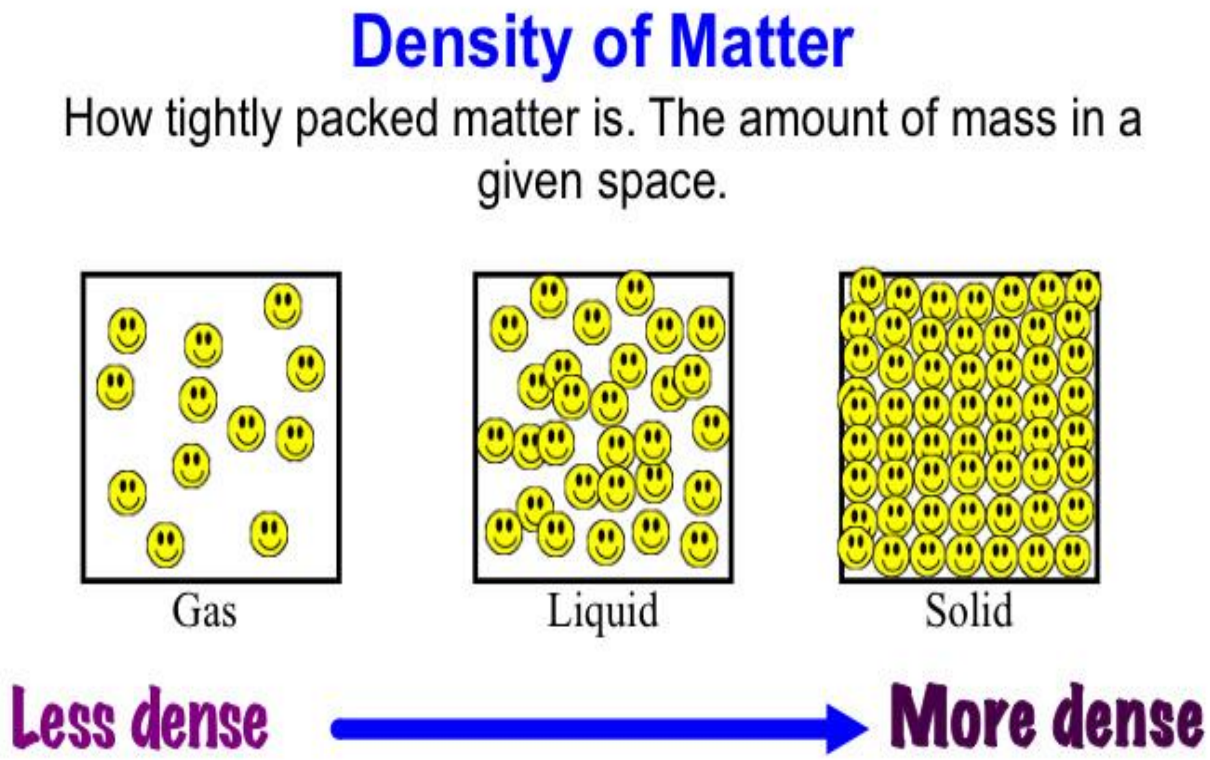
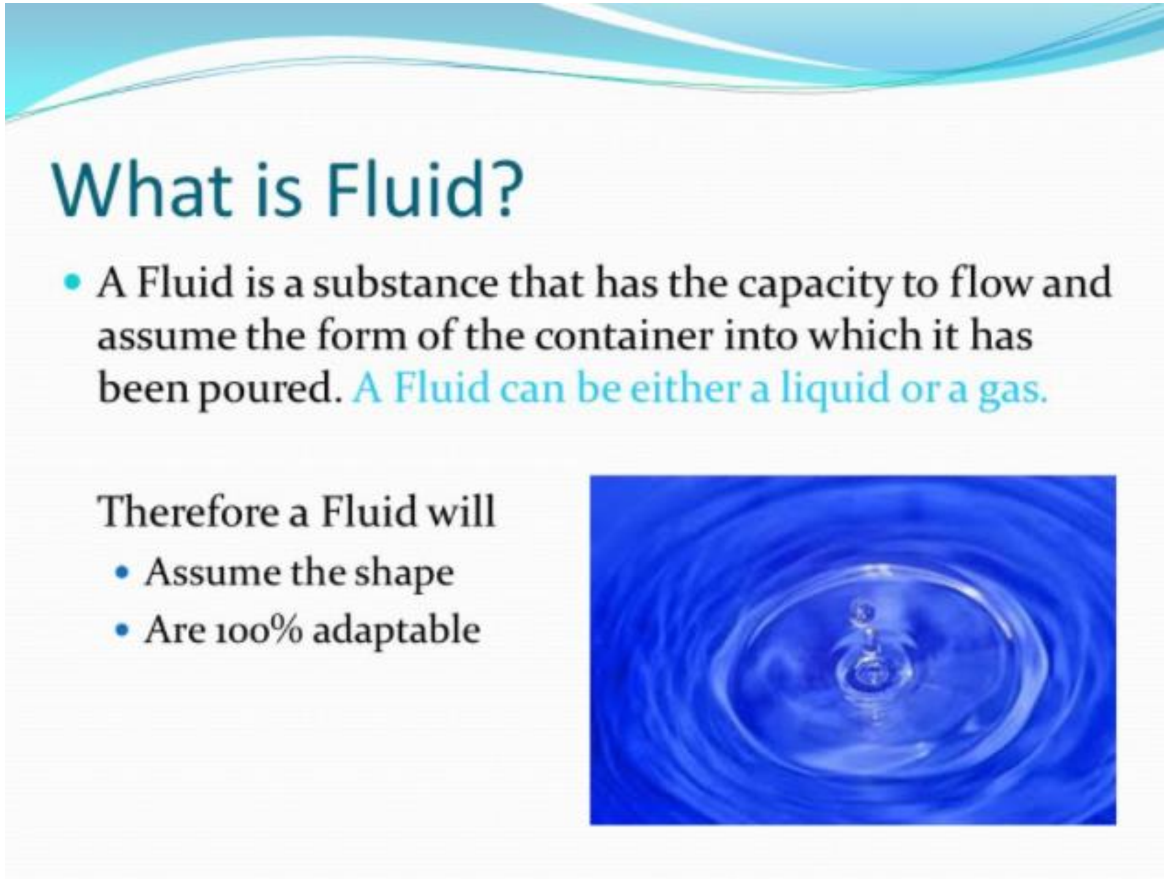
Flow measurement

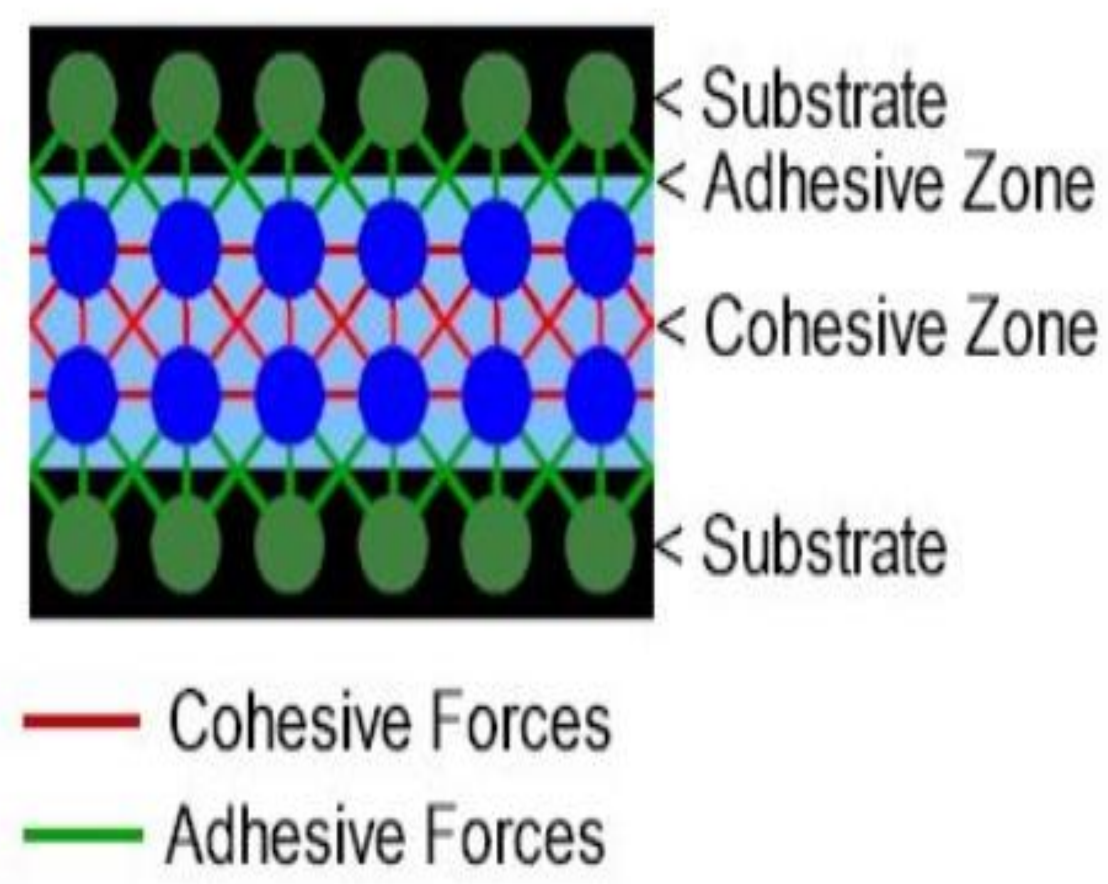

Density of Matter
How tightly packed matter is. The amount of mass in a given space.
Gas
Liquid
Solid
Less dense
More dense


What is Fluid?
A Fluid is a substance that has the capacity to flow and assume the form of the container into which it has been poured. A Fluid can be either a liquid or a gas.
Therefore a Fluid will
Assume the shape
Are 100% adaptable

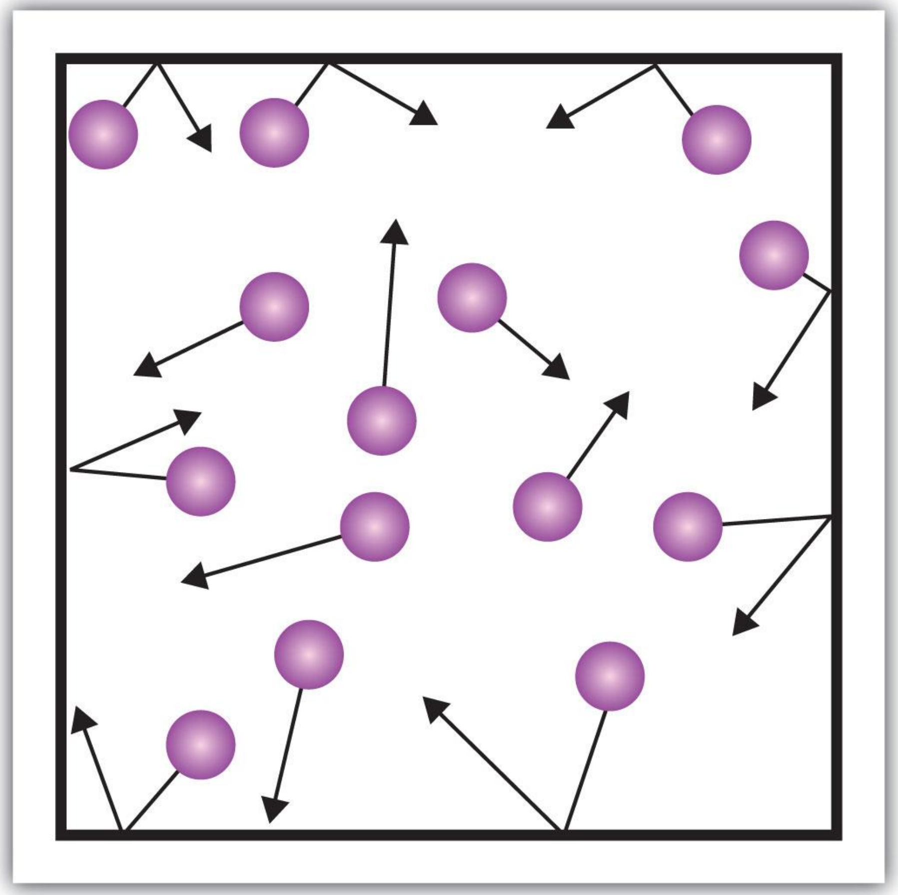
VISCOSITY

- exists in both liquids and gases
- a frictional force between adjacent layers of fluid as the layers move past one another.
- in liquids – due to the cohesive force
- in gases – arises from collisions between the molecules
- coefficient of viscosity, η (unit Poiseuille, P*l* or Pa.s)
- the more viscous the fluid, the greater is the required force.

$$F = \eta \frac{Av}{l}$$

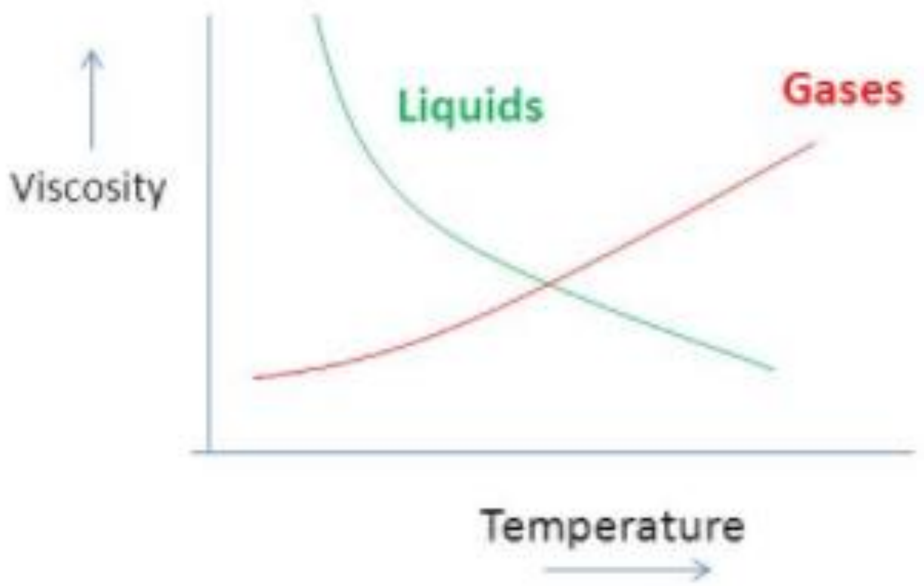


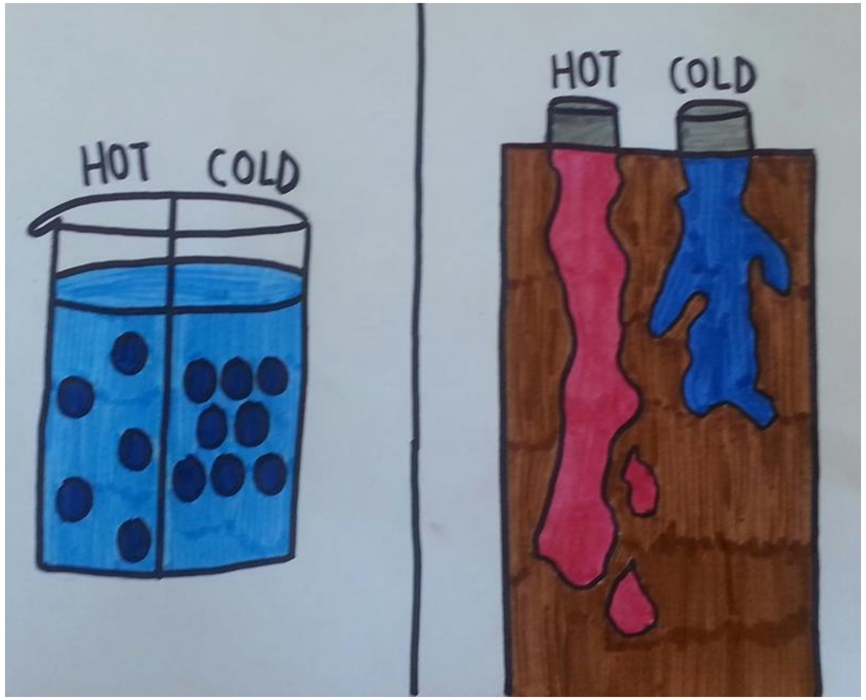
Liquid

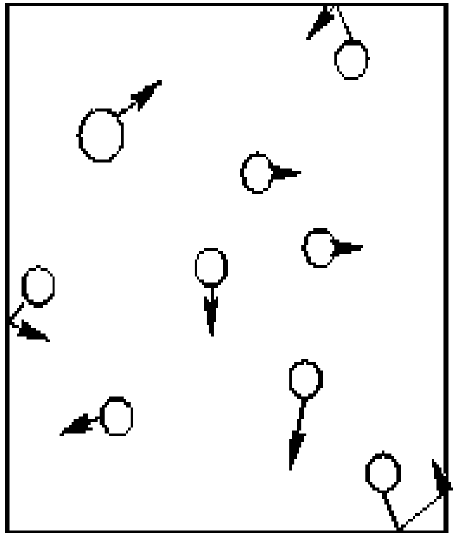


Gases

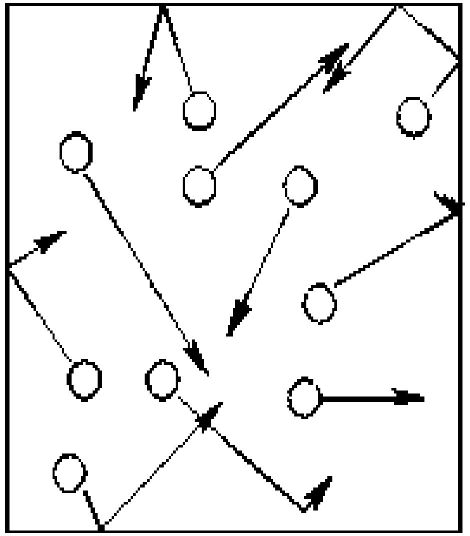
- In Liquids: **T** inversely related to Viscosity
- In Gases: **T** directly related to Viscosity







Cool gas, fewer and less energetic collisions



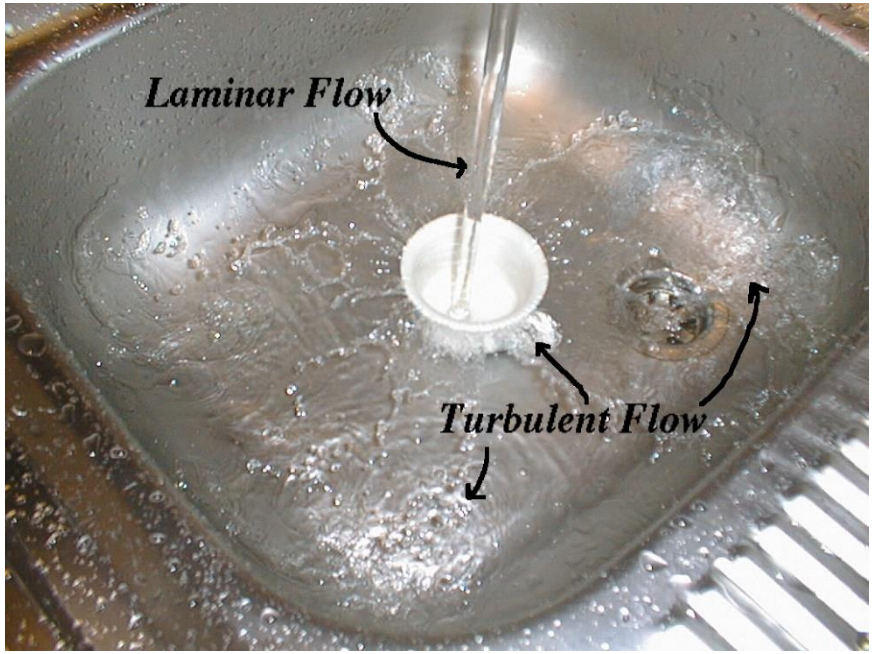
Hot gas, more and more energetic collision

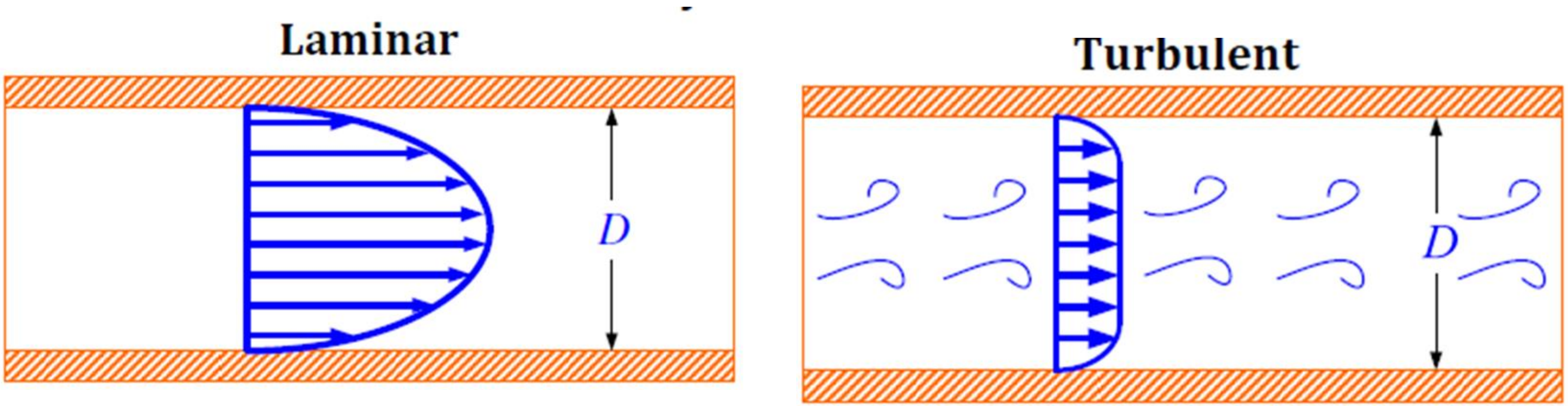
Flow characteristics

Two types of flows, namely

- ***Laminar* flows**
- ***Turbulent* flows.**

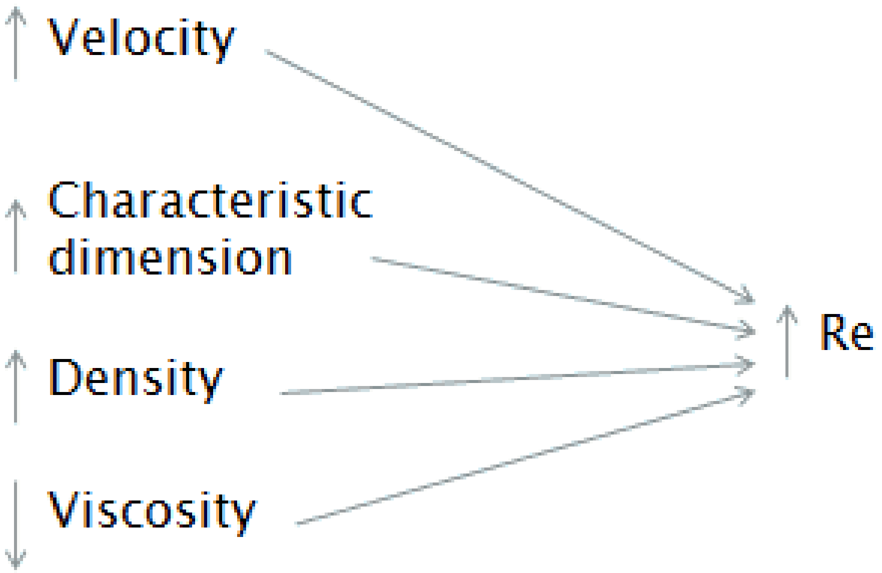
Roughly speaking we can say that a laminar flow is a 'simple' flow while a turbulent flow is a 'complicated' flow

