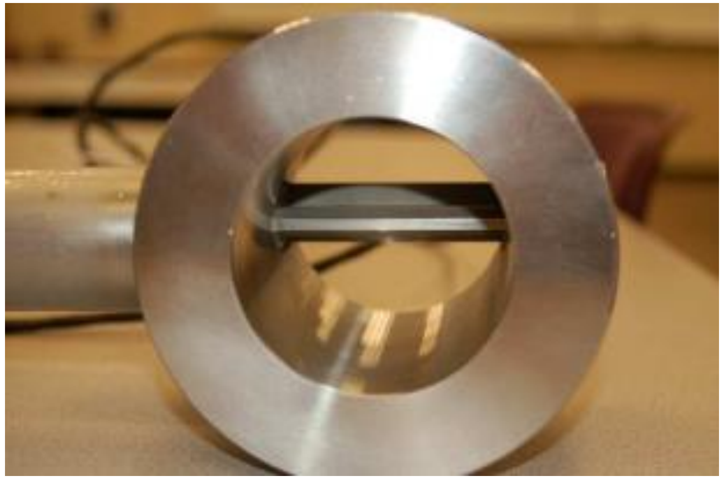
$$v = \frac{d}{0.17} f$$



$$f = kQ$$

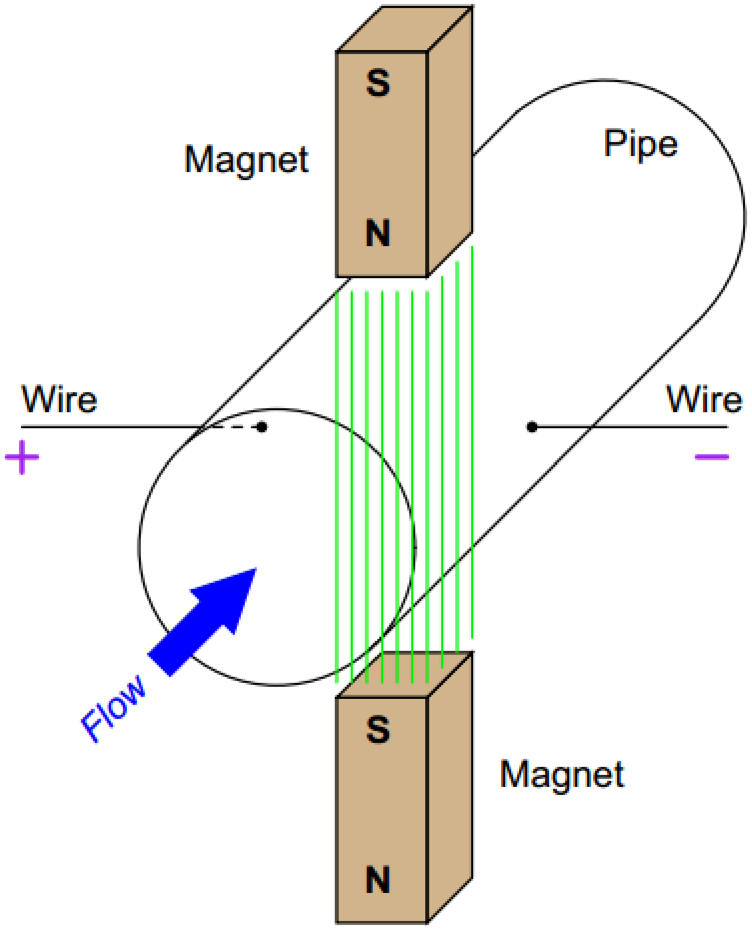
Vortex flowmeters



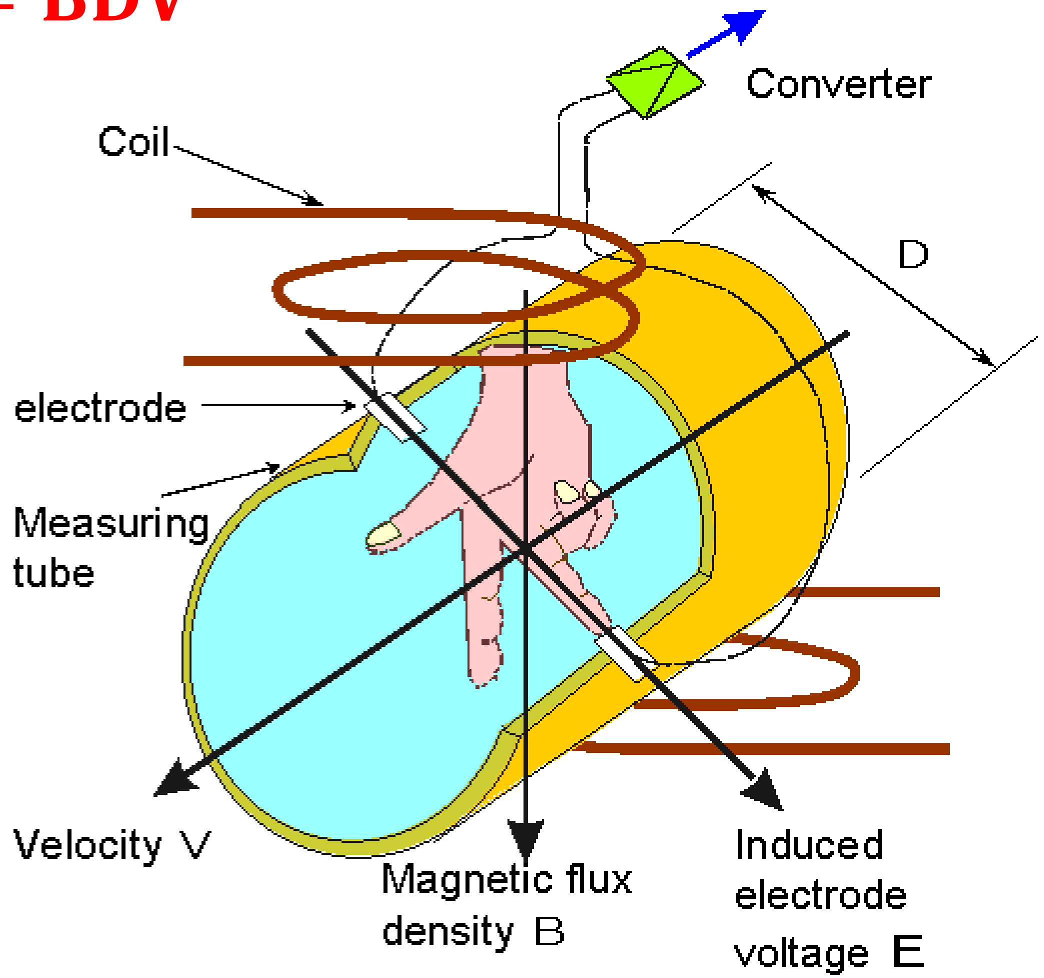


Flow Sensors

- **Magnetic**

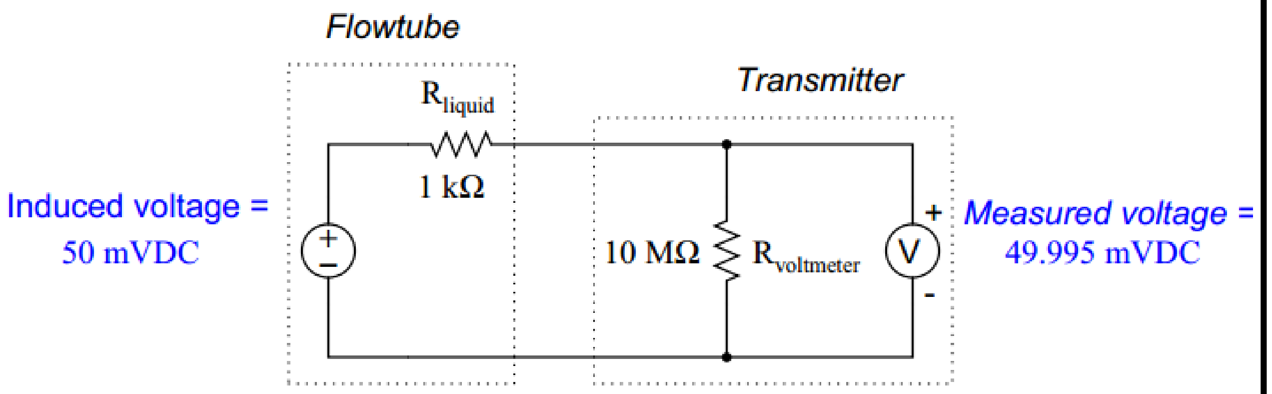


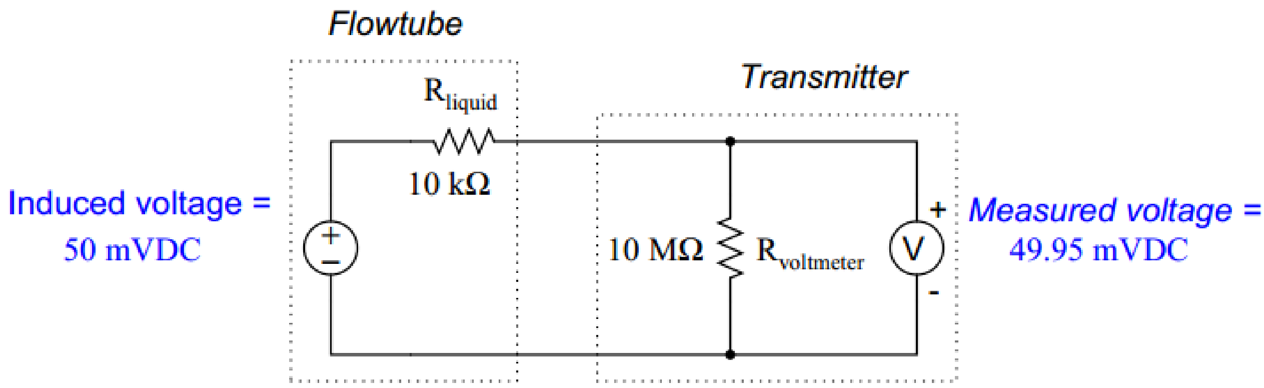
$$\mathbf{E = BDV}$$



Magnetic flowmeters

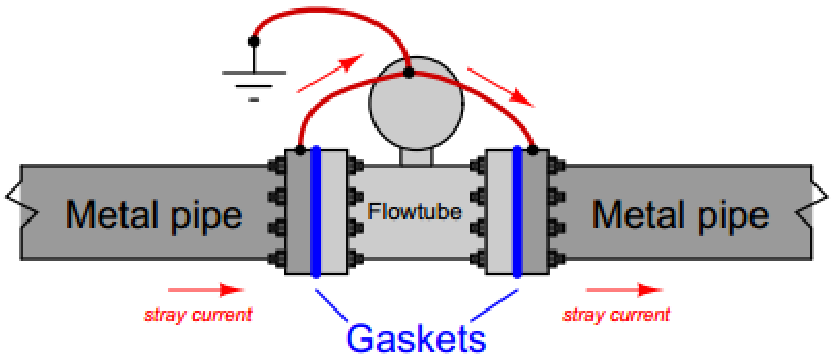
- The liquid must be a reasonably good conductor of electricity .





- The pipe must be completely filled with liquid to ensure contact with both probes as well as to ensure flow across the entire cross-section of the pipe.

- The flowtube must be properly grounded to avoid errors caused by stray electric currents in the liquid.