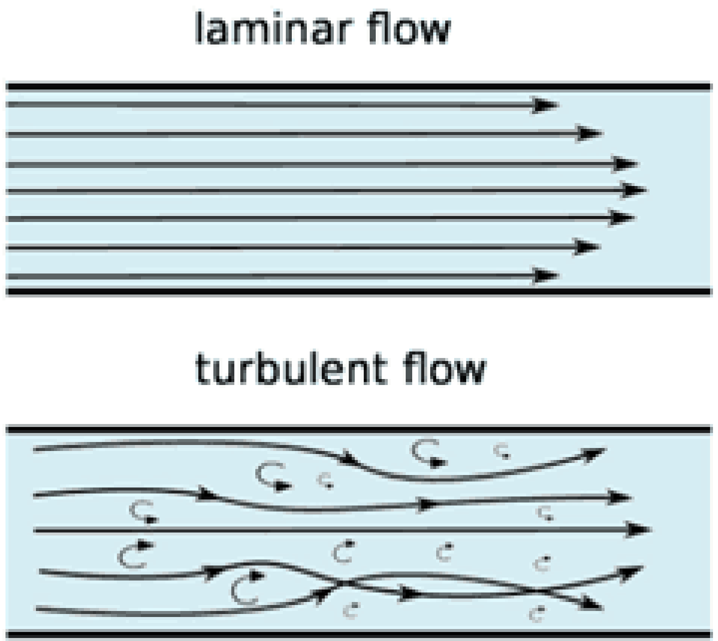


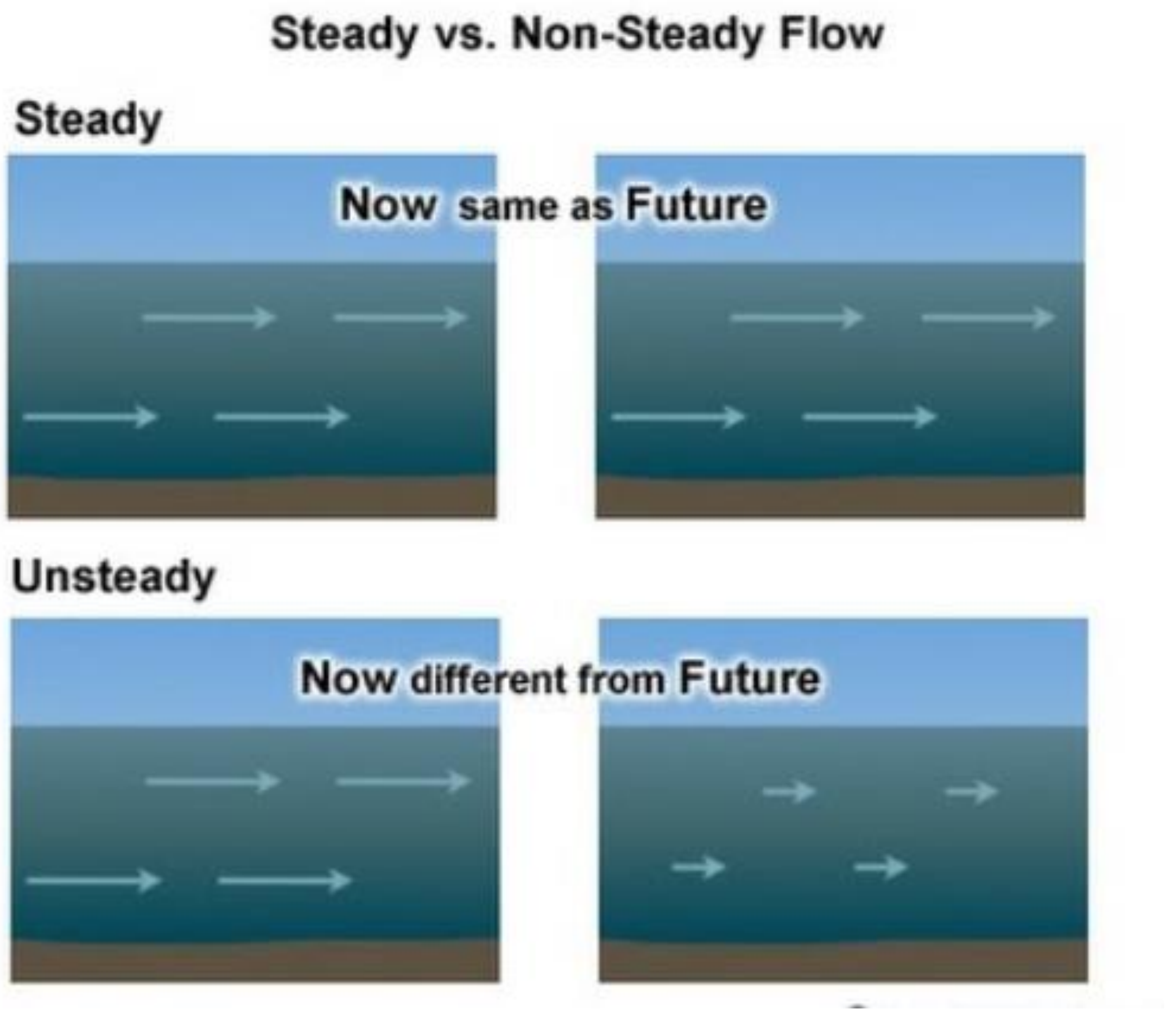

Laminar
D
Turbulent
D

Reynolds number

$$Re = \frac{\text{inertia forces}}{\text{viscous forces}} = \frac{\rho \,.\, V \,.\, D}{\mu}$$





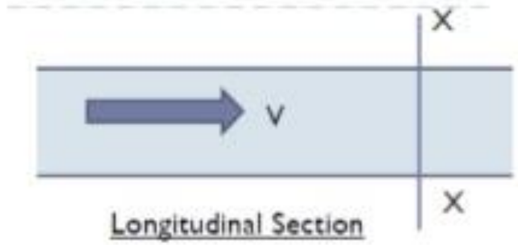

Steady vs. Non-Steady Flow
Steady
Now same as Future
Unsteady
Now different from Future

Uniform and Non-uniform flow

✓ **Uniform flow:**

❖ The flow in which velocity at a given time does not change with respect to space (length of direction of flow) is called as uniform flow.

❖ e.g. Constant discharge though a constant diameter pipe.



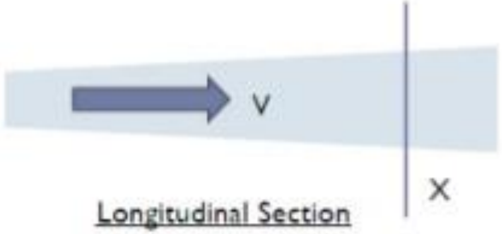
Longitudinal Section

$$\frac{\partial V}{\partial x} = 0; \Rightarrow V = contt$$

✓ **Non – Uniform flow :**

❖ The flow in which velocity at a given time changes with respect to space (length of direction of flow) is called as non – uniform flow.

❖ e.g., Constant discharge through variable diameter pipe.

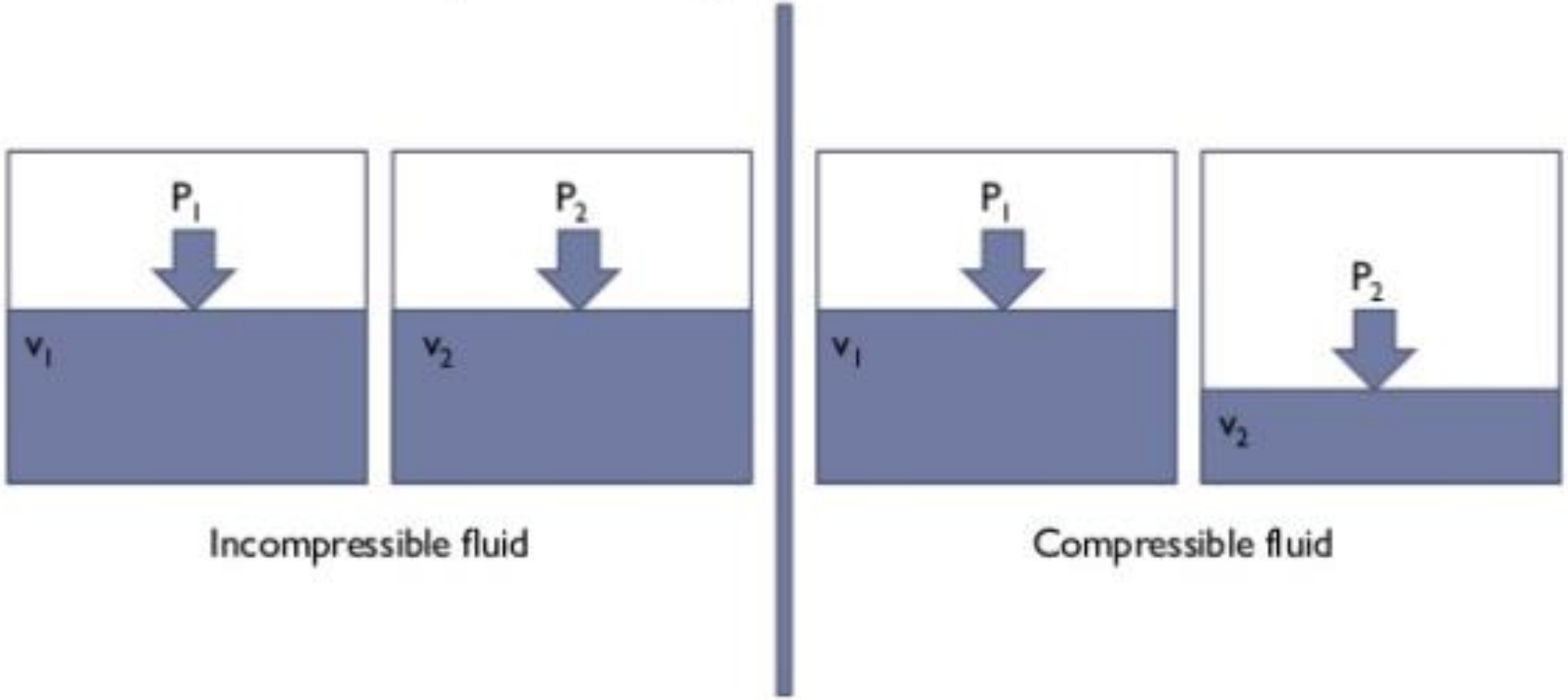


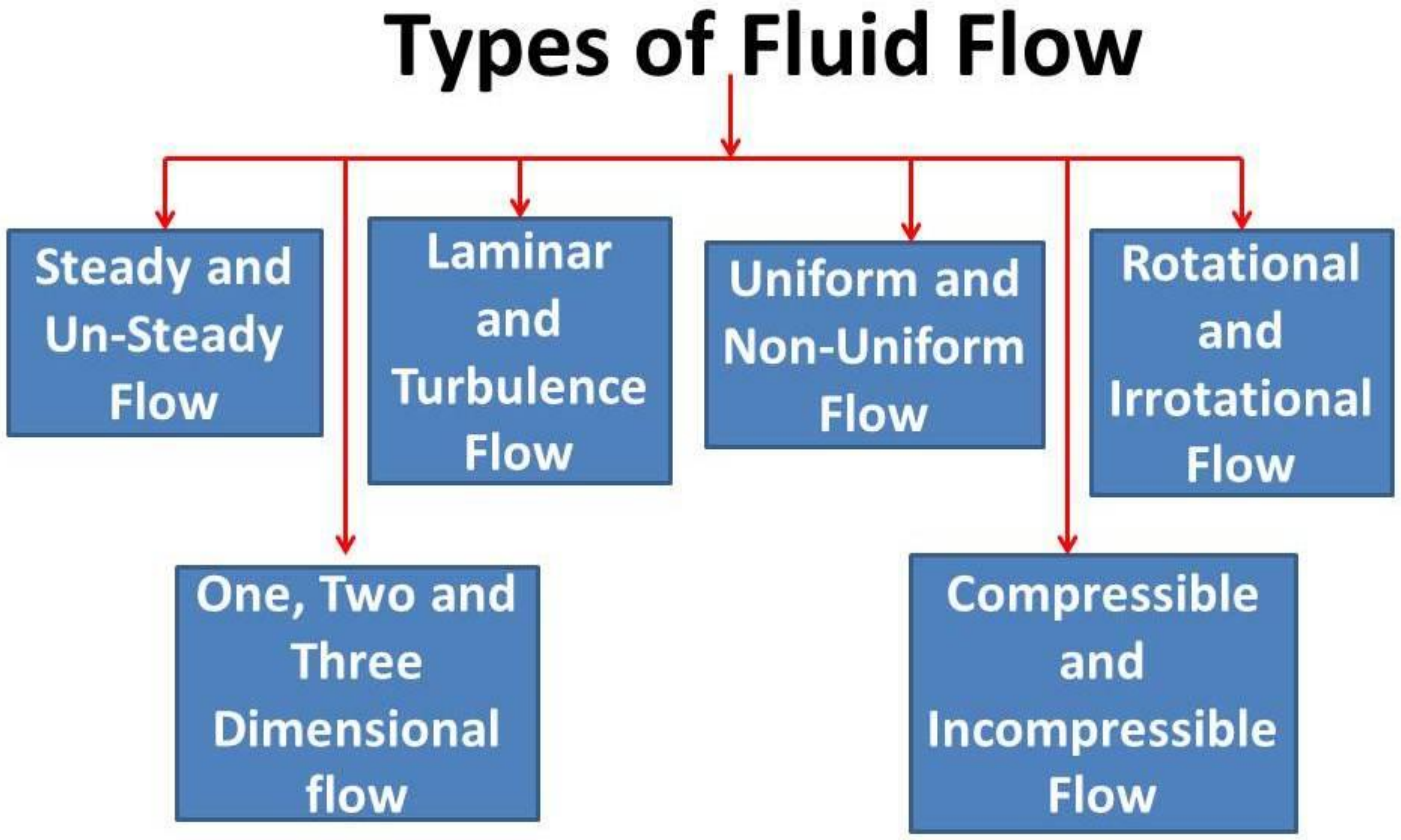
Longitudinal Section

$$\frac{\partial V}{\partial x} \neq 0; \Rightarrow V = \text{variable}$$

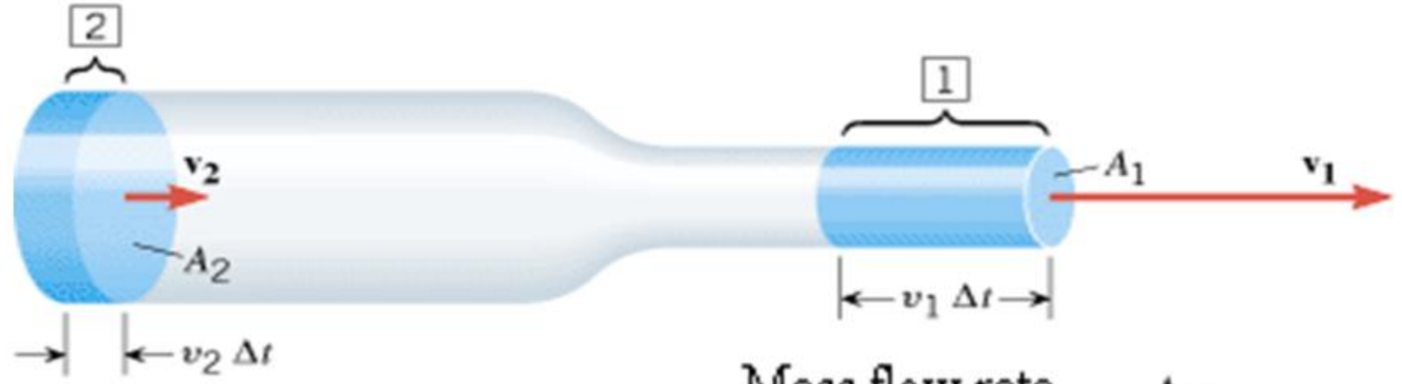
Compressible and incompressible flows

- Incompressible fluid flows assumes the fluid have constant density while in compressible fluid flows density is variable and becomes function of temperature and pressure.




Types of Fluid Flow
Steady and Un-Steady Flow
Laminar and Turbulence Flow
Uniform and Non-Uniform Flow
Rotational and Irrotational Flow
One, Two and Three Dimensional flow
Compressible and Incompressible Flow

Equation of Continuity

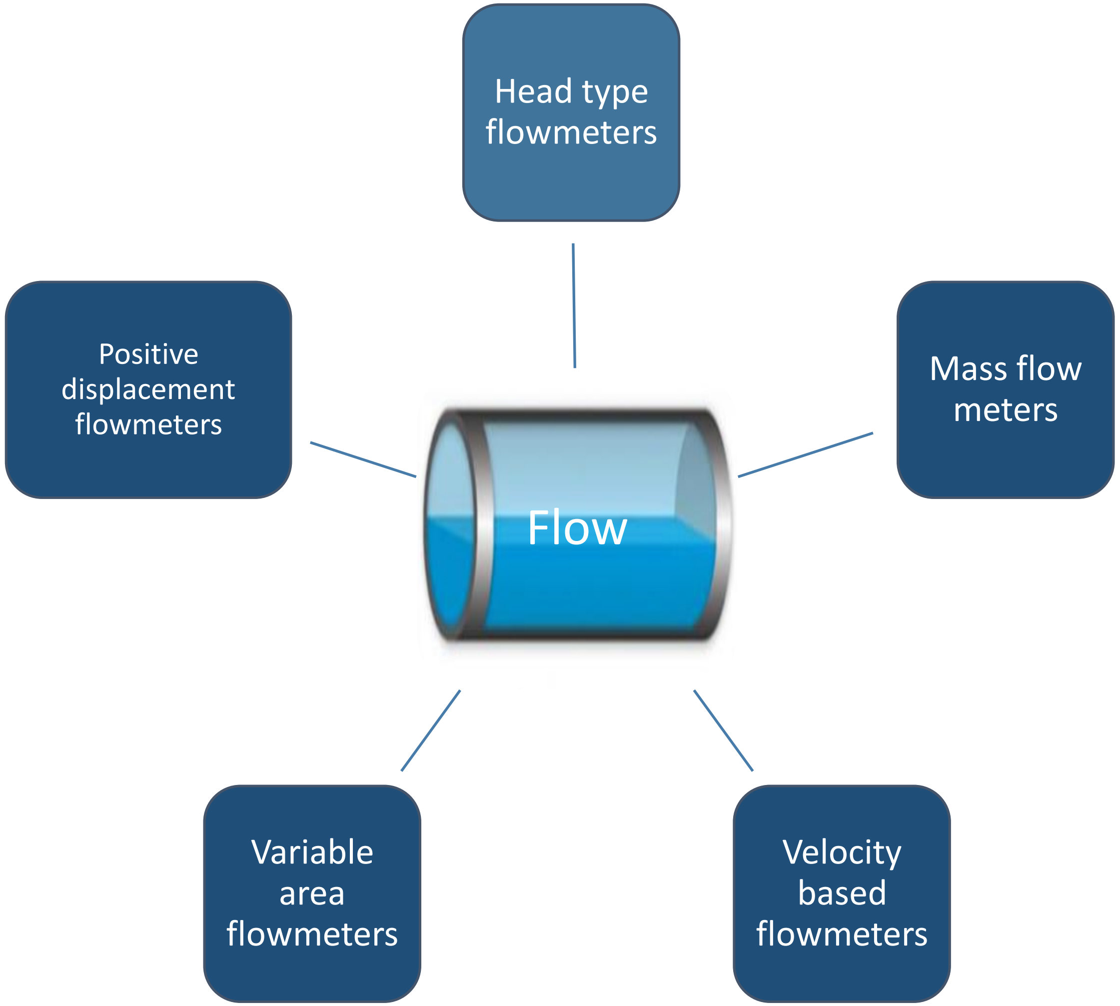


Mass flow rate at position 1 $= \frac{\Delta m_1}{\Delta t} = \rho_1 A_1 v_1$

Mass flow rate at position 2 $= \frac{\Delta m_2}{\Delta t} = \rho_2 A_2 v_2$

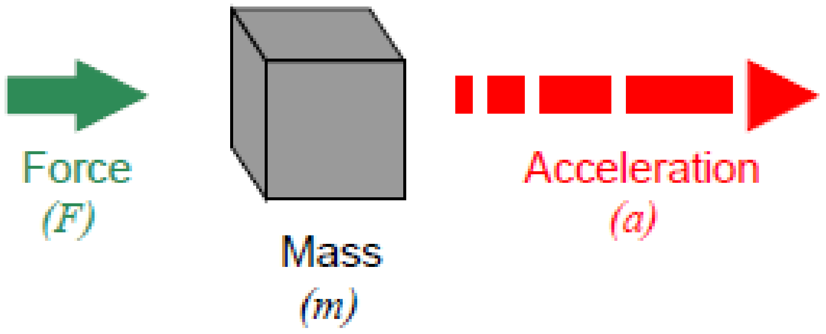
$$\rho_1 A_1 v_1 = \rho_2 A_2 v_2$$

Flow meters


Head type flowmeters
Positive displacement flowmeters
Mass flow meters
Flow
Variable area flowmeters
Velocity based flowmeters