Flow Sensors

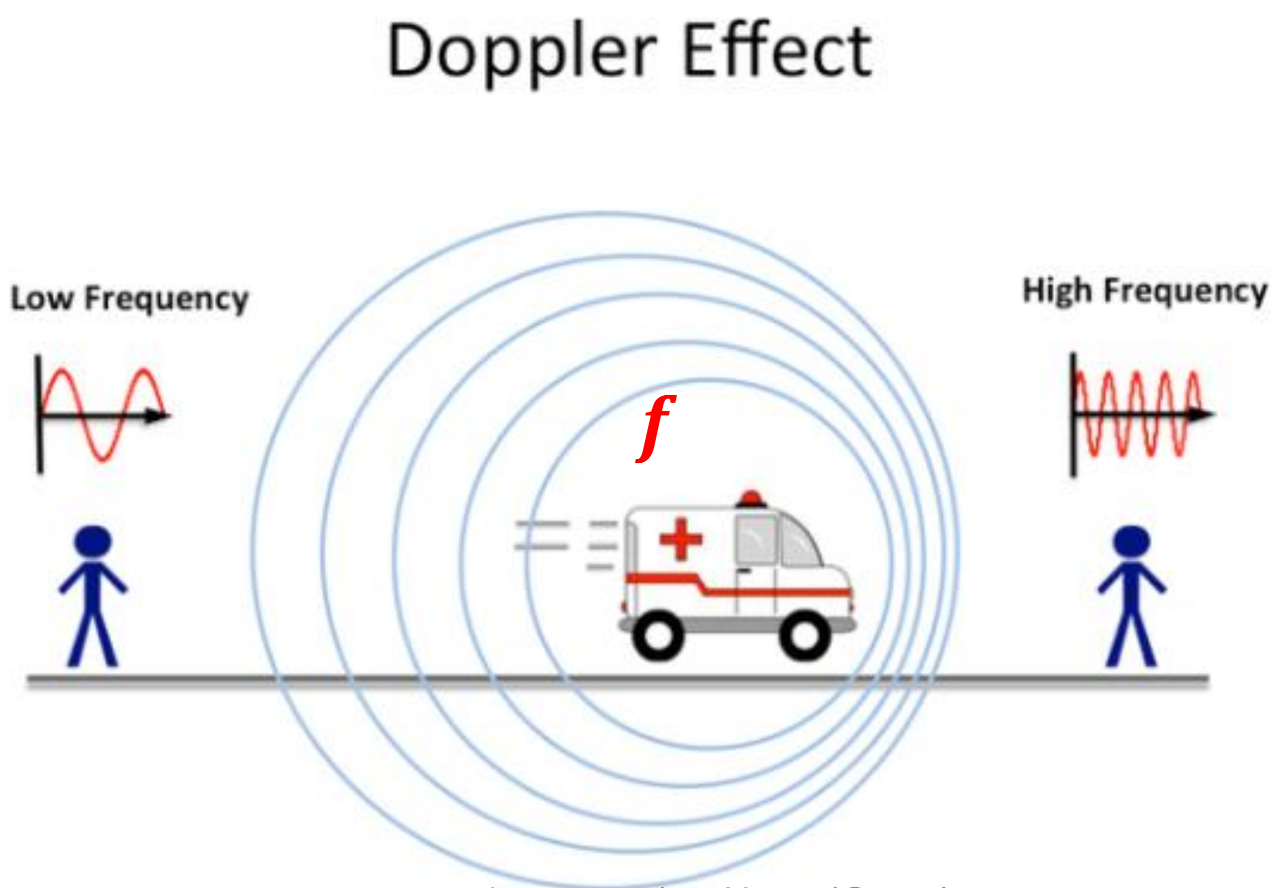
- **Magnetic**

Flow Sensors

- **Magnetic**

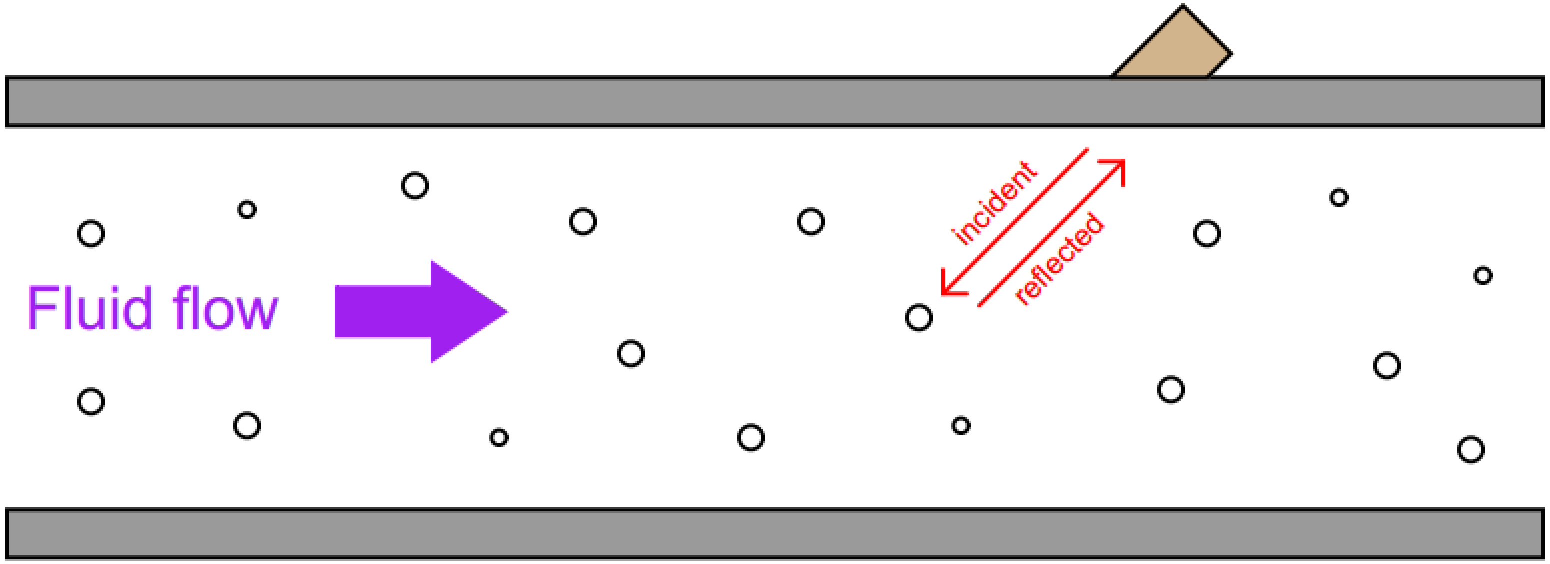
Flow Sensors

- **Doppler ultrasonic**



Flow Sensors

- **Doppler ultrasonic**



$$\Delta f = \frac{2vf\cos\theta}{c}$$

Δf = Doppler frequency shift
v = Velocity of fluid (actually, of the particle reflecting the sound wave)
f = Frequency of incident sound wave
θ = Angle between transducer and pipe centerlines
c = Speed of sound in the process fluid