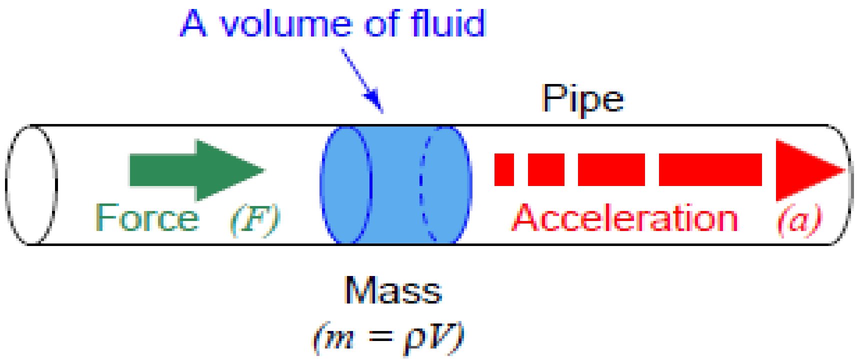
Pressure based flowmeter/Head type flowmeters

Pressure based flowmeters



Newton's Second Law formula

$F = ma$



Newton's Second Law formula

$F = ma$ $F = \rho V a$

$$F = \rho V a$$

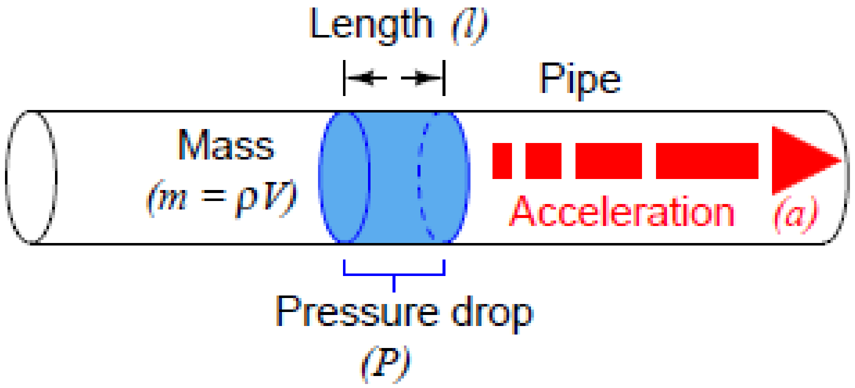
$$\frac{F}{A} = \rho \frac{V}{A} a$$

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

$$P = \rho l a$$

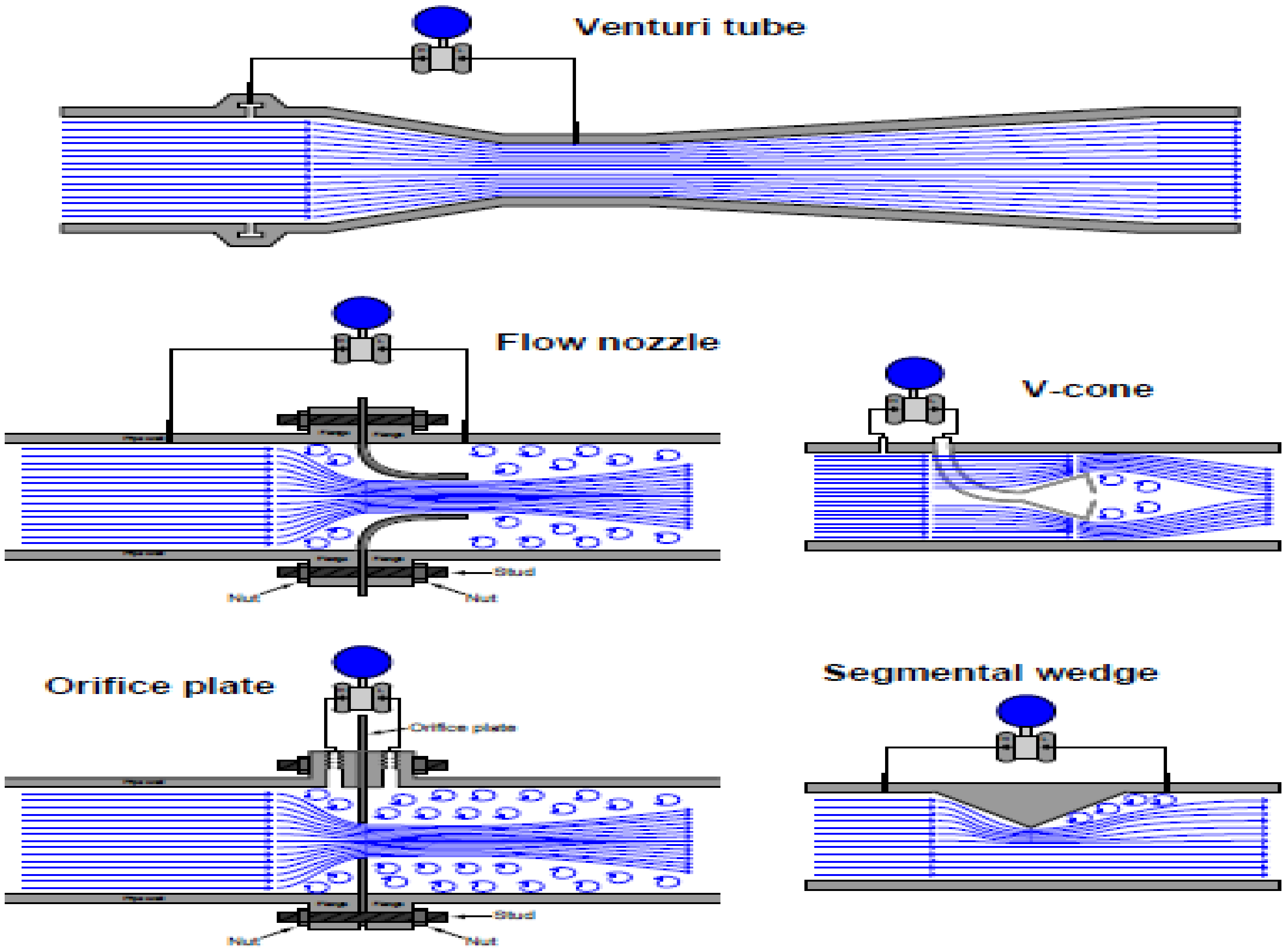
$$P = \rho l a$$

The pressure described by the equation is actually a differential pressure drop from one side of the fluid mass to the other, with the length variable (l) describing the spacing between the differential pressure ports

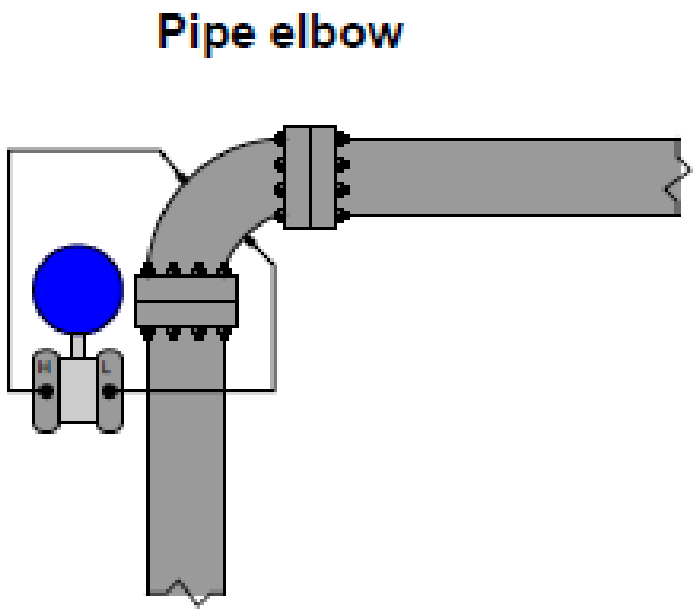


we can accelerate a “plug” of fluid by applying a difference of pressure across its length. The amount of pressure we apply will be in direct proportion to the density of the fluid and its rate of acceleration. Conversely, **we may measure a fluid’s rate of acceleration by measuring the pressure developed across a distance over which it accelerates**.

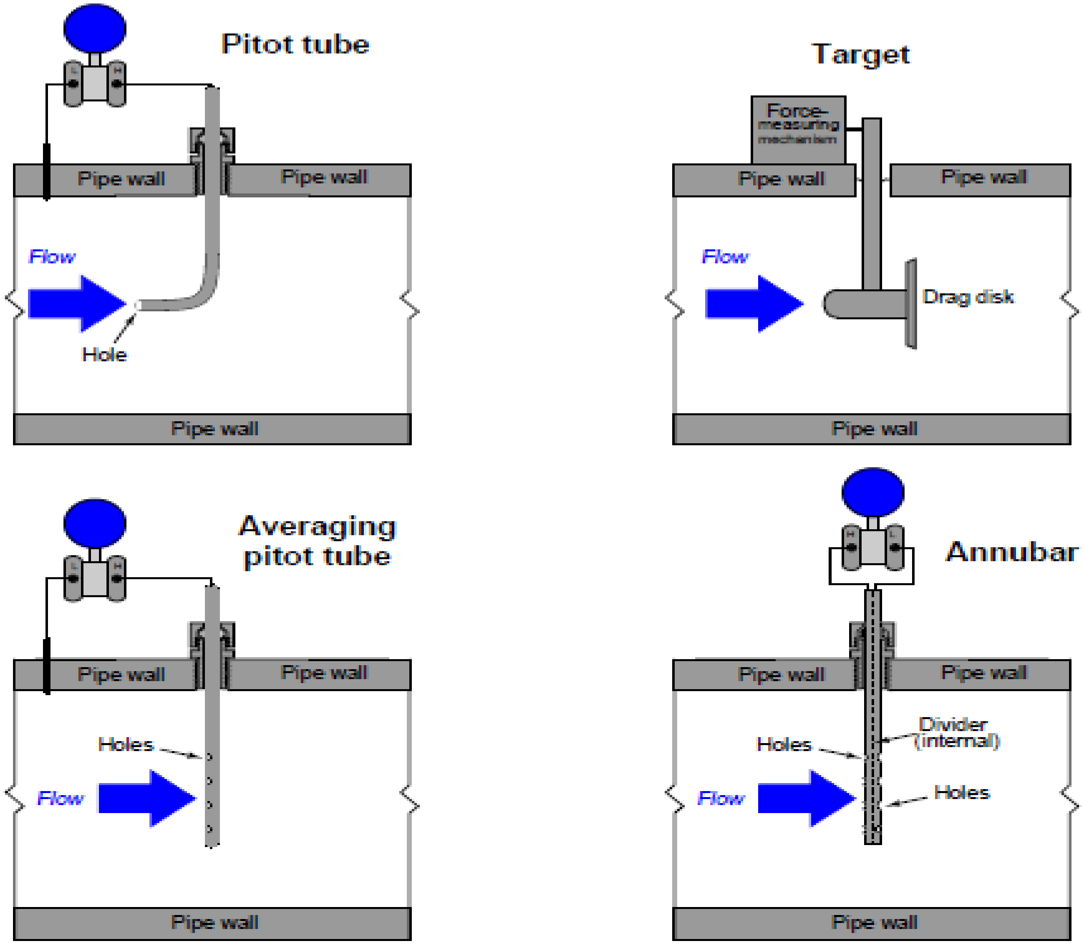
To cause **linear acceleration** in a moving fluid is to pass the fluid through a **constriction in the pipe**, thereby increasing its velocity (remember that the definition of acceleration is a change in velocity).



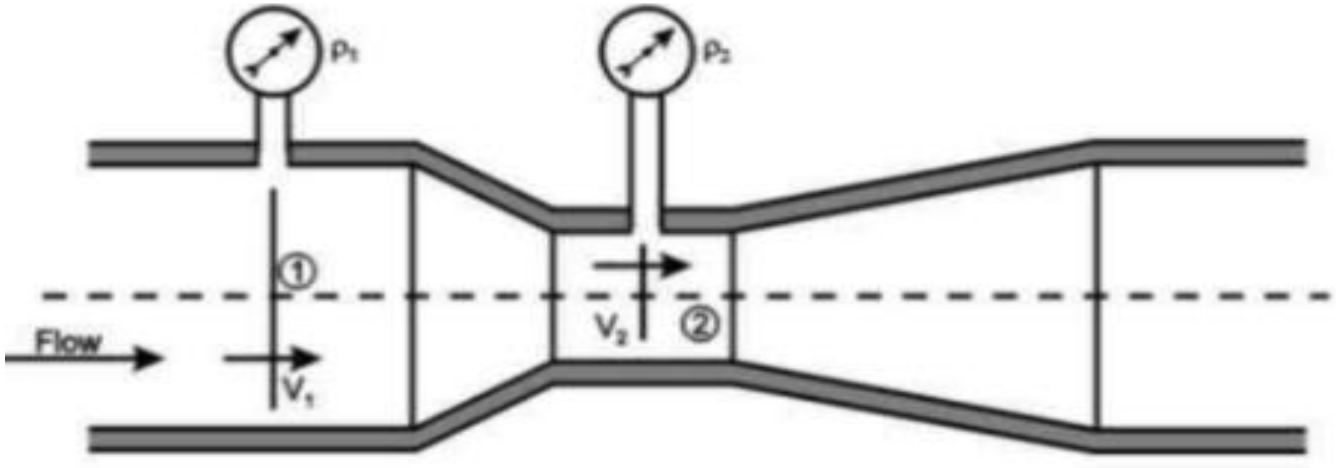
Accelerate a fluid is to force it to **turn a corner through a pipe** fitting called an elbow. This will generate radial acceleration, causing a pressure difference between the outside and inside of the elbow which may be measured by a differential pressure transmitter

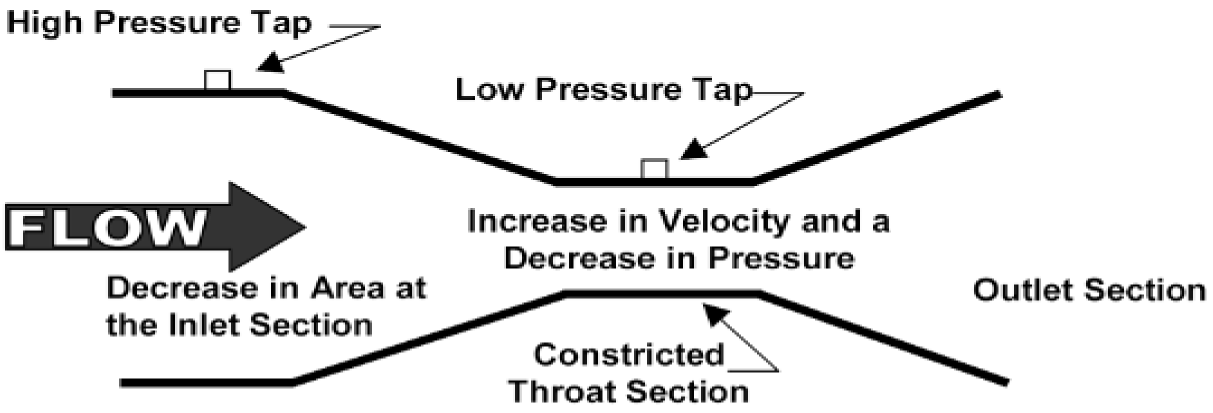


A change in fluid velocity is to **force it to decelerate by bringing a portion of it to a full stop**. The pressure generated by this deceleration (called the stagnation pressure) tells us how fast it was originally flowing.

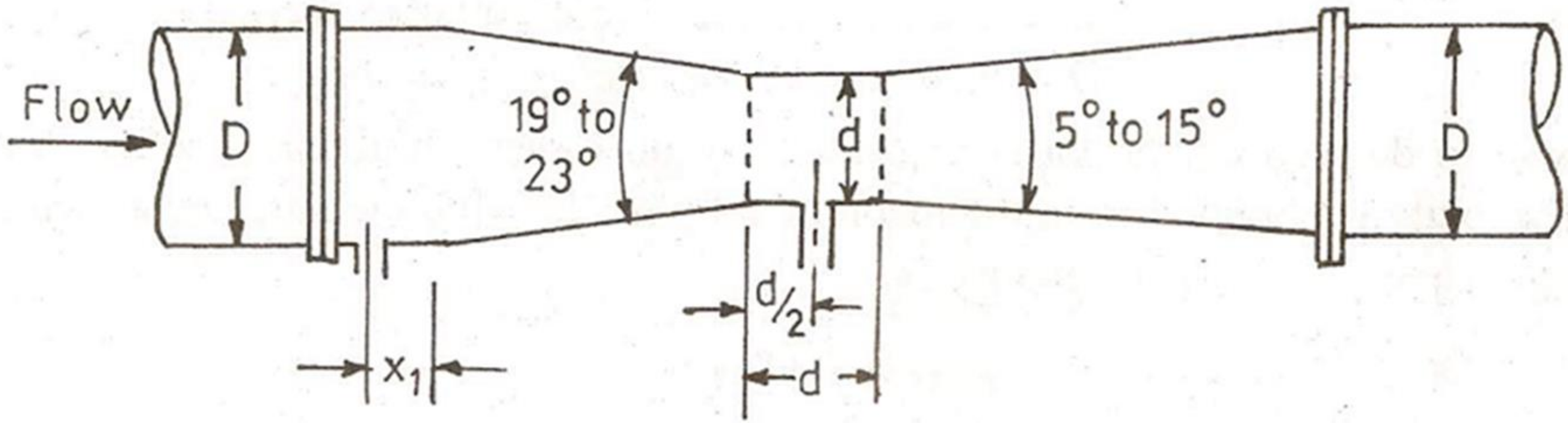


Venturi tubes





Dimensions of venturi



Conservation of energy at different points in a fluid stream is neatly expressed in Bernoulli's Equation as a constant sum of elevation, pressure, and velocity "heads".

$$z_1\rho g + \frac{v_1^2\rho}{2} + P_1 = z_2\rho g + \frac{v_2^2\rho}{2} + P_2$$

Where,
z = Height of fluid (from a common reference point, usually ground level)
ρ = Mass density of fluid
g = Acceleration of gravity
v = Velocity of fluid
P = Pressure of fluid

Use Bernoulli's equation to develop a precise mathematical relationship between pressure and flow rate in a venturi tube. To simplify our task, we will hold to the following assumptions for our venturi tube system:

- No energy lost or gained in the venturi tube (all energy is conserved)
- No mass lost or gained in the venturi tube (all mass is conserved)
- Fluid is incompressible
- Venturi tube centerline is level (no height changes to consider)

$$\frac{v_1^2\rho}{2} + P_1 = \frac{v_2^2\rho}{2} + P_2 \longrightarrow \frac{\rho}{2}(v_2^2 - v_1^2) = P_1 - P_2$$

$$A_1 v_1 = A_2 v_2 \longrightarrow \frac{\rho}{2}\left(v_2^2 - \left[\left(\frac{A_2}{A_1}\right) v_2\right]^2\right) = P_1 - P_2$$

$$v_2 = \sqrt{2}\frac{1}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}}\sqrt{\frac{P_1 - P_2}{\rho}}$$

General flow/area/velocity relationship:

$$Q = Av$$

Equation for throat velocity:

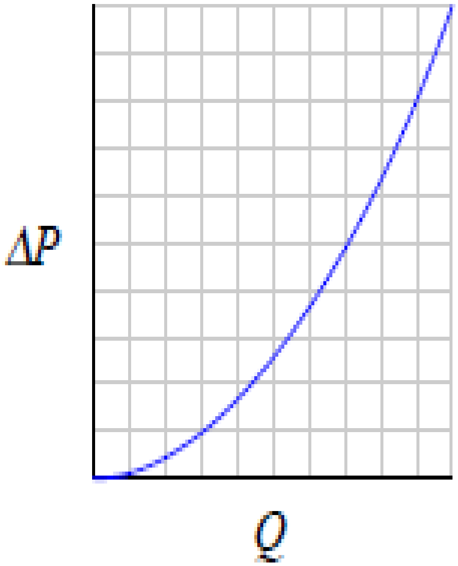
$$v_2 = \sqrt{2}\frac{1}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}}\sqrt{\frac{P_1-P_2}{\rho}}$$

Multiplying both sides of the equation by throat area:

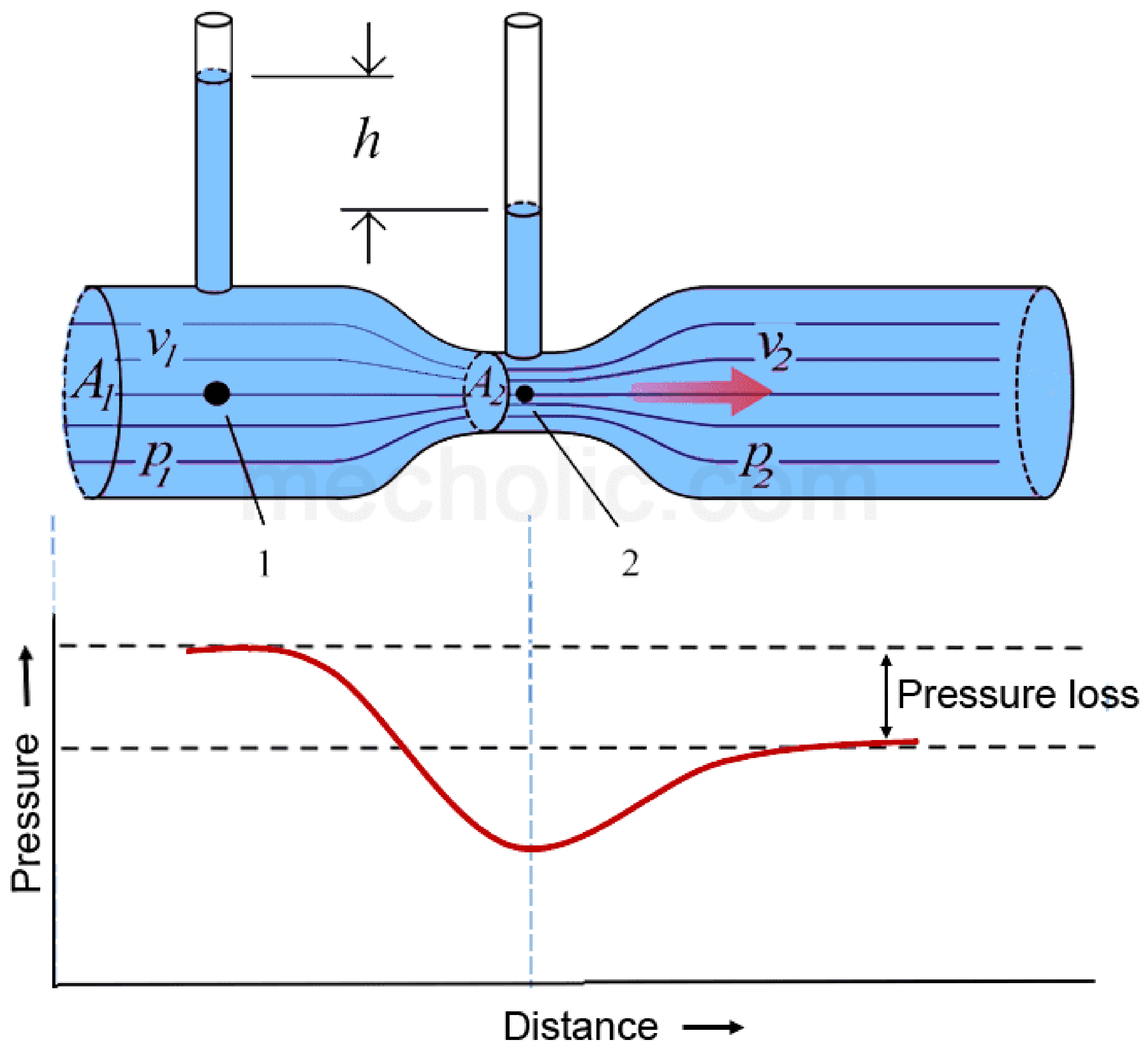
$$A_2v_2 = \sqrt{2}A_2\frac{1}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}}\sqrt{\frac{P_1-P_2}{\rho}}$$

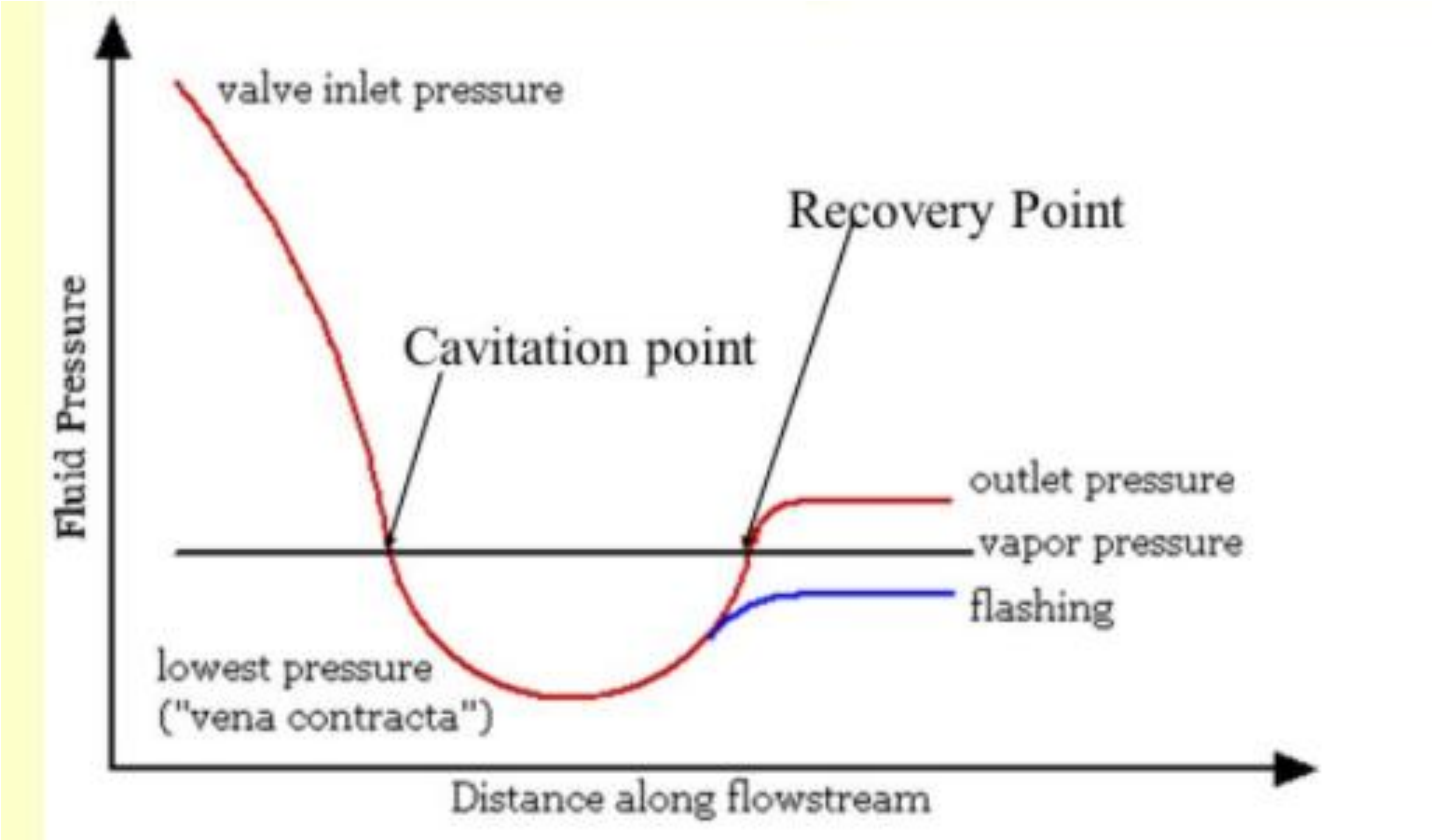
$$Q = \sqrt{2}A_2\frac{1}{\sqrt{1-\left(\frac{A_2}{A_1}\right)^2}}\sqrt{\frac{P_1-P_2}{\rho}}$$

$$Q \propto \sqrt{\frac{P_1-P_2}{\rho}}$$

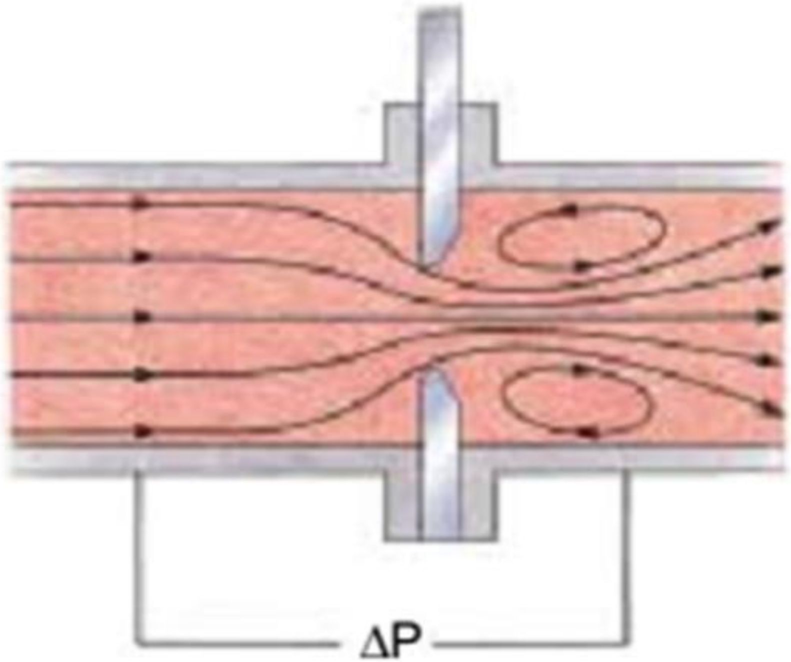


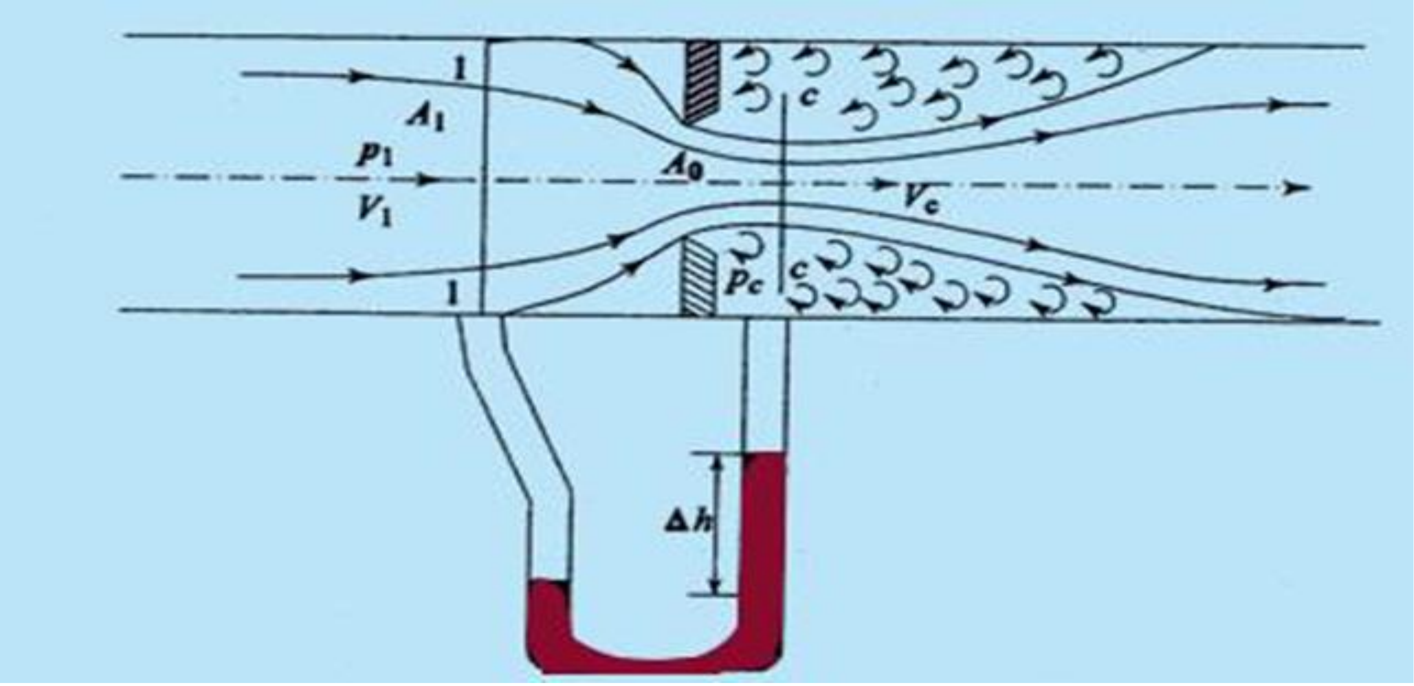
$$\boxed{\Delta P \propto Q^2}$$


h
v_1
A_1
p_1
A_2
v_2
p_2
1
2
Pressure
Pressure loss
Distance


valve inlet pressure
Recovery Point
Cavitation point
Fluid Pressure
outlet pressure
vapor pressure
flashing
lowest pressure
("vena contracta")
Distance along flowstream

Orifice plates

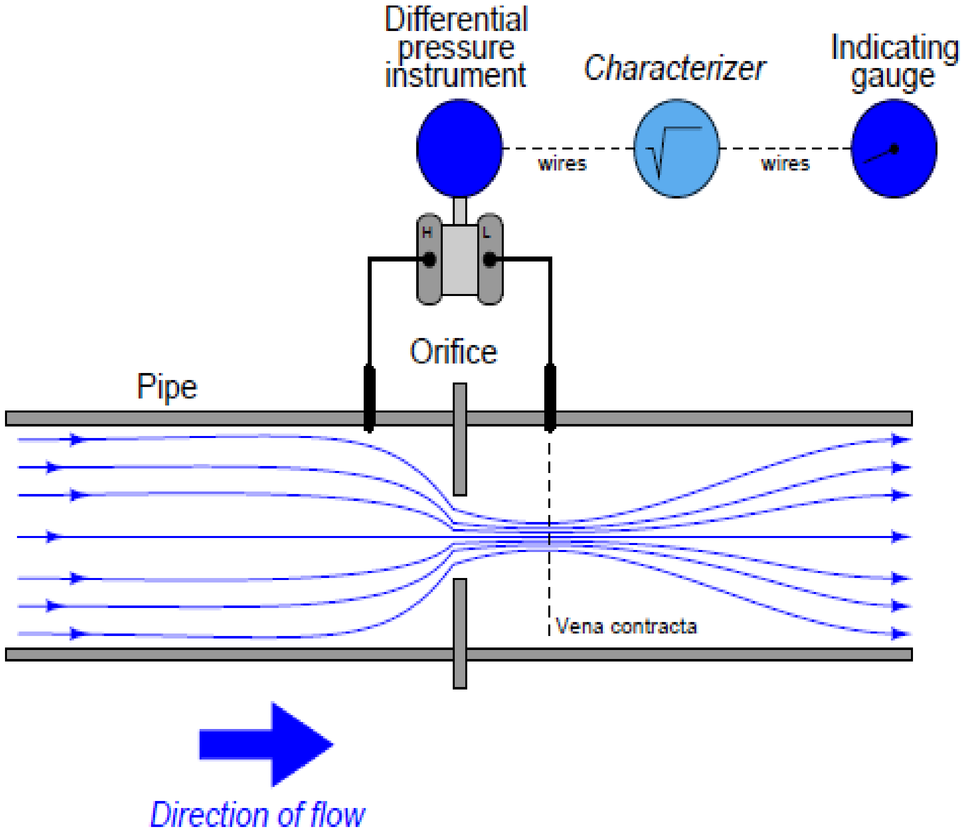


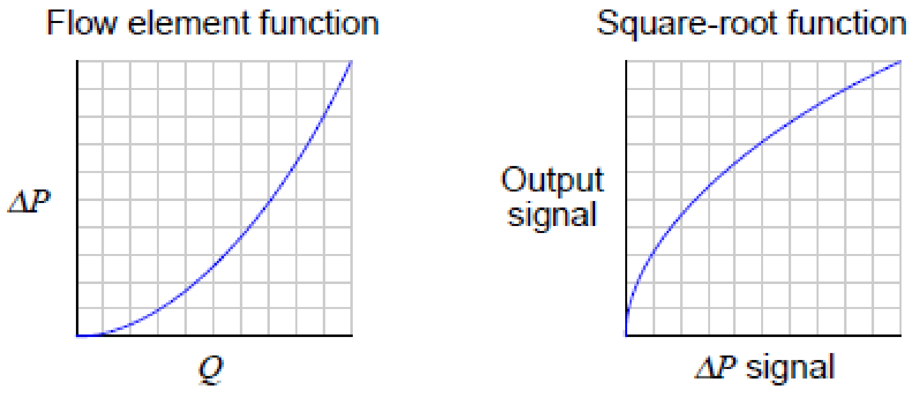


$$Q = \sqrt{2} A_2 \frac{1}{\sqrt{1 - \left(\frac{A_2}{A_1}\right)^2}} \sqrt{\frac{P_1 - P_2}{\rho}}$$