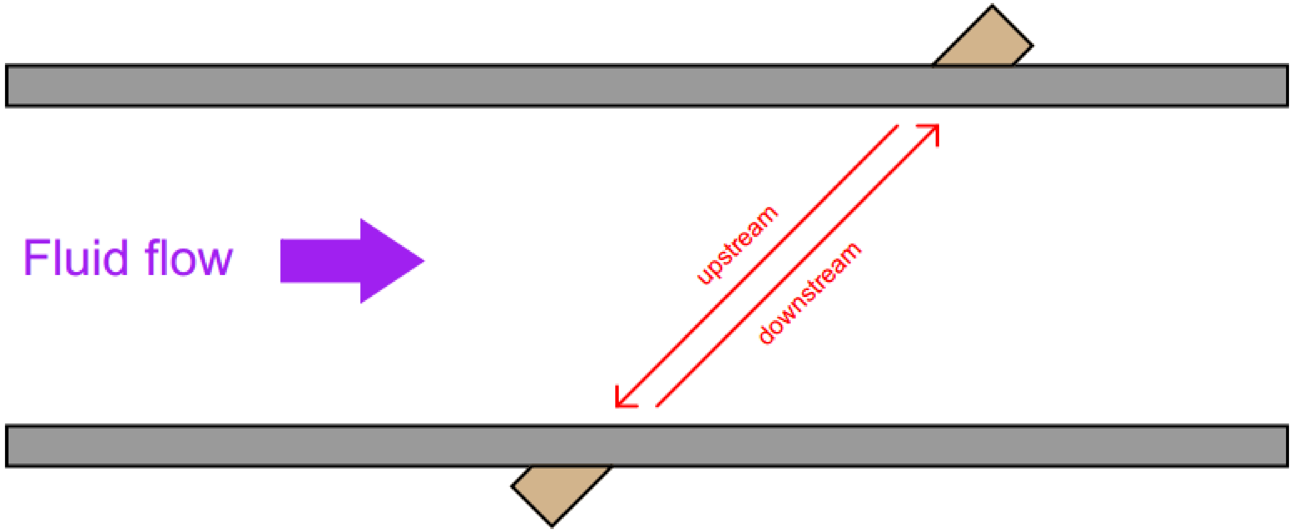
limitation of Doppler ultrasonic flowmeters is their inability to measure flow rates of liquids that are too clean and too homogeneous. In such applications, the sound-wave reflections will be too weak to reliably measure.

Ultrasonic flowmeters

Transit-time flowmeters

$$Q = k\frac{t_{up} - t_{down}}{(t_{up})(t_{down})}$$

?



Q = Calculated volumetric flow rate

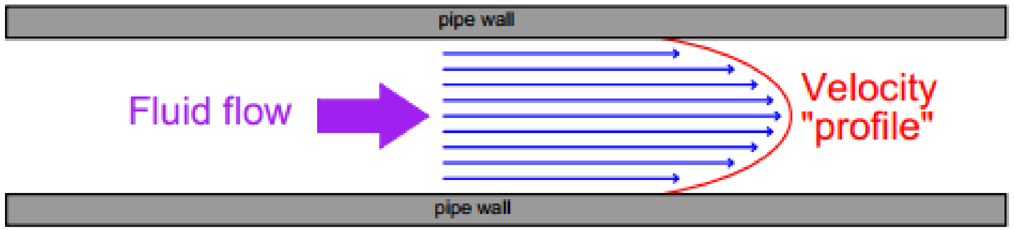
k = Constant of proportionality

t_{up} = Time for sound pulse to travel from downstream location to upstream location (upstream, against the flow)

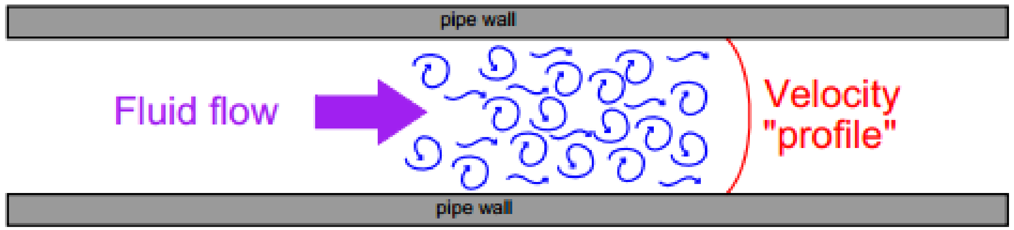
t_{down} = Time for sound pulse to travel from upstream location to downstream location (downstream, with the flow)

Ultrasonic flowmeters

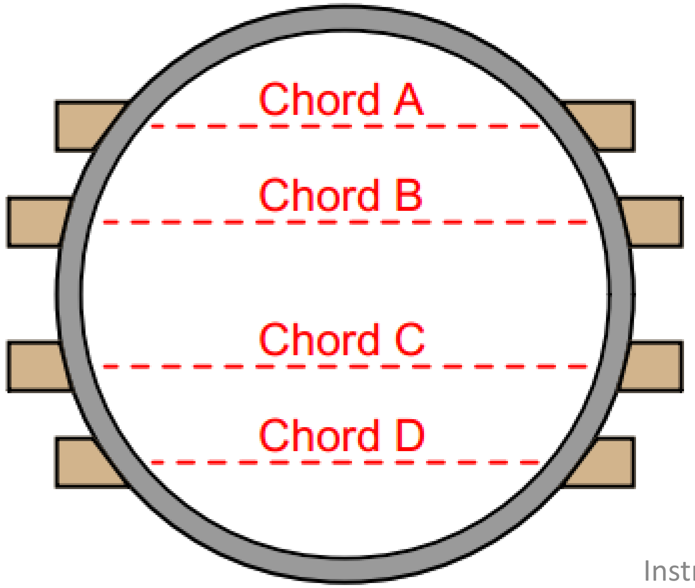
Laminar flow (low Re)



Turbulent flow (high Re)



Daniel 4-chord ultrasonic flowmeter

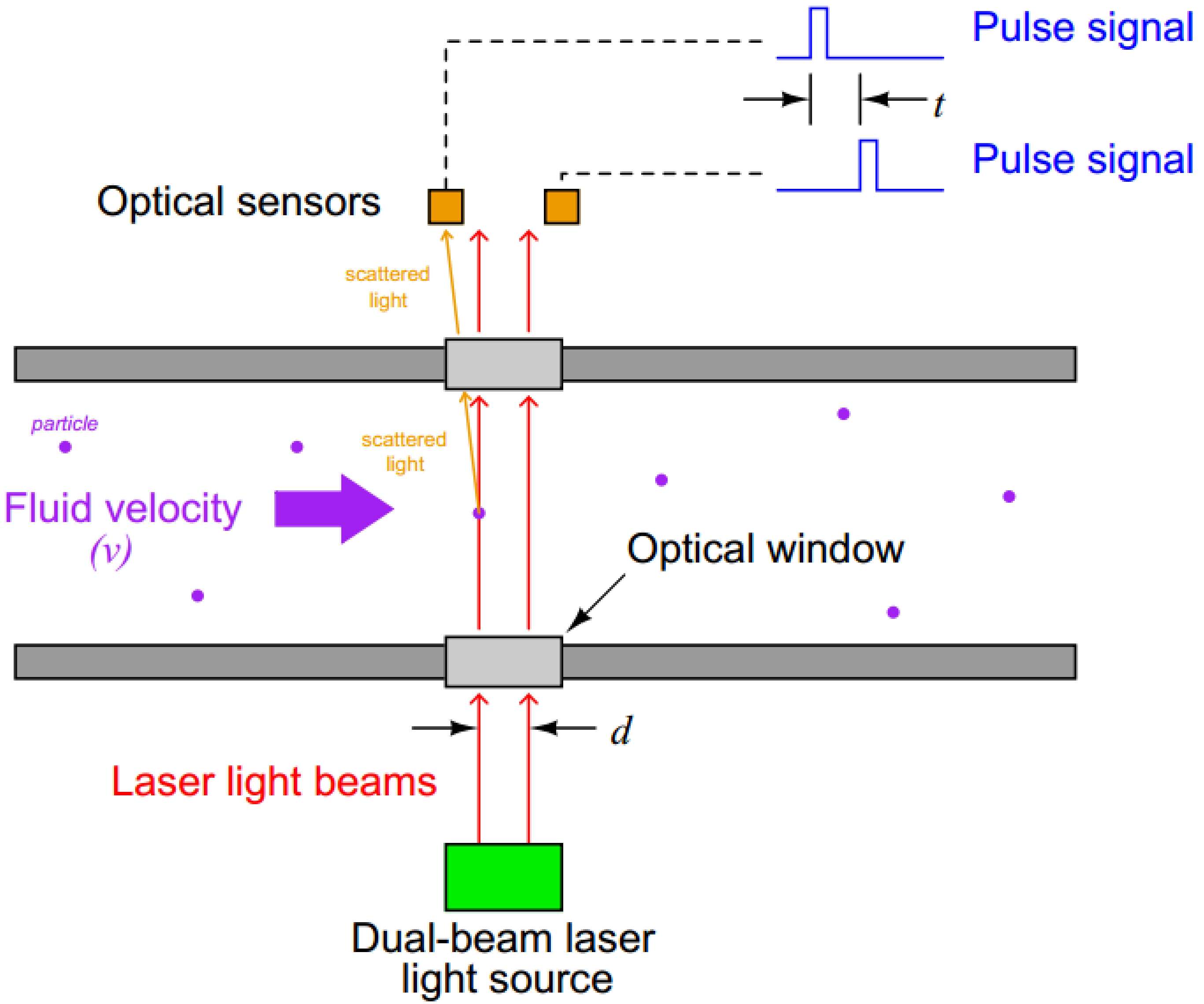


Optical flowmeters

Laser-Two-Focus (L2F)