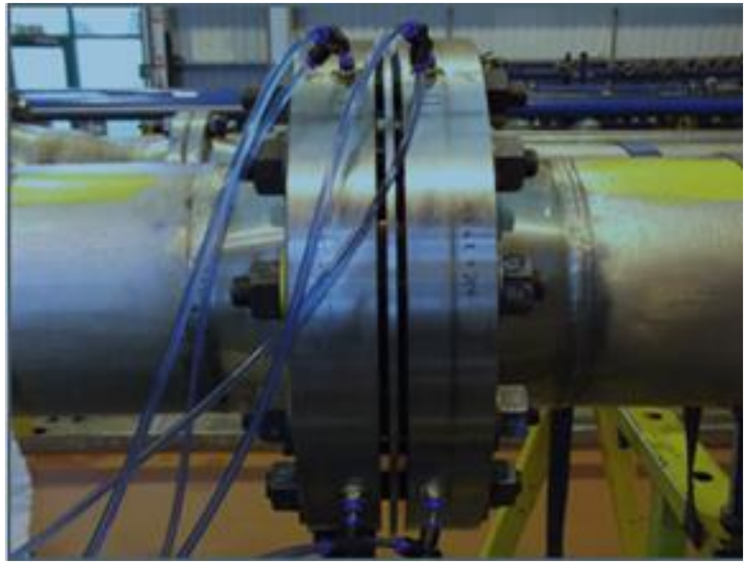
$A_2 = A_0$

For linear measurement

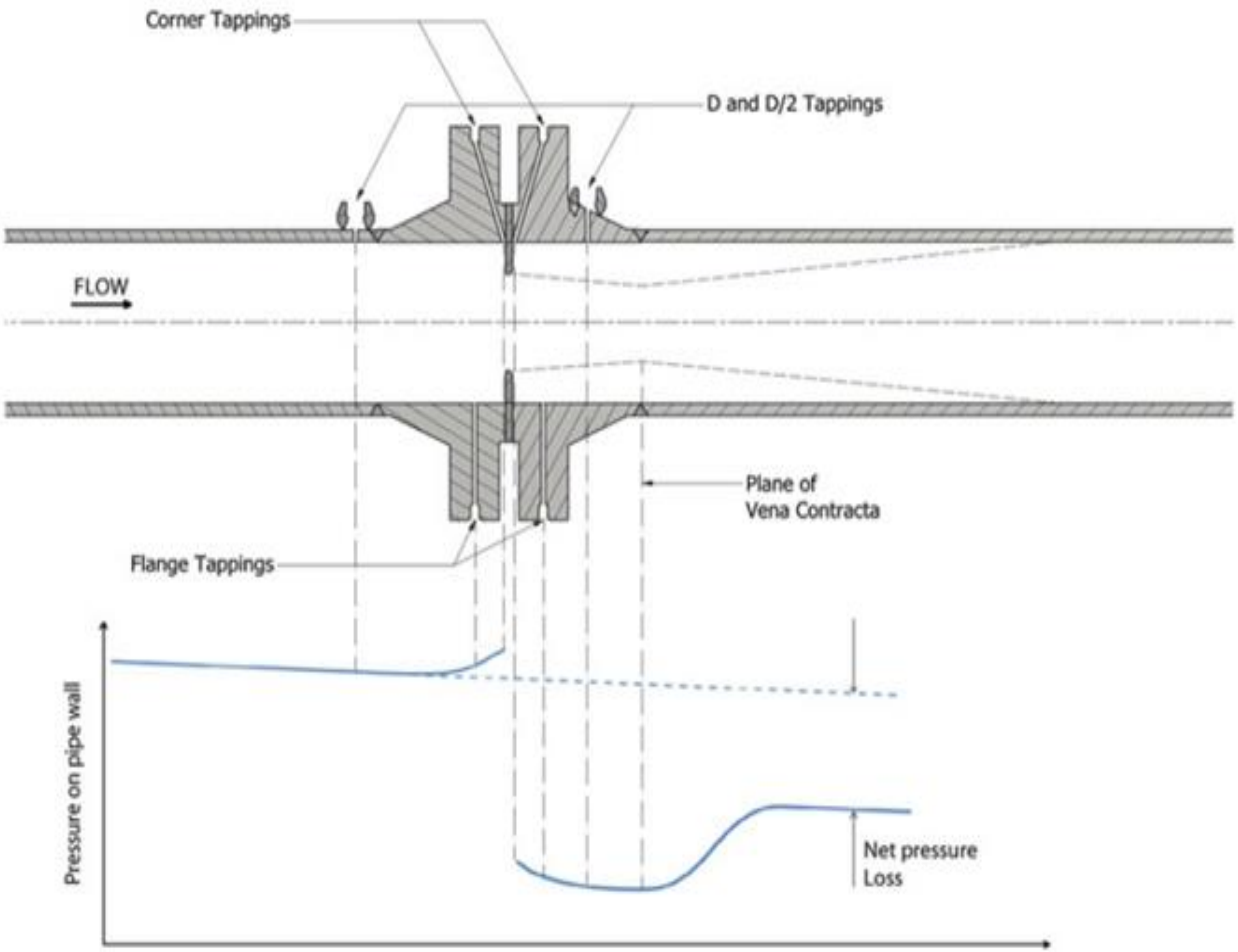




Different types of tappings



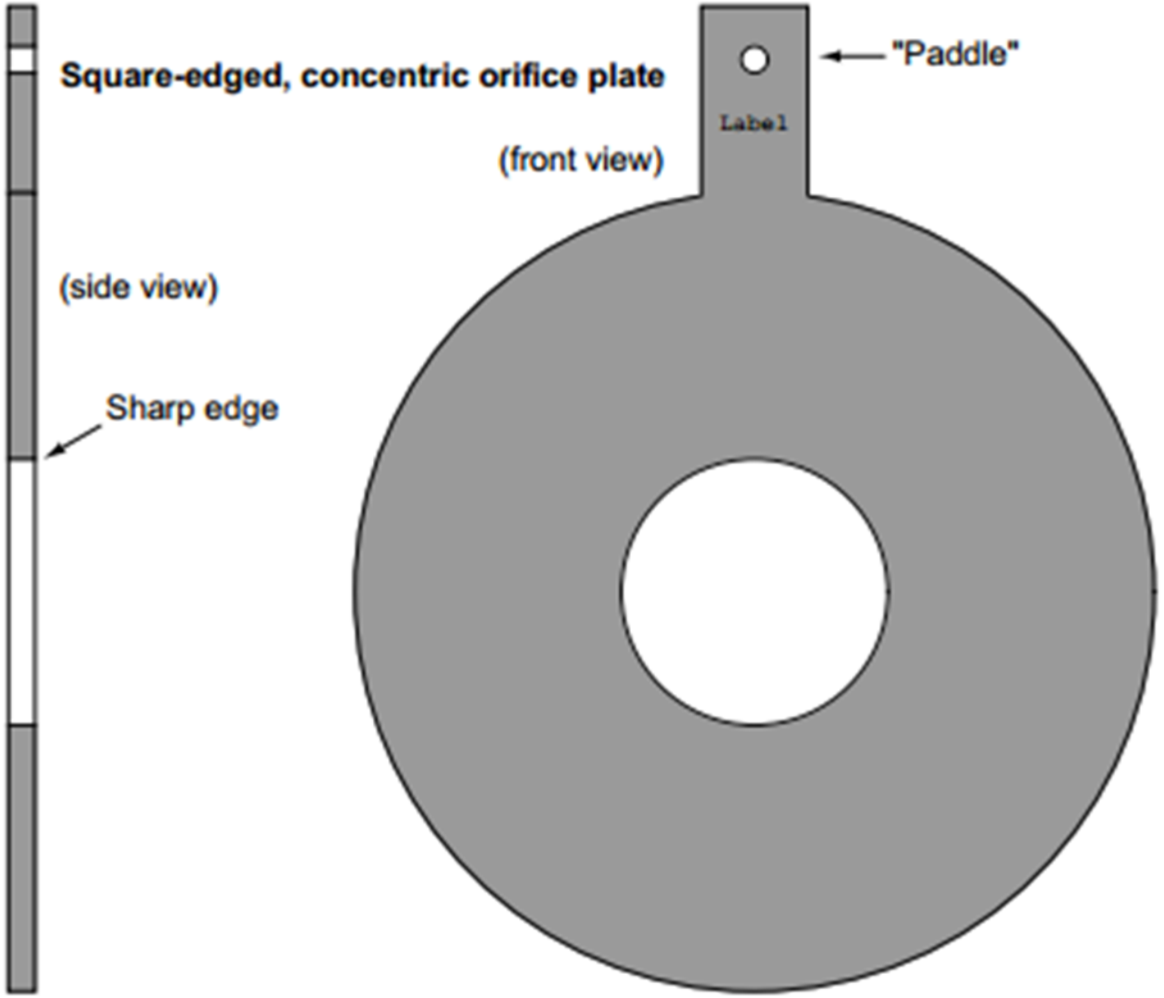
Orifice with flange tapping's



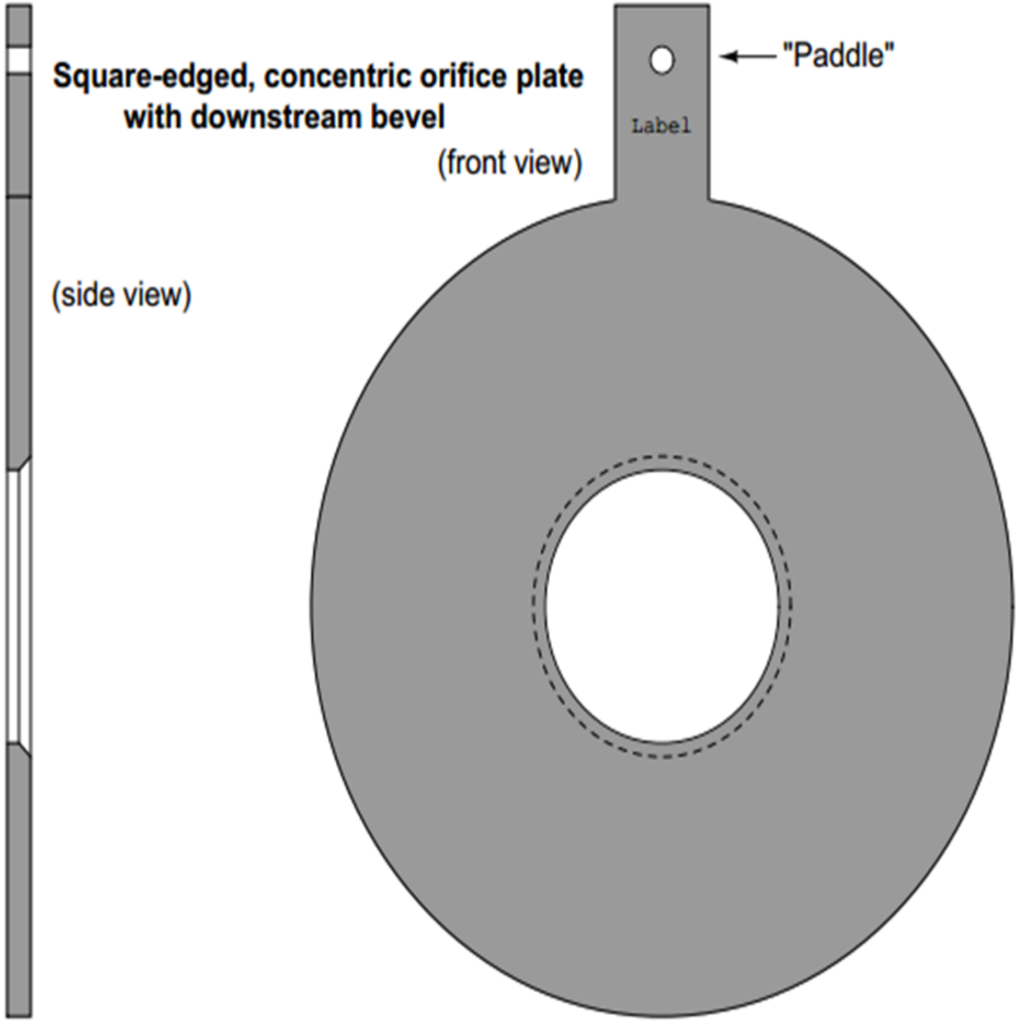
Tapping type	d_1	d_2	Remarks
Pipe taps	$2\frac{1}{2}D$	$8D$	Mainly used for gas lines, when D is small and pressure differential is small, $\beta < 0.70$.
Radius taps	D	$\frac{1}{2}D$	Prescribed to keep the tapping positions fixed irrespective of β, Not as common as the others.
Flange taps, or, Corner taps	1 in.	1 in.	Used mainly for $D > 1$ in. It is the most popular tapping position.

Types of orifice plates

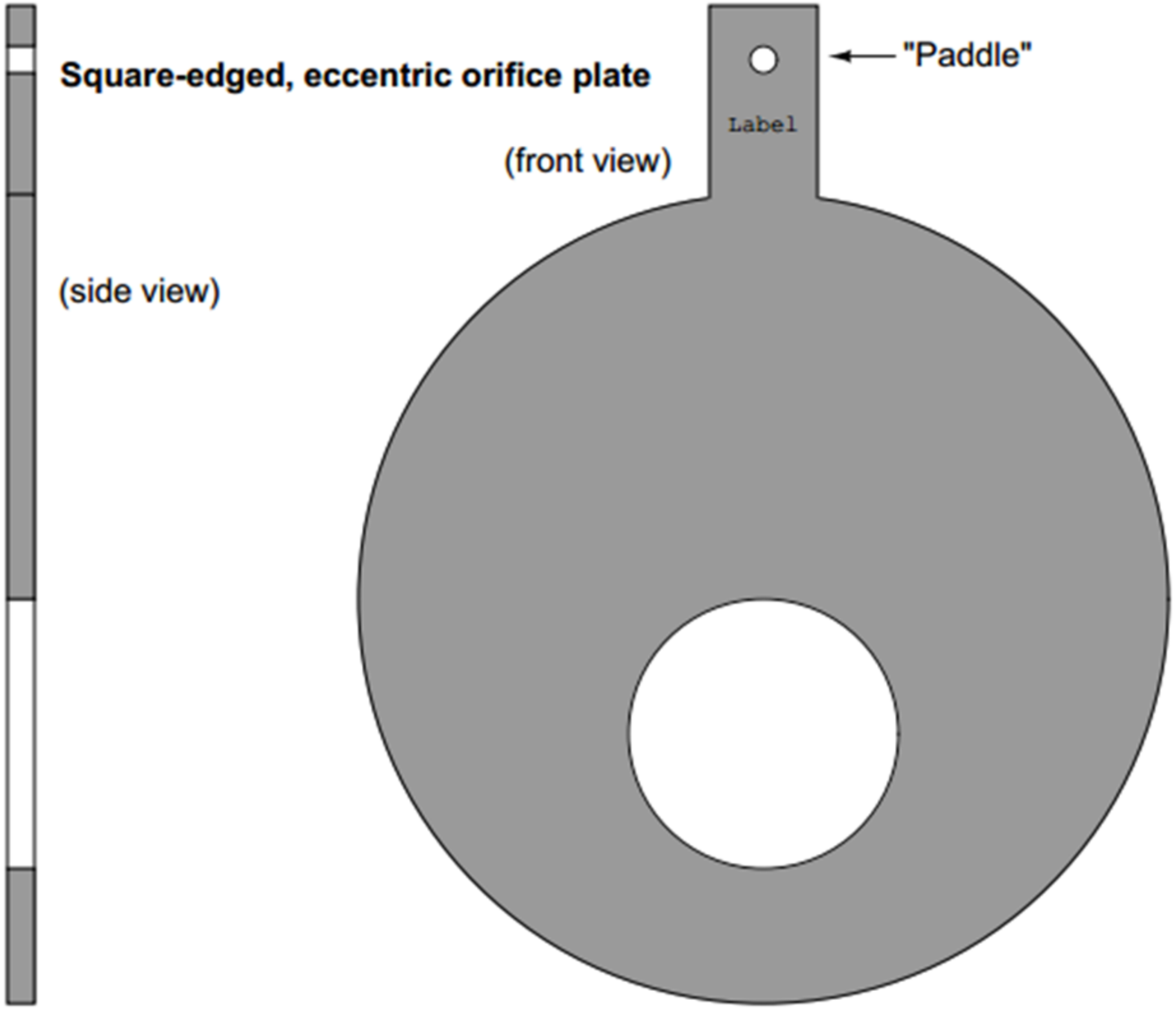
- **Concentric**
- **Eccentric**
- **Segmental**
- **Quadrant**



Square-edged orifice plates may be installed in either direction, since the orifice plate “appears” exactly the same from either direction of fluid approach. “**paddle**” of any orifice plate customarily identifies **the upstream side of that plate**, but in the case of the square-edged orifice plate it does not matter



If the orifice plate is relatively thick (1/8 or an inch or more), it may be necessary to **bevel** the downstream side of the hole to minimize contact with the fluid stream.
Beveled orifice plates are obviously uni-directional, and must be installed with the paddle text facing upstream.

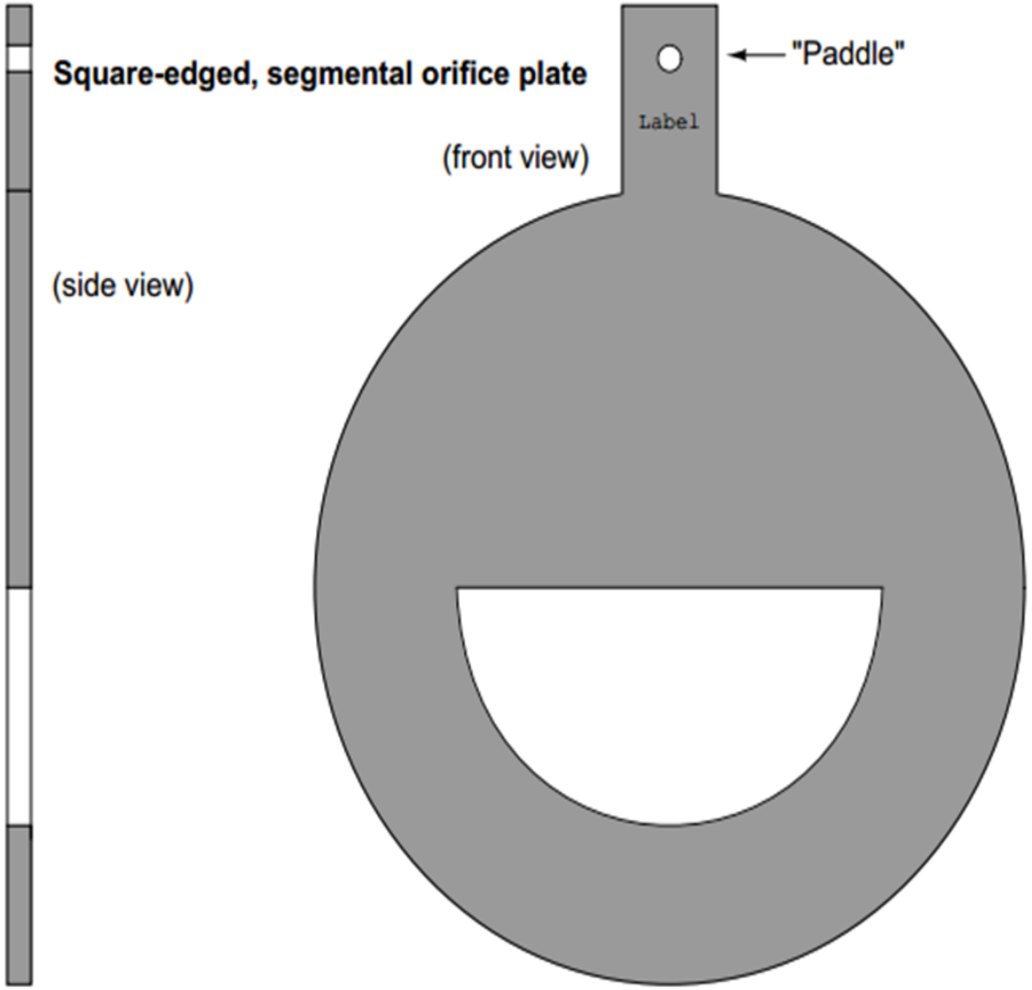


Orifice plates to address conditions where gas bubbles or solid particles may be present in liquid flows, or where liquid droplets or solid particles may be present in gas flows.

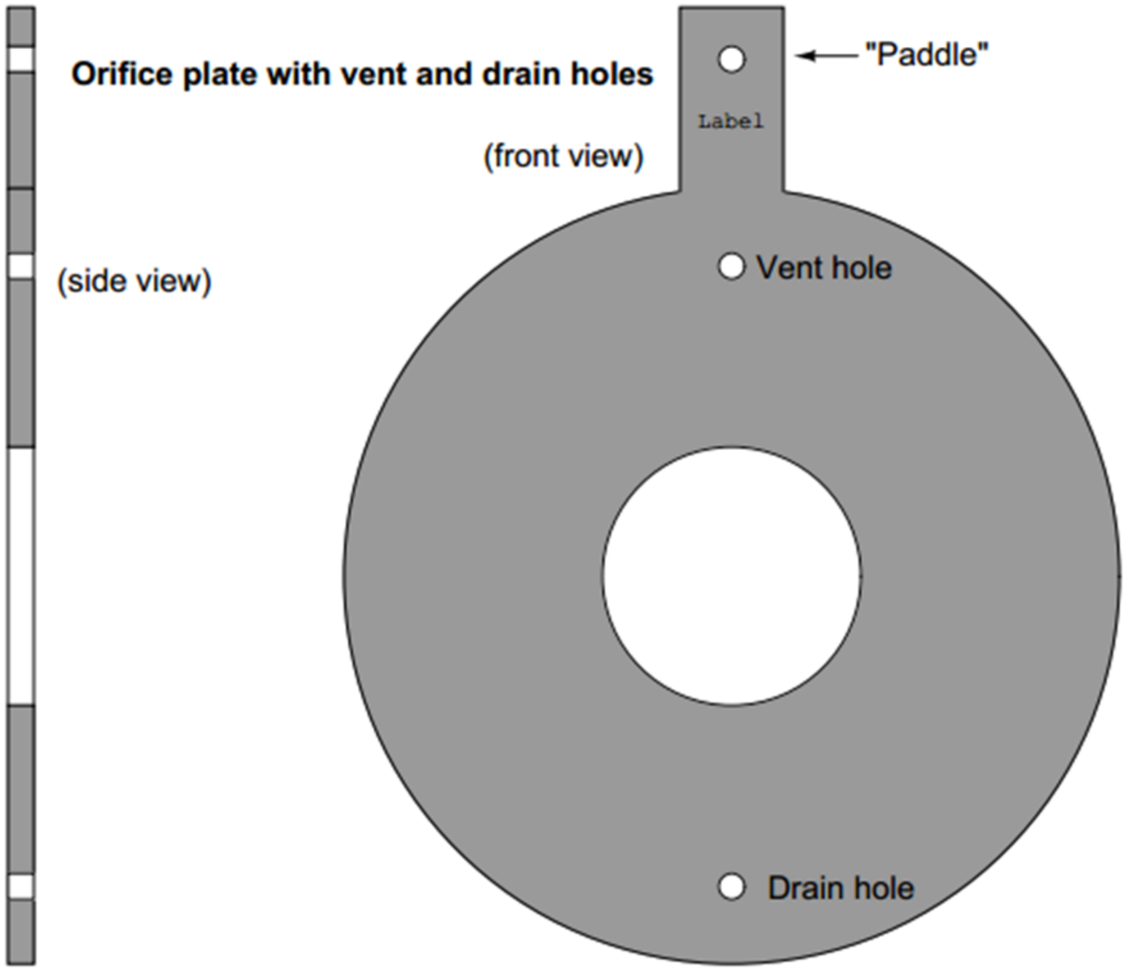
The hole is located off-center to allow the undesired portions of the fluid to pass through the orifice rather than build up on the upstream face.

For gas flows, the hole should be offset downward, so any liquid droplets or solid particles may easily pass through.

For liquid flows, the hole should be offset upward to allow gas bubbles to pass through and offset downward to allow heavy solids to pass through.



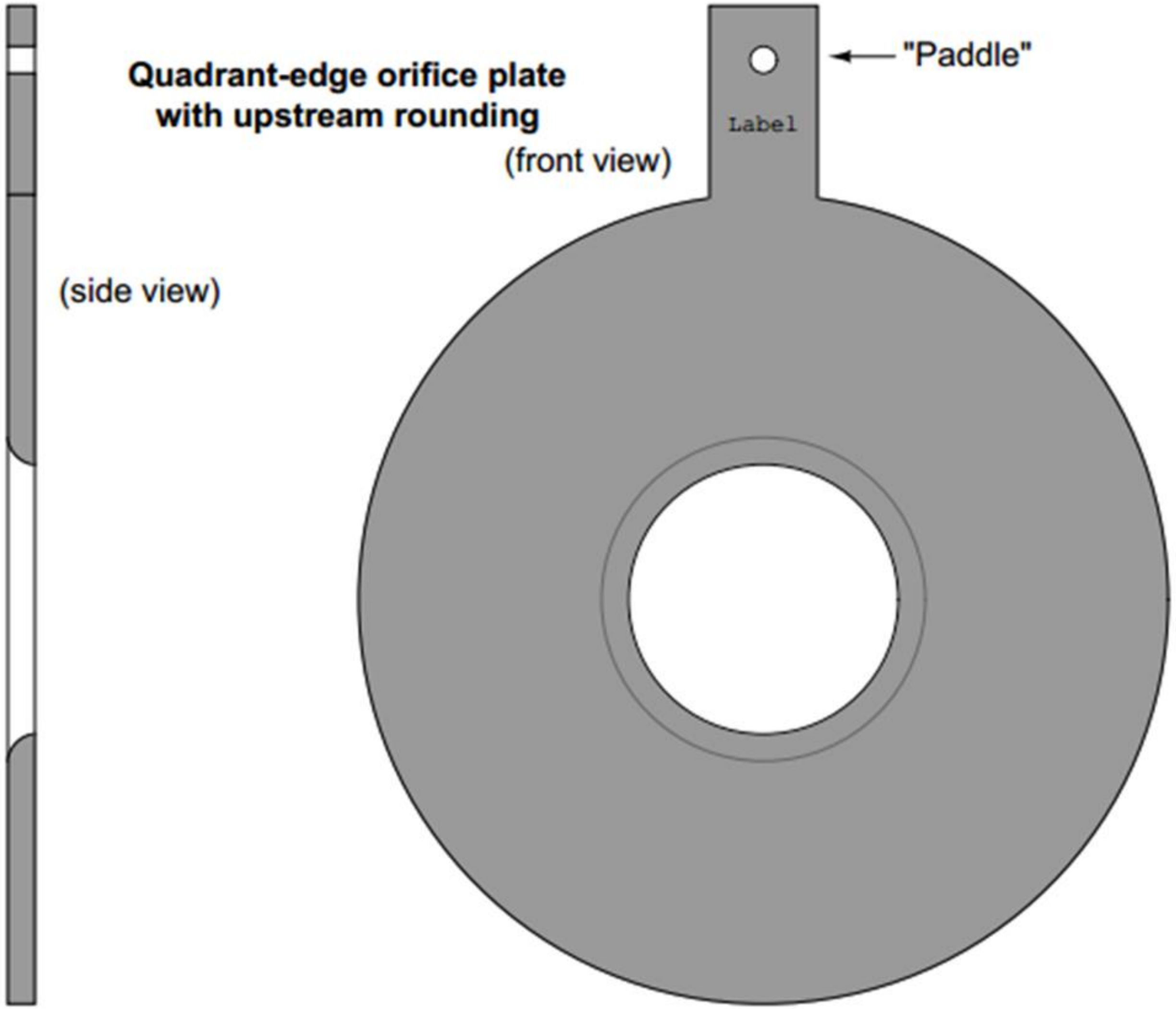
The segmental hole should be offset downward in gas flow applications and either upward or downward in liquid flow applications depending on the type of undesired material(s) in the flow stream.



An alternative to offsetting or re-shaping the bore hole of an orifice plate is to simply drill a small hole near the edge of the plate.

If such a hole is oriented upward to pass vapor bubbles, it is called a vent hole. If the hole is oriented downward to pass liquid droplets or solids, it is called a drain hole.