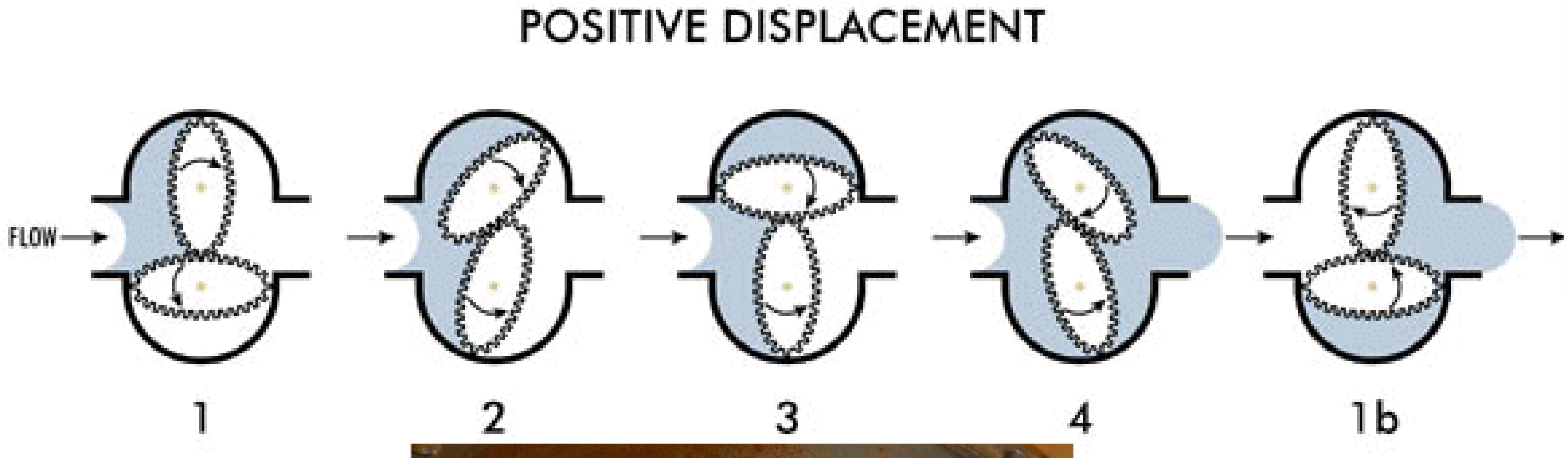
$$v = \frac{d}{t}$$

$v =$ Velocity of particle
$d =$ Distance separating laser beams
$t =$ Time difference between sensor pulses

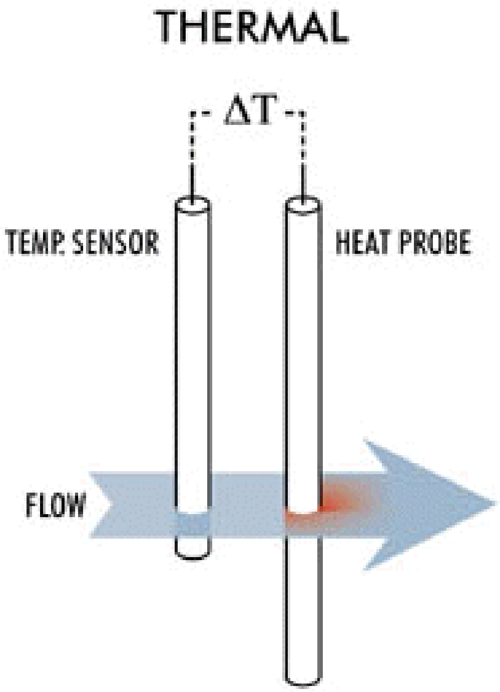


Positive displacement flow meter

A positive displacement flow meter is a cyclic mechanism built to pass a fixed volume of fluid through with every cycle



Thermal flowmeters



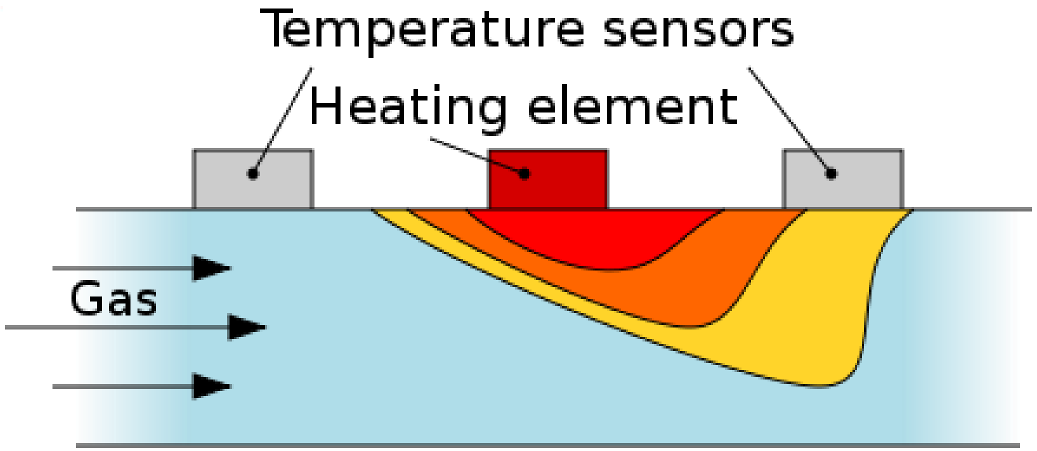
$$W = \frac{H}{\Delta T C_p}$$

where W = mass flow

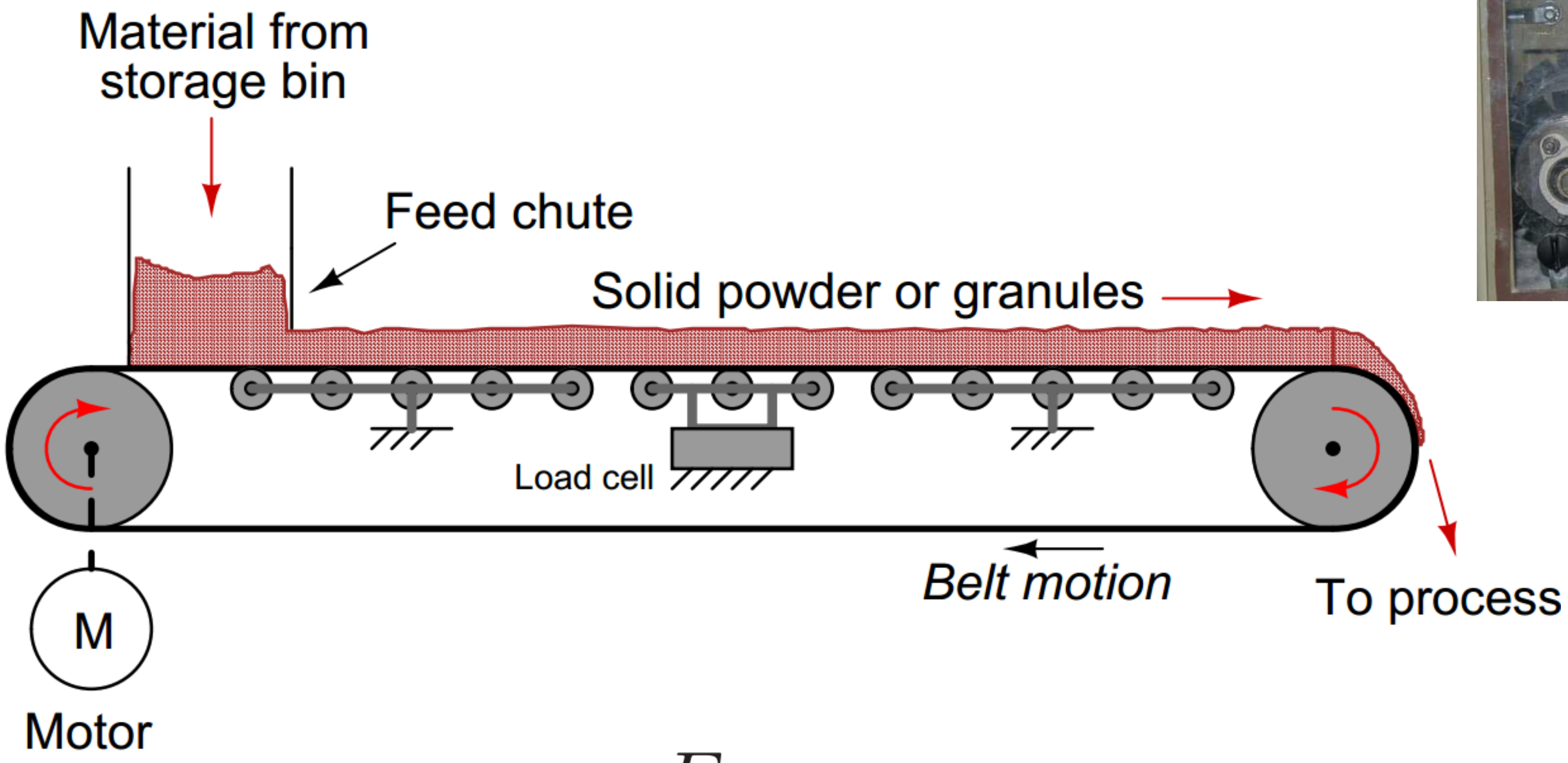
H = heat (power) input

ΔT = temperature change

Cp = specific heat at constant pressure



Weighfeeders



$$W = \frac{Fv}{d}$$

Change of quantity flow measurement