Vent and drain holes are useful when the concentration of these undesirable substances is not significant enough to warrant either an eccentric or segmental orifice



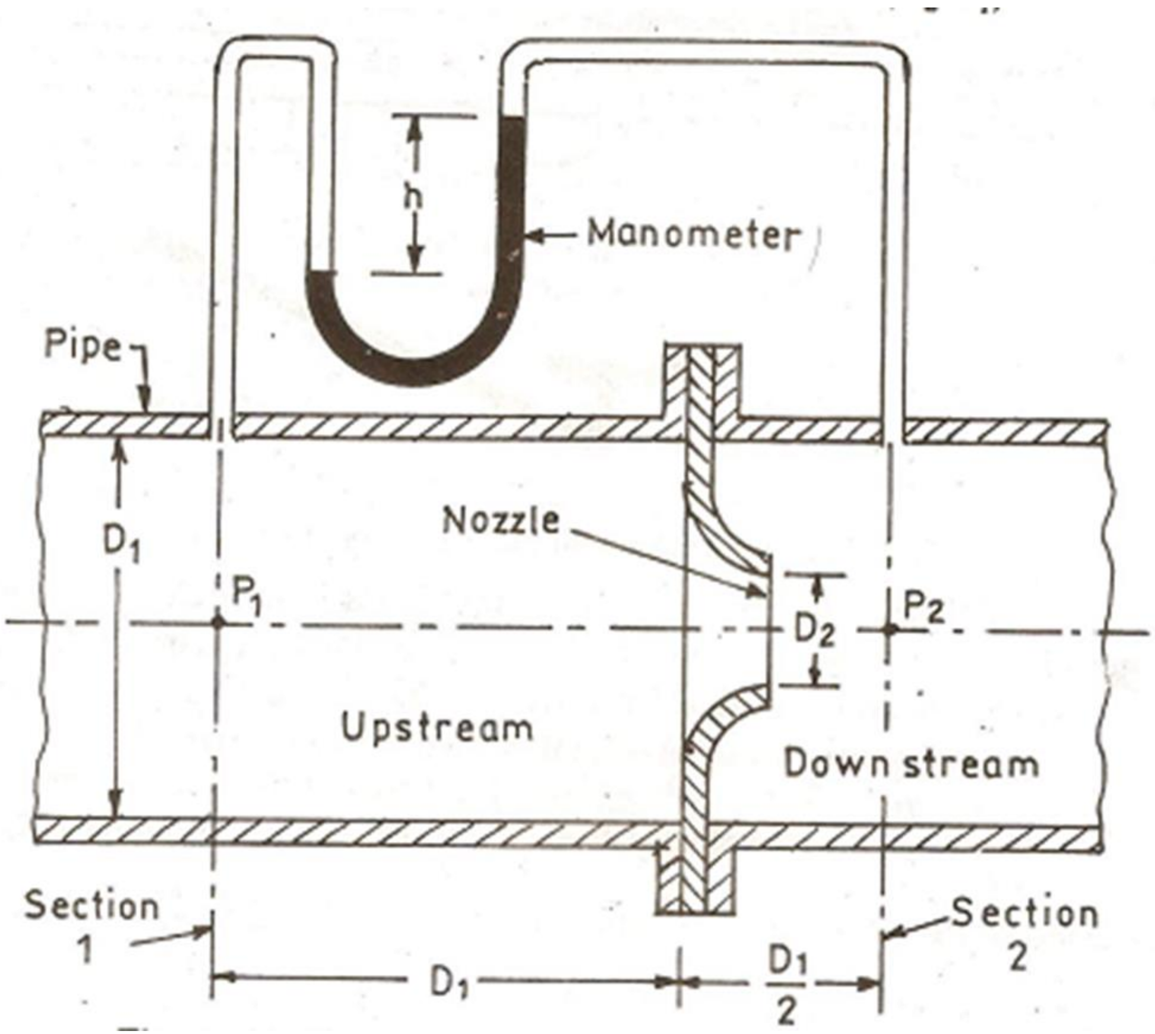
Orifice plates employ non-square-edged holes for the purpose of improving performance at low Reynolds number values, where the effects of fluid viscosity are more apparent.
These orifice plate types employ rounded- or conical-entrance holes in an effort to minimize the effects of fluid viscosity

Orifice Type	*Appropriate Process Fluid*	*Reynolds Number Range*
Concentric, square edge	Clean gas and liquid	Over 2000
Concentric, quadrant, or conical edge	Viscous clean liquid	200 to 10,000
Eccentric or segmental square edge	Dirty gas or liquid	Over 10,000

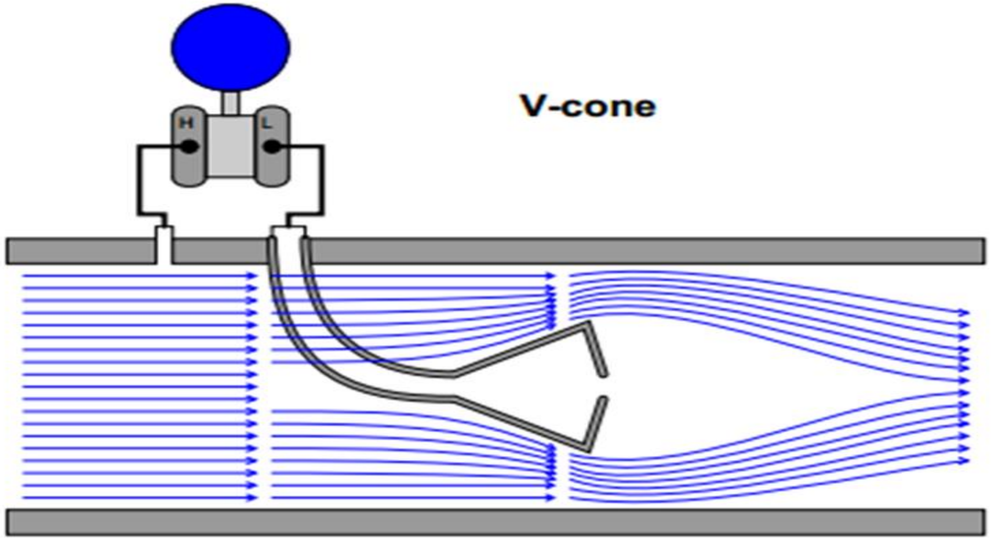
Orifice Meter	Venturi meter
Simple in construction	Relatively complex in construction
Low Space requirement	Occupies considerable space
Relatively cheap	Expensive
Pressure recovery is poor	Pressure recovery is high.
Coefficient of discharge is about 0.61	Coefficient of discharge is about 0.98
Larger power loss.	Smaller power loss

Flow nozzles

Flow nozzle

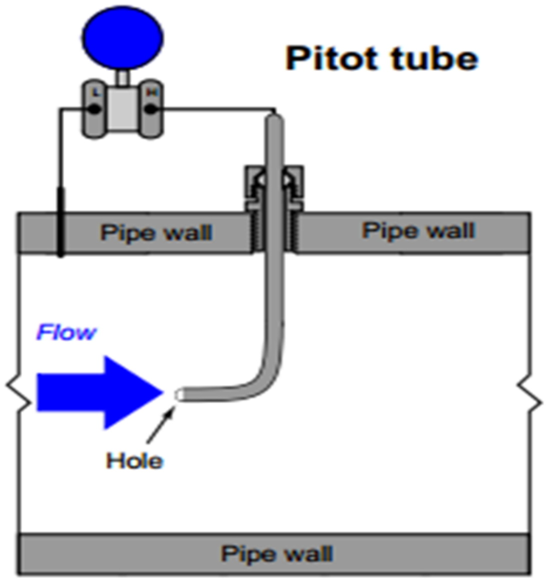


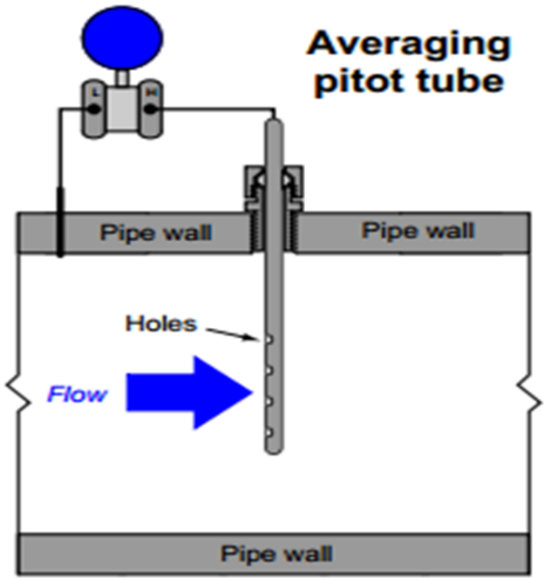
h
Manometer
Pipe
D_1
Nozzle
P_1
D_2
P_2
Upstream
Down stream
Section 1
Section 2
D_1
$\frac{D_1}{2}$

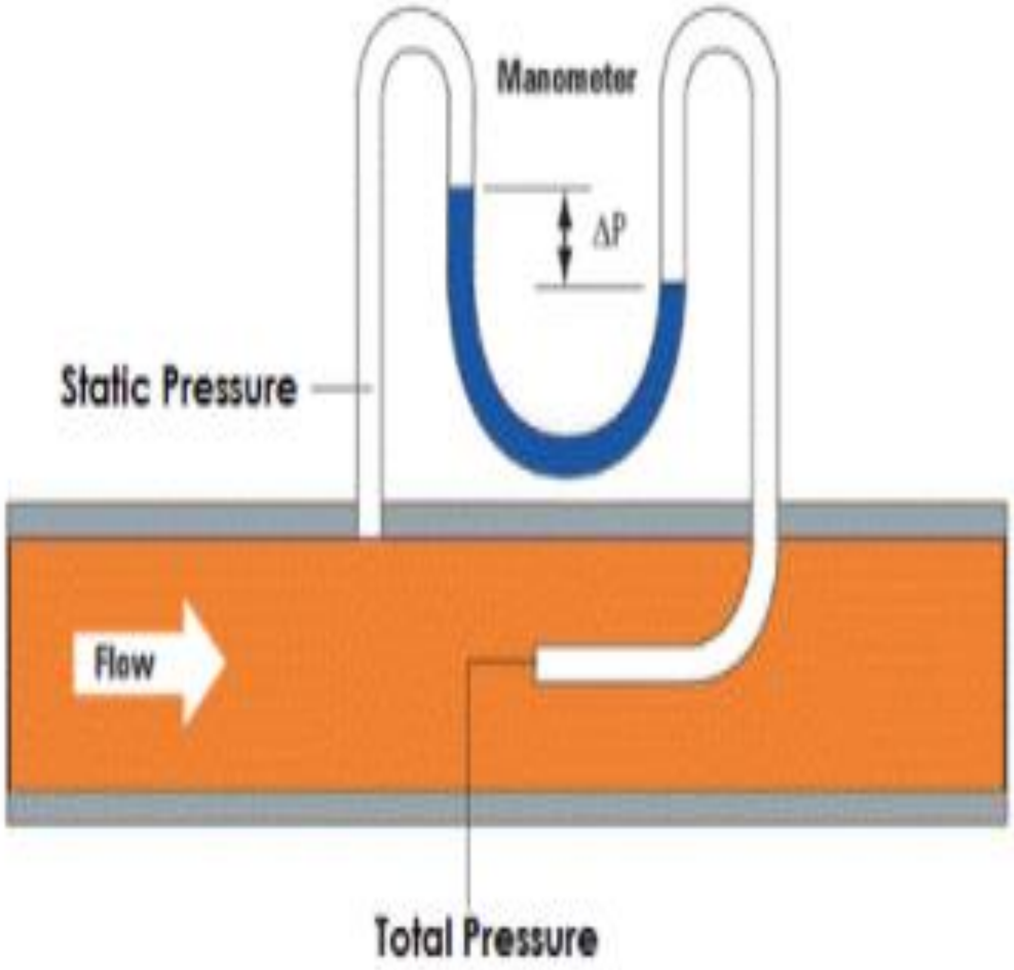

V-cone
H
L

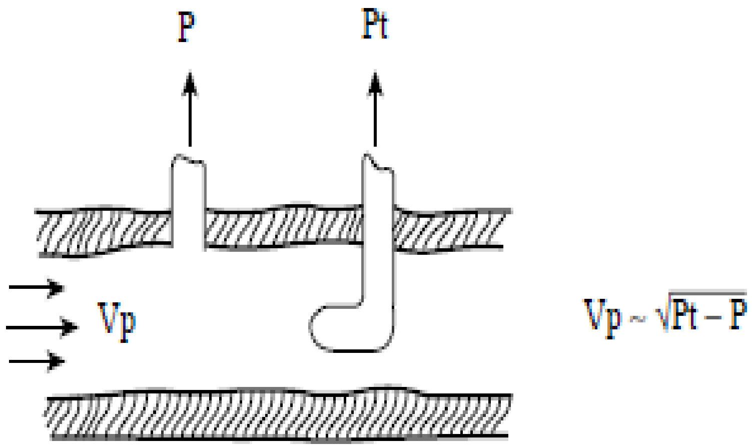
Pitot tubes

Pitot tubes detect the flowing velocity at a single point (standard), at several points that lead into an averaging probe (multiported), or at many points across the cross section of a pipe or duct (area-averaging).
Their advantages are low cost, low permanent pressure loss
The disadvantages of pitot tube-type sensors are low accuracy, low rangeability, and the limitation of being suitable only for clean liquid, gas, or vapor service unless purged.






Manometer
ΔP
Static Pressure
Flow
Total Pressure



The impact pressure or stagnation pressure on a body, which is immersed in a moving fluid is the sum of the static pressure and the dynamic pressure.

$$P_t = P + P_v$$

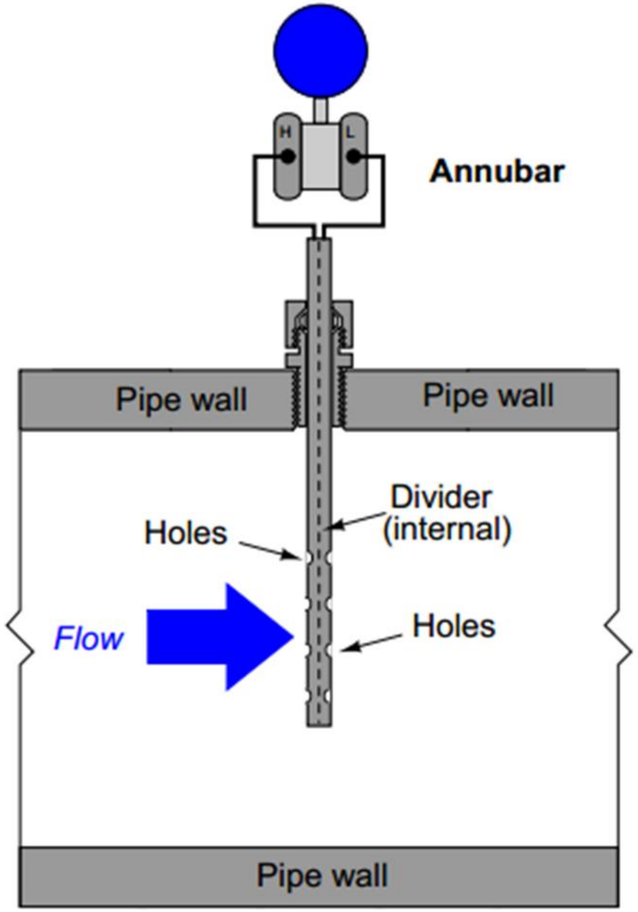
where

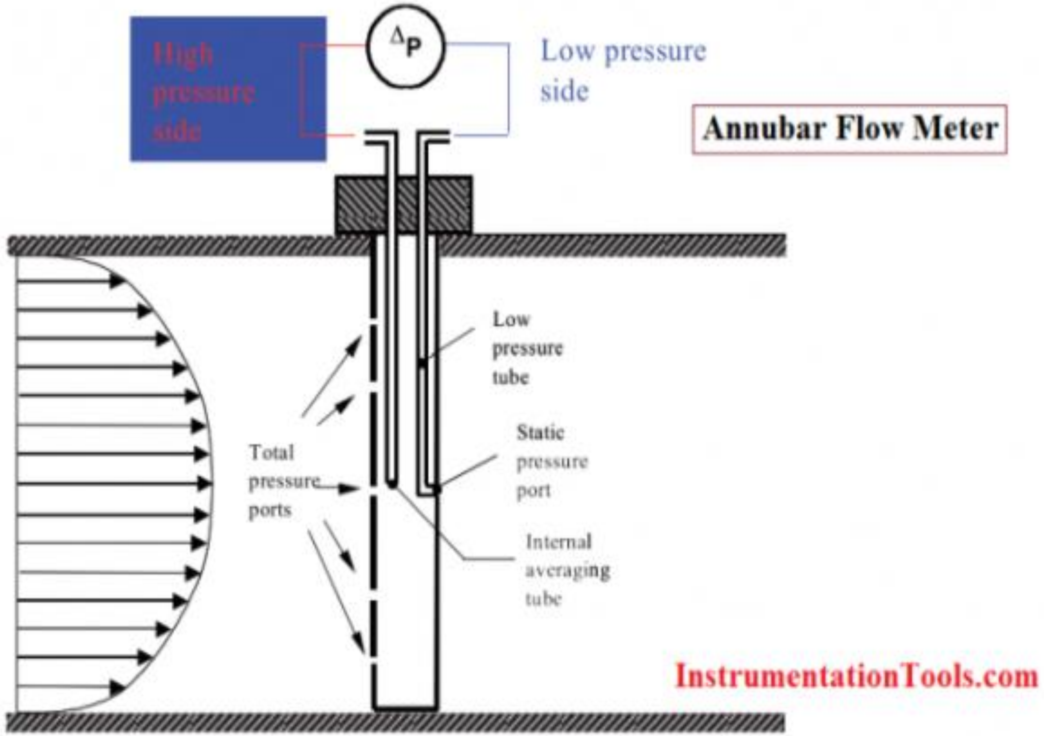
P_t = total pressure, which can be sensed by a fixed probe when the fluid at the sensing point is in an isentropic state (constant entropy)

P = static pressure of the fluid whether in motion or at rest

P_v = dynamic pressure caused by the kinetic energy of the fluid as a continuum

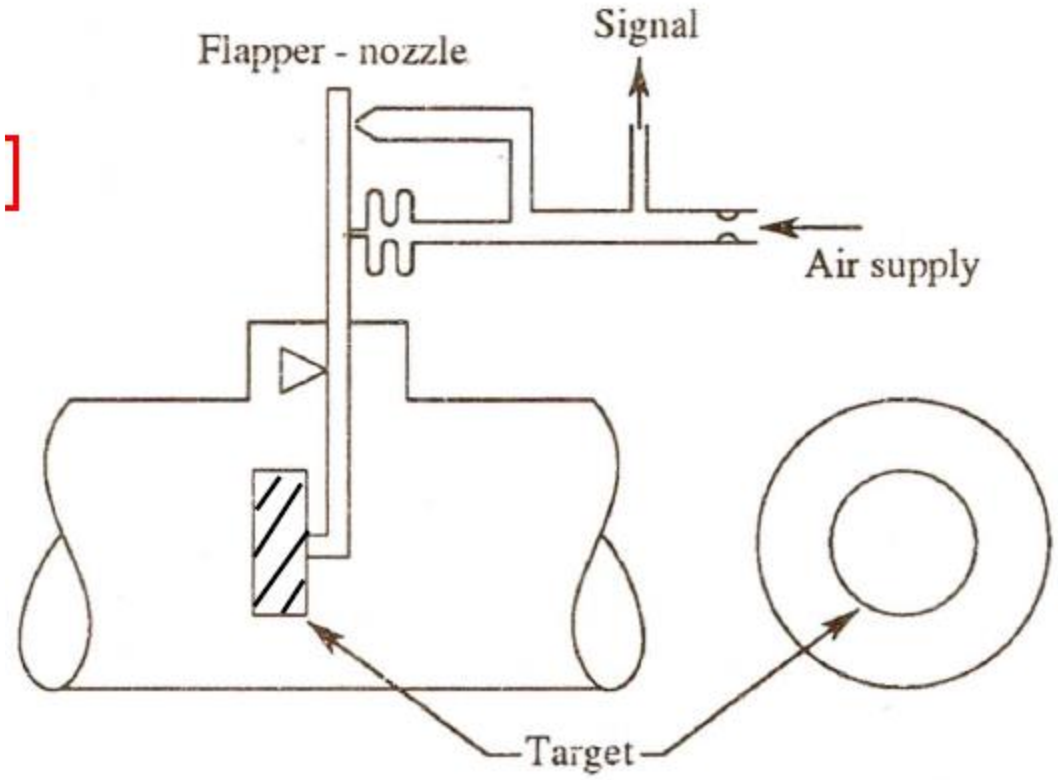
At a stagnation point the fluid velocity is zero and all the kinetic energy has been converted into pressure energy.





An “Annubar” is an averaging pitot tube consolidating high and low pressure sensing ports in a single probe assembly

Target Flow meter



$$F = c_d \rho v^2 A_t / 2$$

where

F = force on the target (N)

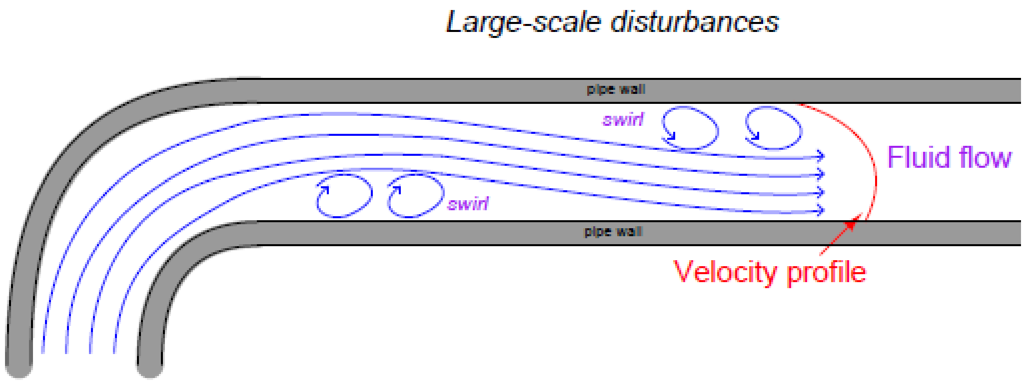
c_d *= overall drag coefficient obtained from empirical data*

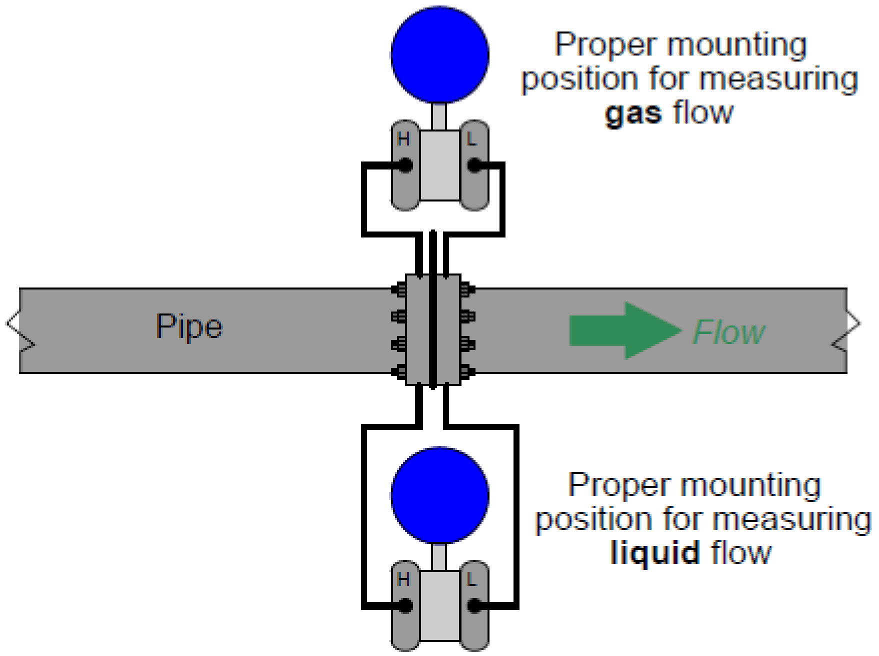
ρ *= density of fluid* (kg/m^3)

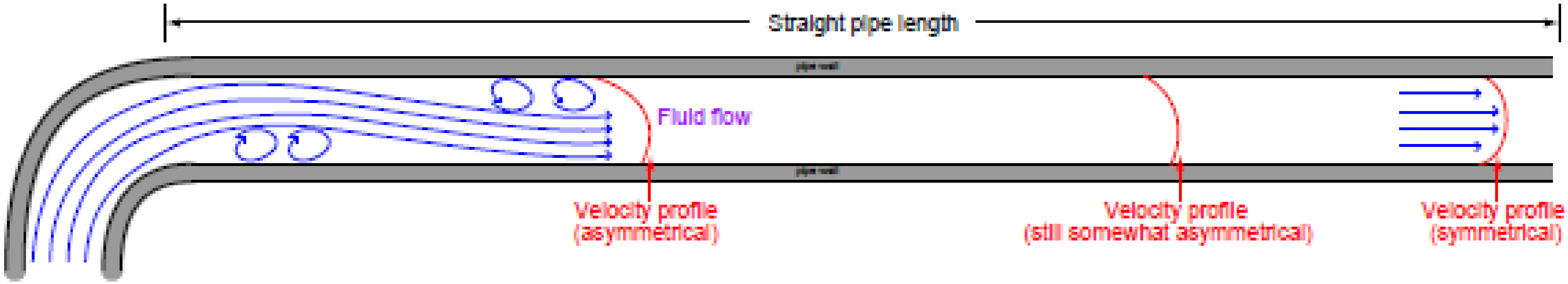
v = fluid velocity (m/s)

A_t *= target area* (m^2)

Proper installation

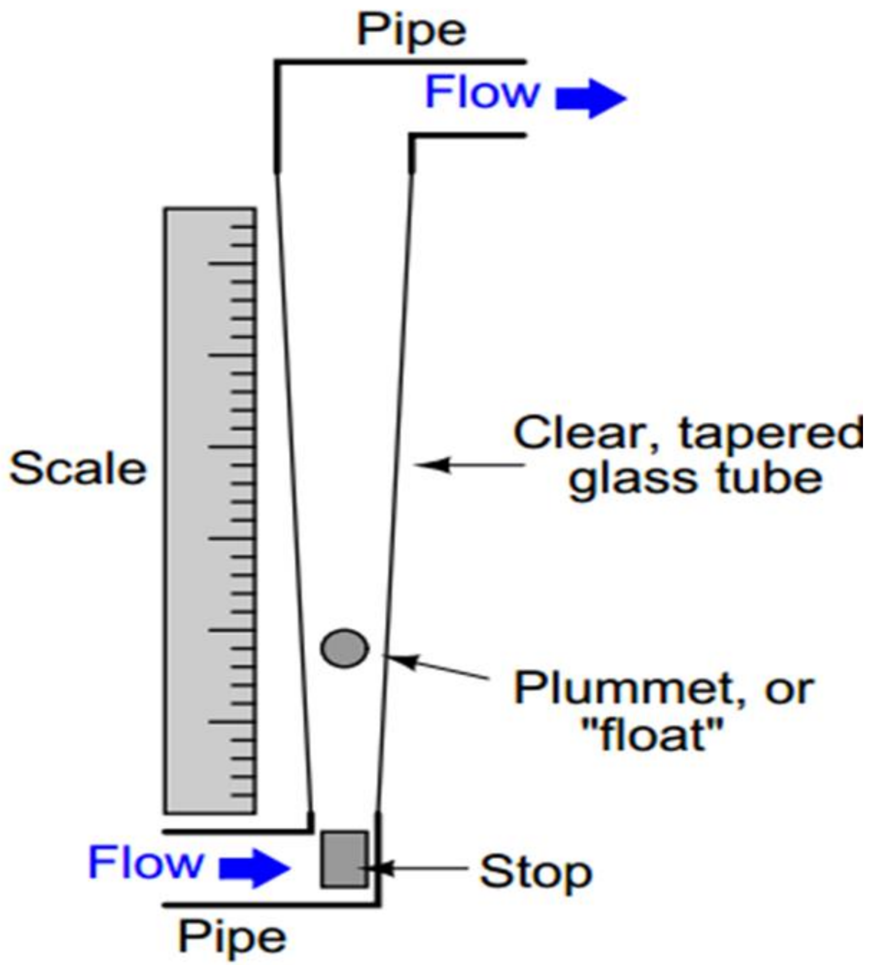


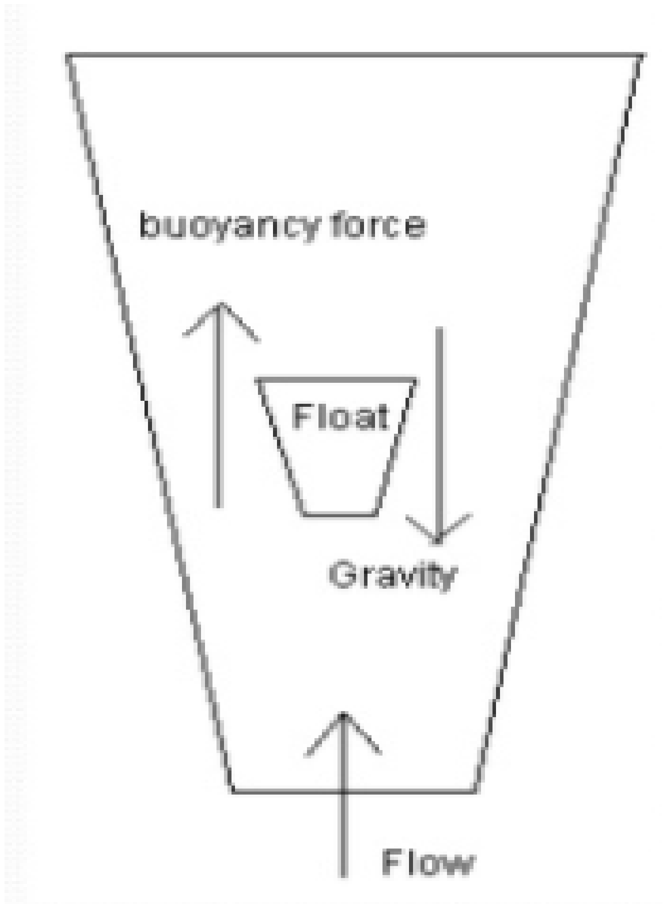




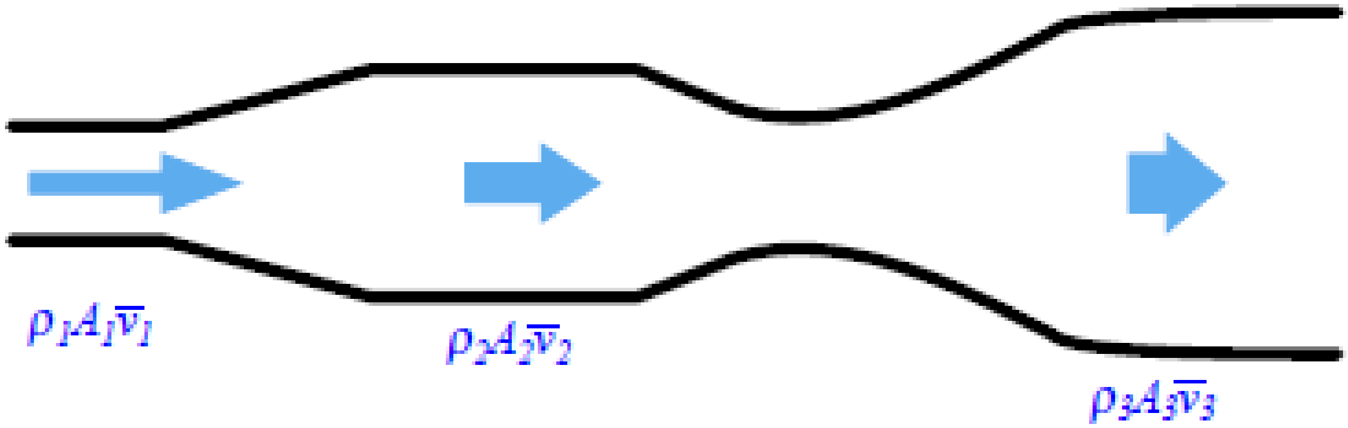
Variable Area flowmeters

Rotameter


Pipe
Flow
Scale
Clear, tapered glass tube
Plummet, or "float"
Flow
Stop
Pipe


buoyancy force
Float
Gravity
Flow

Velocity-based flowmeters

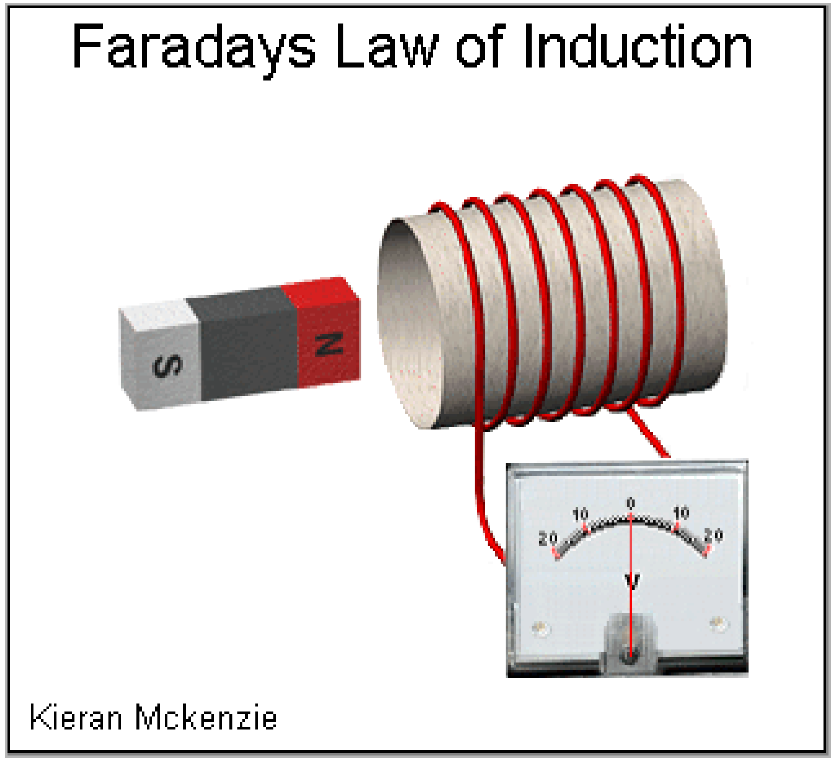


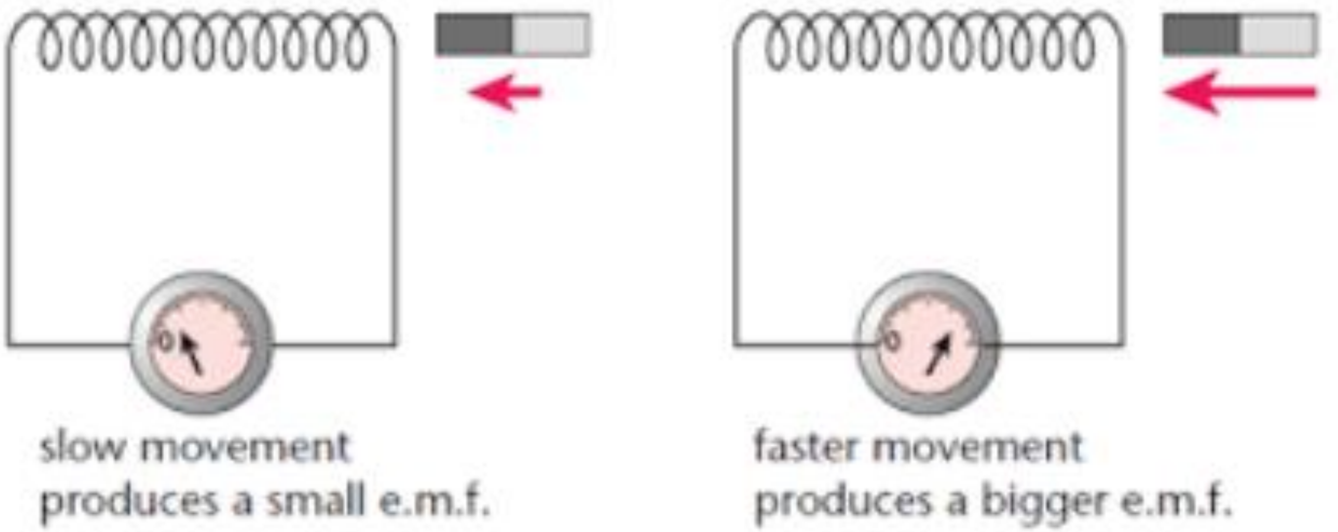
The Law of Continuity for fluids states that the product of mass density (ρ), cross-sectional pipe area (A) and average velocity (v) must remain constant through any continuous length of pipe.

Fluid velocity will be directly proportional to volumetric flow rate given a known cross-sectional area and a constant density for the fluid flow stream.

Magnetic flowmeters

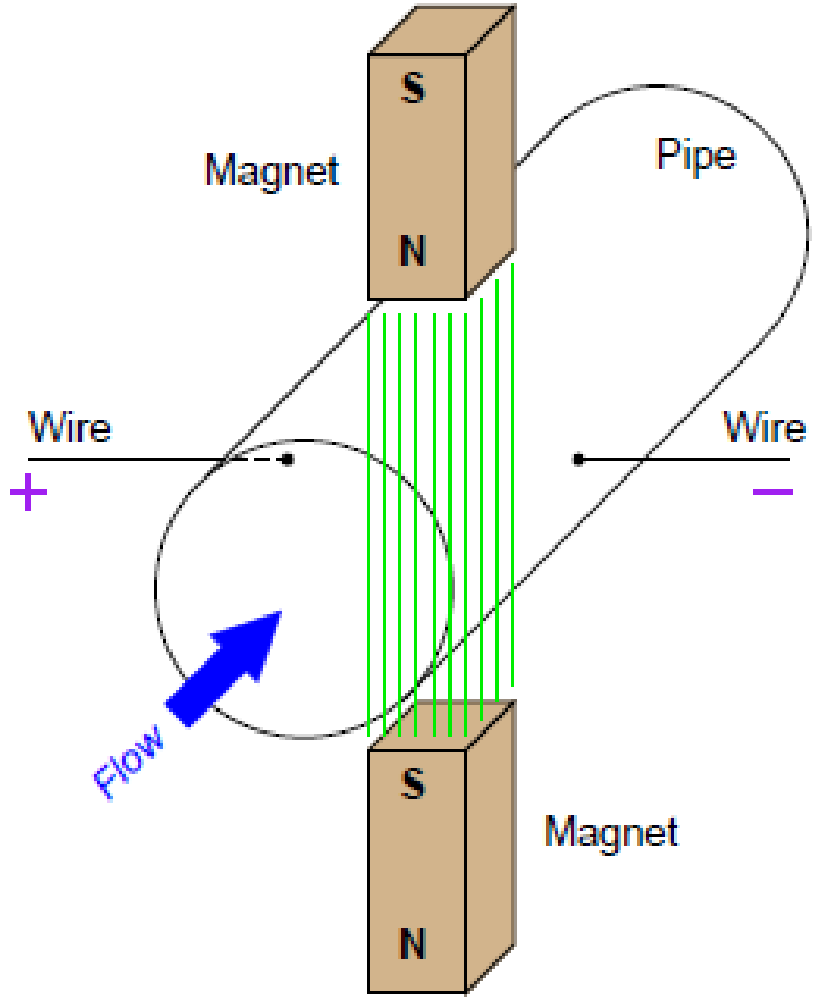
Faraday's law states that, if a conductor of length l (m) is moving with a velocity v (m/sec) perpendicular to a magnetic field of flux density B (Tesla), a voltage e will be induced across the ends of the conductor





Is water a conductor?

- Pure water is an insulator
- You may have heard that it’s dangerous to be in the water when lighting may strike. This is true. So does that mean that water isn’t an insulator?
- Only pure water is an insulator. The water in lakes and rivers is not pure. It has minerals in it. Therefore, it’s a fair conductor.



The direction of liquid flow cuts perpendicularly through the lines of magnetic flux, generating a voltage along an axis perpendicular to both. Metal electrodes opposite each other in the pipe wall intercept this voltage, making it readable to an electronic circuit.

$$\mathcal{E} = Blv$$

Where,

$\mathcal{E}$ = Motional EMF (volts)
B = Magnetic flux density (Tesla)
l = Length of conductor passing through the magnetic field (meters)
v = Velocity of conductor (meters per second)

$$Q = A\overline{v}$$

$$\frac{Q}{A} = \overline{v}$$

$$\mathcal{E} = Bd\overline{v}$$

$$\mathcal{E} = Bd\frac{Q}{A}$$

$$\mathcal{E} = \frac{BdQ}{A}$$

$$\mathcal{E} = \frac{BdQ}{\frac{\pi d^2}{4}}$$

$$\mathcal{E} = \frac{BdQ}{1}\frac{4}{\pi d^2}$$

$$\mathcal{E} = \frac{4BQ}{\pi d}$$

$$Q = \frac{\pi d\mathcal{E}}{4B}$$

$$Q = k\frac{\pi d\mathcal{E}}{4B}$$

Where,

Q = Volumetric flow rate (cubic meters per second)
$\mathcal{E}$ = Motional EMF (volts)
B = Magnetic flux density (Tesla)
d = Diameter of flowtube (meters)
k = Constant of proportionality

A few conditions must be met for this formula to successfully infer volumetric flow rate from induced voltage:

• The liquid must be a reasonably good conductor of electricity (note: it is okay if the conducting fluid contains some non-conducting solids; the conductive fluid surrounding the non-conducting solid matter still provides electrical continuity between the electrodes necessary for induction).

• 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

Advantages of Electro-Magnetic flow meters

- Fairly tolerant of swirl and other large-scale turbulent fluid behavior, because the induced voltage is proportional only to the perpendicular velocity of the conductor.
- Magnetic flowmeters do not require the long straight-runs of pipe upstream and downstream that orifice plates do, which is a great advantage.
- The magnetic flowmeter is totally obstruction less and has no moving parts.
- Electric power requirements can be low, particularly with the pulsed DC-types. Electric power requirements as low as 15 or 20 W.
- The meters are suitable for most acids, bases, waters, and aqueous solutions, because the lining materials selected are not only good electrical insulators but also are corrosion resistant.
- Mag-meters are capable of handling extremely low flows. Their minimum size is less than 0.125 in. (3.175 mm) inside diameter. The meters are also suitable for very high-volume flow rates with sizes as large as 10 ft (3.04 m) offered.
- The meters can be used as bidirectional meters

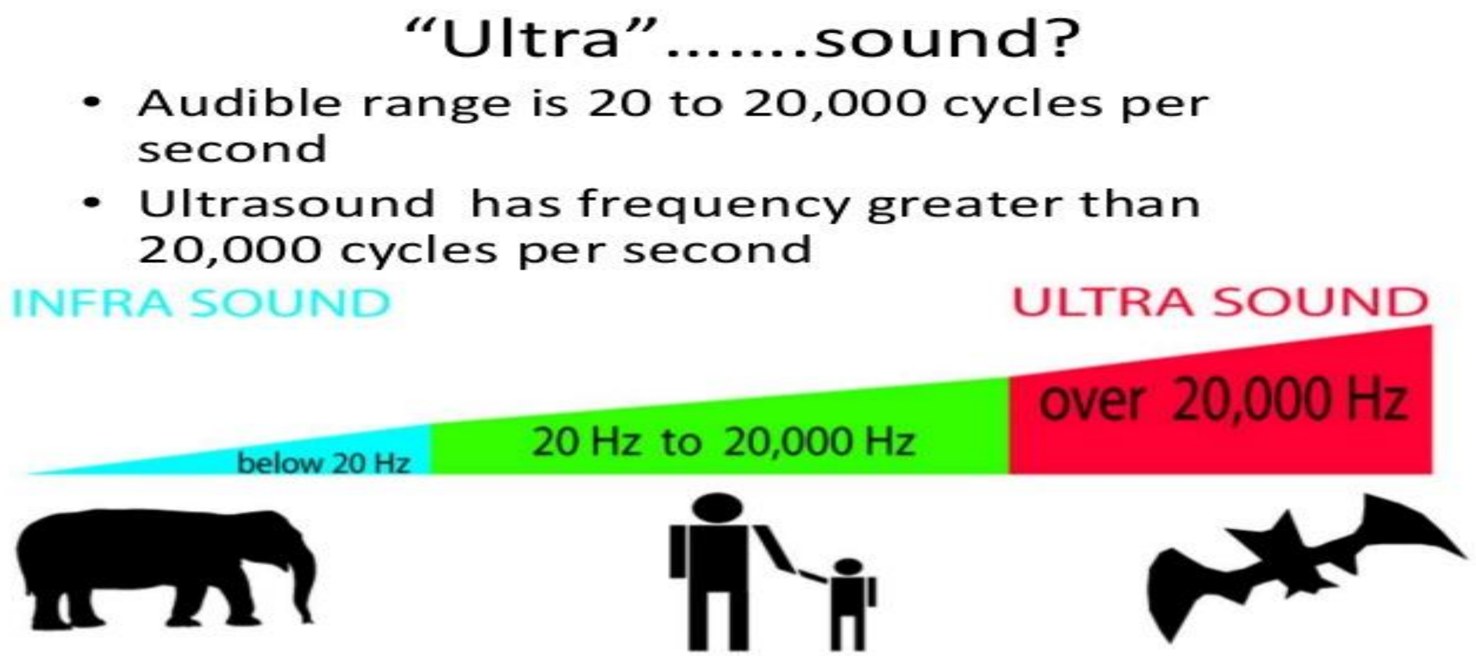
Limitations

1) The meters work only with conductive fluids. Pure substances, hydrocarbons, and gases cannot be measured. Most acids, bases, water, and aqueous solutions can be measured.
2. The conventional meters are relatively heavy, especially in larger sizes. Ceramic and probe-type units are lighter.
3. Electrical installation care is essential.
4. The price of magnetic flowmeters ranges from moderate to expensive.

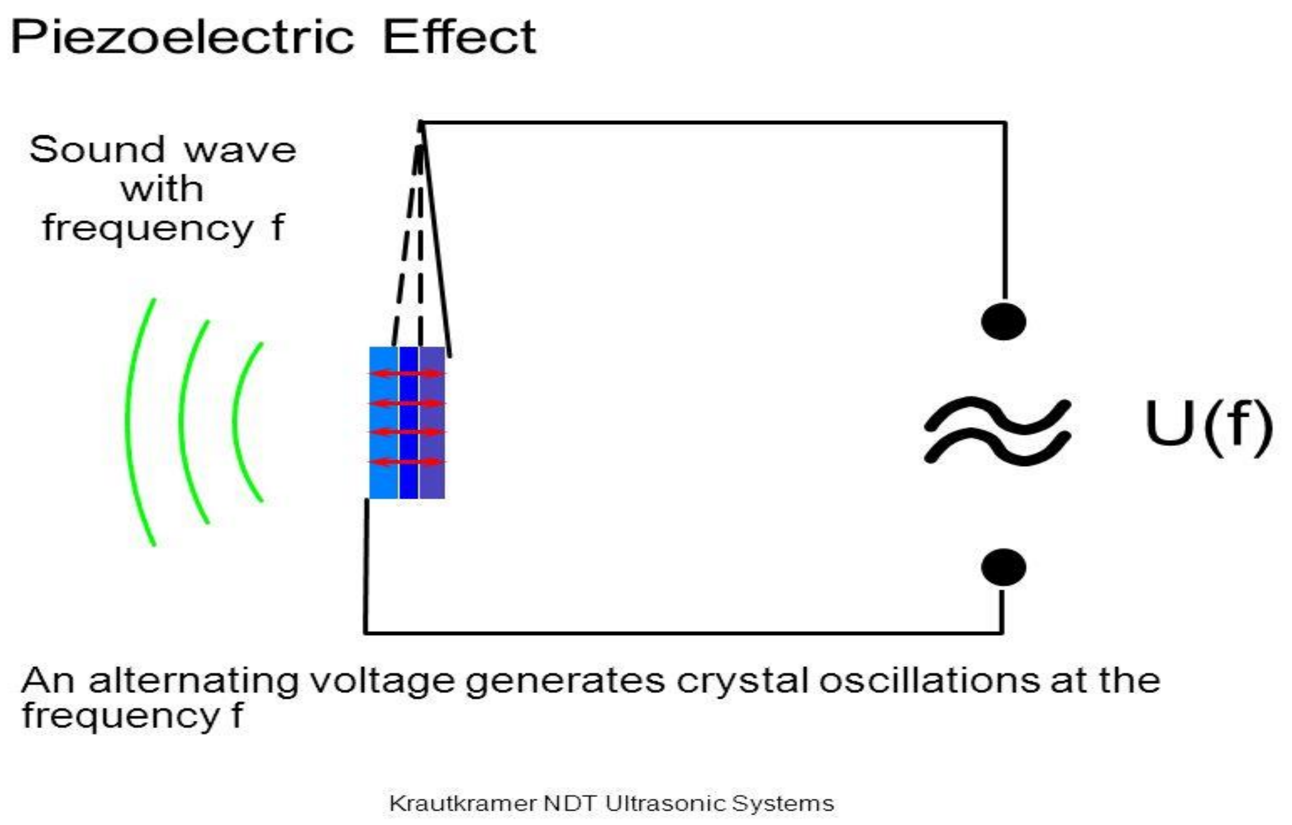
Ultrasonic flow meter

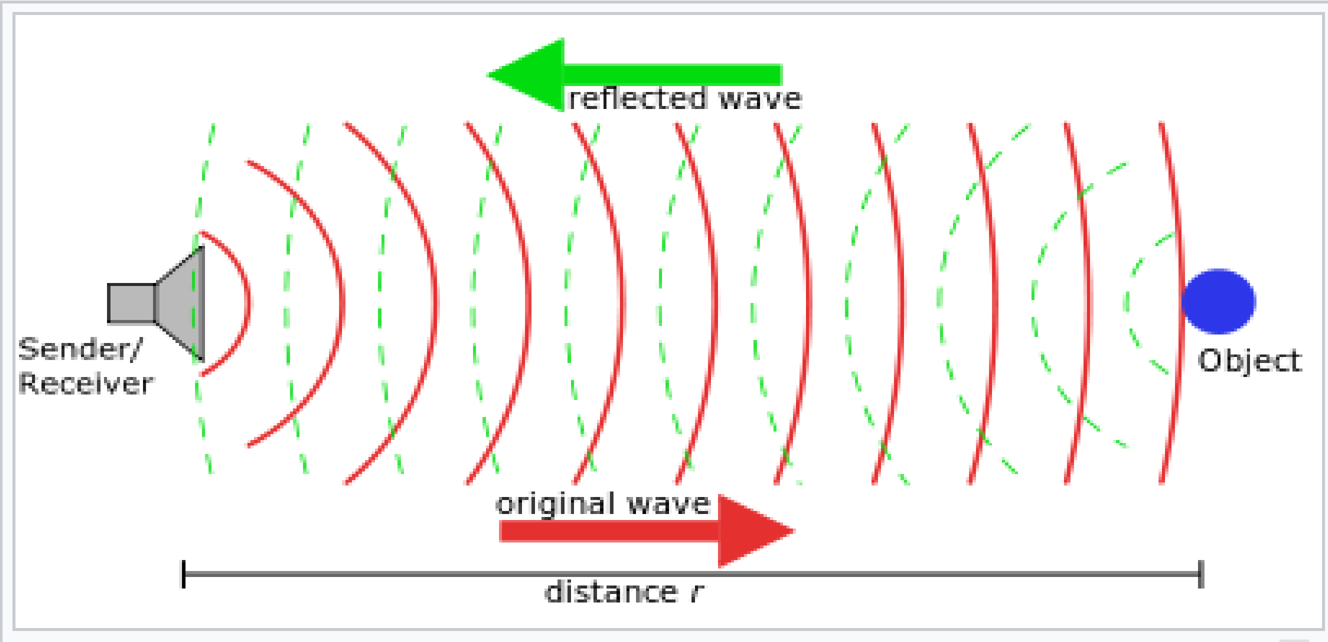
Ultrasonic flowmeters measure fluid velocity by passing high-frequency sound waves along the fluid flow path.

Fluid motion influences the propagation of these sound waves, which may then be measured to infer fluid velocity



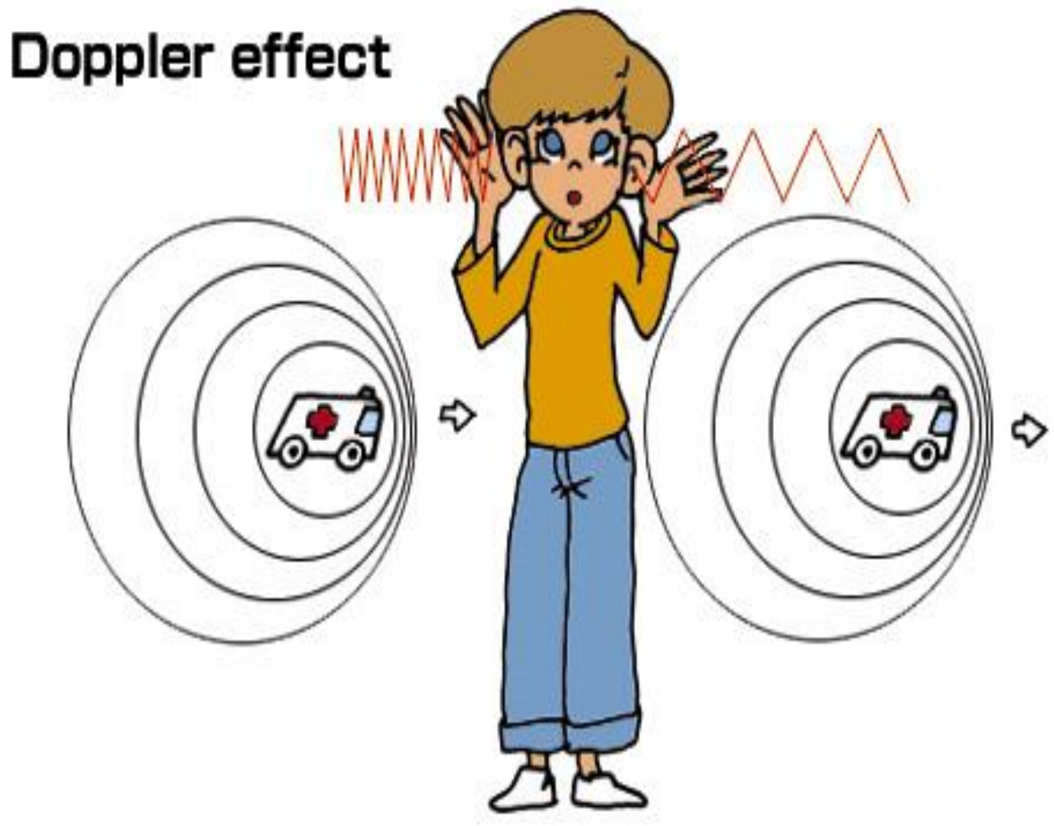
Ultra sound generation





Two major sub-types of ultrasonic flowmeters exist: Doppler and transit-time. Both types of ultrasonic flowmeter work by transmitting a high-frequency sound wave into the fluid stream (the incident pulse) and analyzing the received pulse.

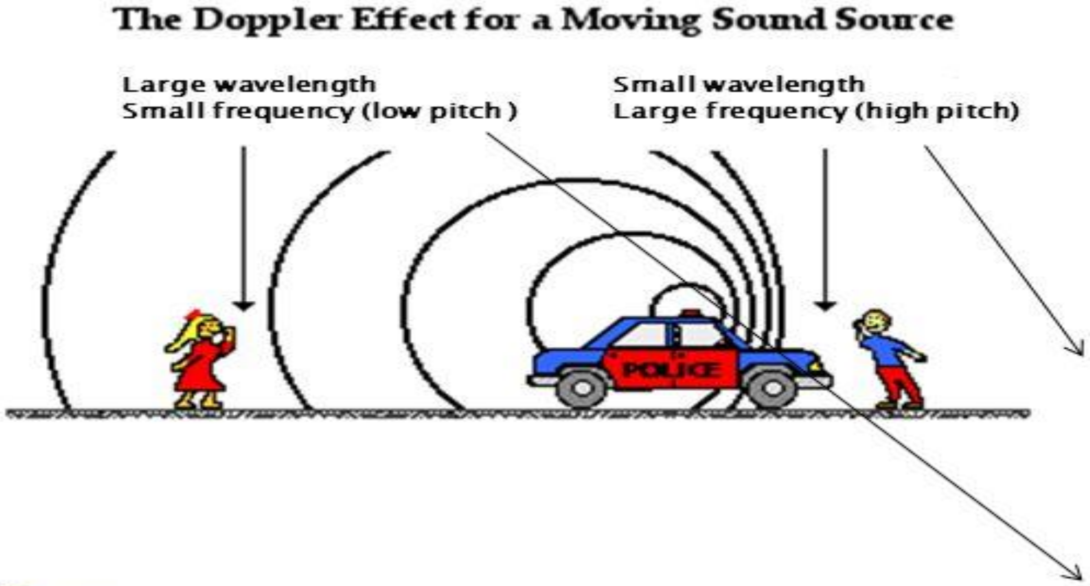
According to the Doppler effect, the change in wavelength of the reflected pulse is a function of the targeted object's relative velocity

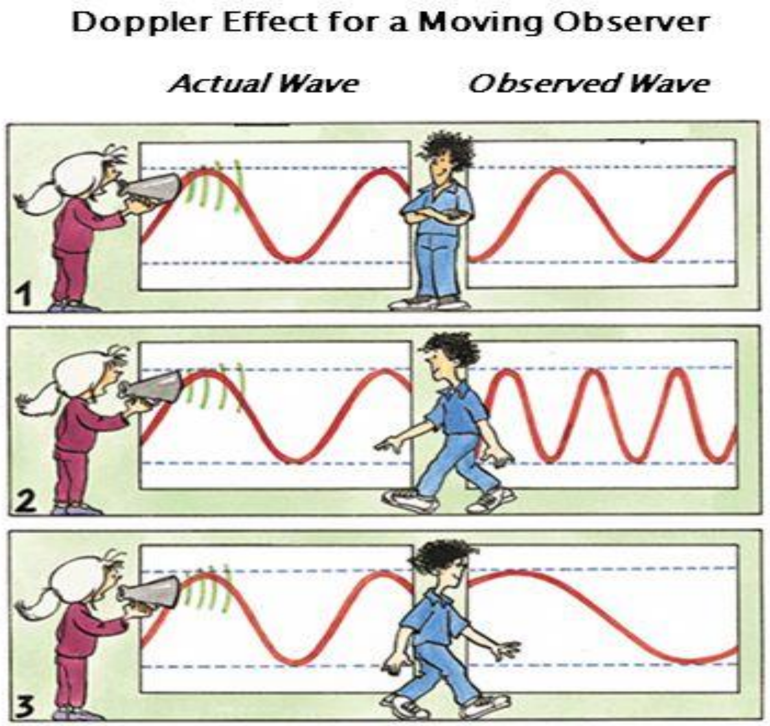


As the vehicle approaches the listener, the pitch of the horn seems higher than normal; when the vehicle passes the listener and begins to move away, the horn's pitch appears to suddenly "shift down" to a lower frequency.

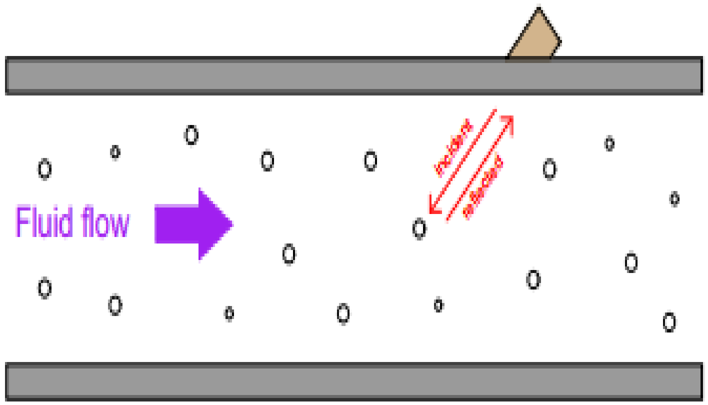
In reality, the horn's frequency never changes, but the velocity of the approaching vehicle relative to the stationary listener acts to "compress" the sonic vibrations in the air. When the vehicle moves away, the sound waves are "stretched" from the perspective of the listener.

- The Doppler Effect can be produced by either the <u>source</u> moving or by the <u>observer</u> moving.



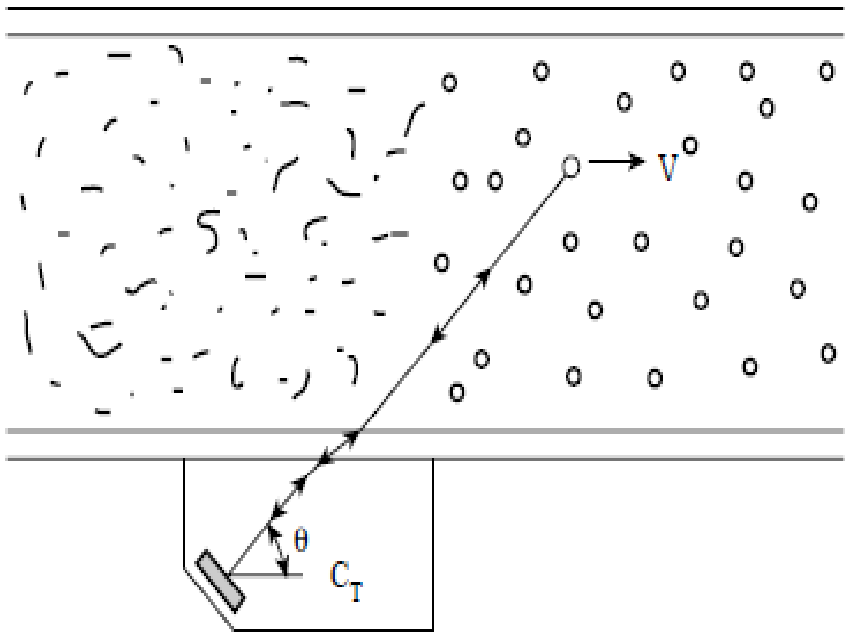


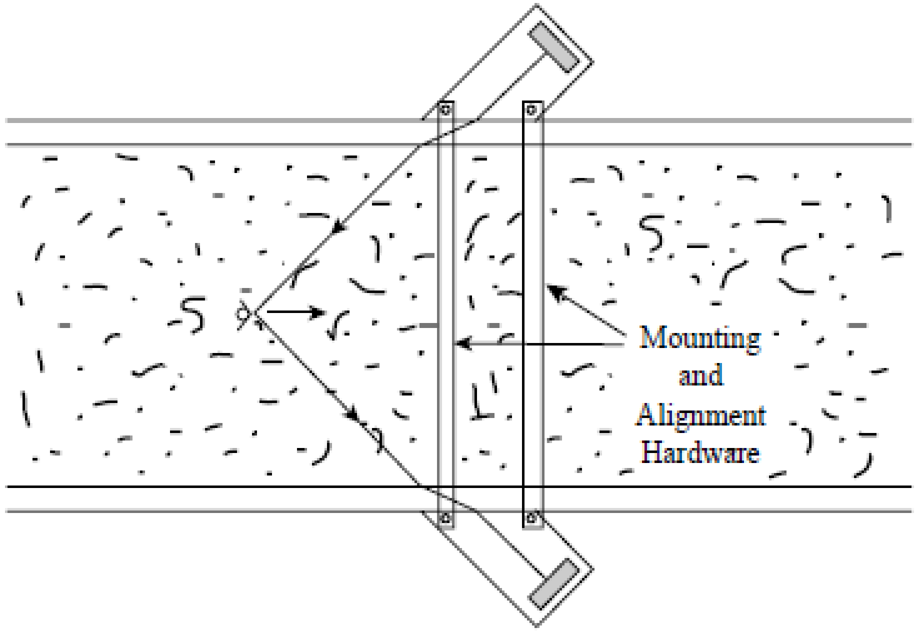
Ultrasonic flowmeter: Doppler based



A Doppler flowmeter bounces sound waves off of bubbles or particulate material in the flow stream, measuring the frequency shift and inferring fluid velocity from the magnitude of that shift.

If the reflected wave returns from a bubble advancing toward the ultrasonic transducer, the reflected frequency will be greater than the incident frequency.
If the flow reverses direction and the reflected wave returns from a bubble traveling away from the transducer, the reflected frequency will be less than the incident frequency.





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

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

Where,

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

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

- Doppler ultrasonic flow measurement is that the calibration of the flowmeter varies with the speed of sound through the fluid (c).

- As c increases, delta f must proportionately decrease for any fixed volumetric flow rate Q. Since the flowmeter is designed to directly interpret flow rate in terms of delta f, an increase in c causing a decrease in delta f, will thus register as a decrease in Q.

The speed of sound through any fluid is a function of that medium's density and bulk modulus (how easily it compresses):

$$c = \sqrt{\frac{B}{\rho}}$$

Where,

c = speed of sound in a material (meters per second)
B = Bulk modulus (pascals, or newtons per square meter)
ρ = Mass density of fluid (kilograms per cubic meter)

Temperature affects liquid density, and composition (the chemical constituency of the liquid) affects bulk modulus

Ultrasonic flowmeter: transit type

The time (t_{AB}) for the ultrasonic energy to go from transducer A to transducer B is given by the expression

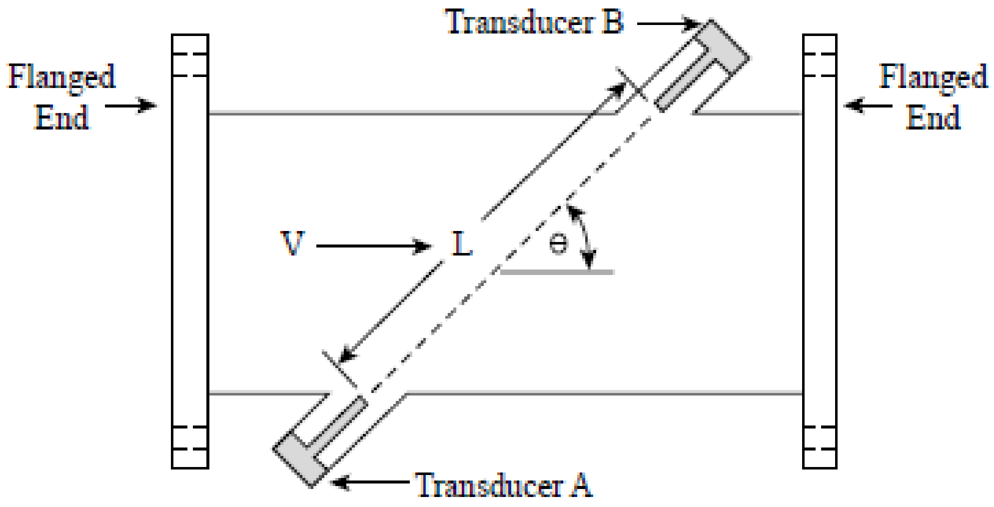
$$t_{AB} = L/(C + V \cdot \cos\theta)$$

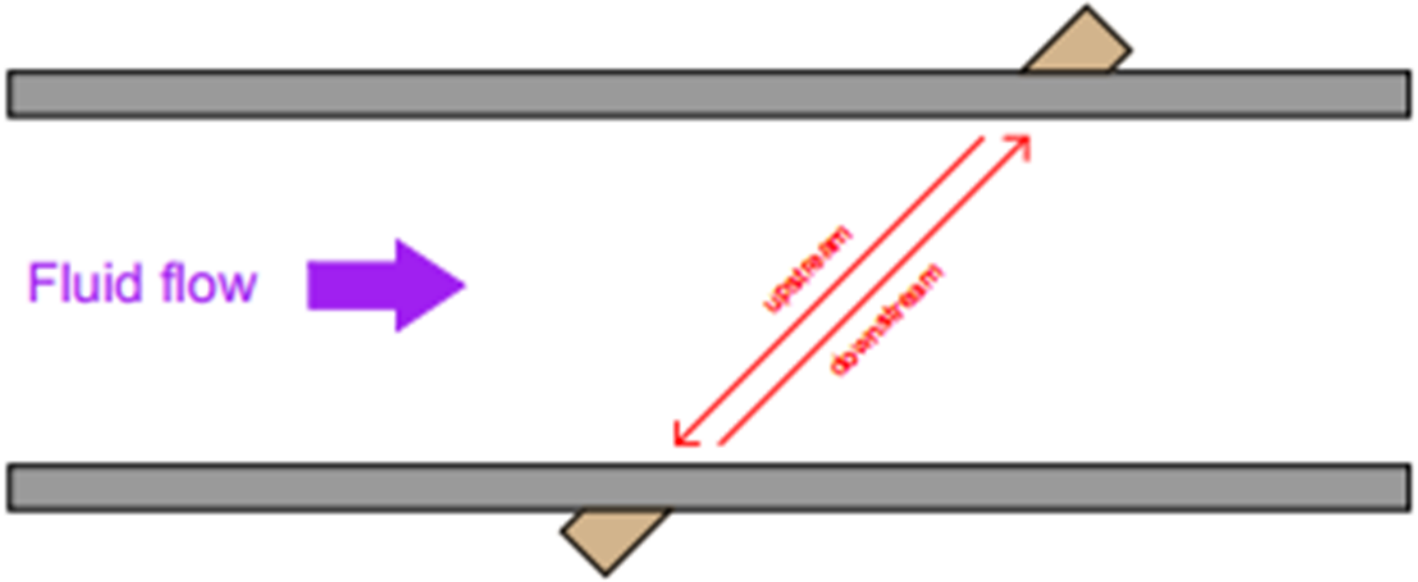
The time (t_{BA}) to go from B to A is given by

$$t_{BA} = L/(C - V \cdot \cos\theta)$$

where

C = speed of sound in the fluid
L = acoustic path length in the fluid
θ = angle of the path with respect to the pipe

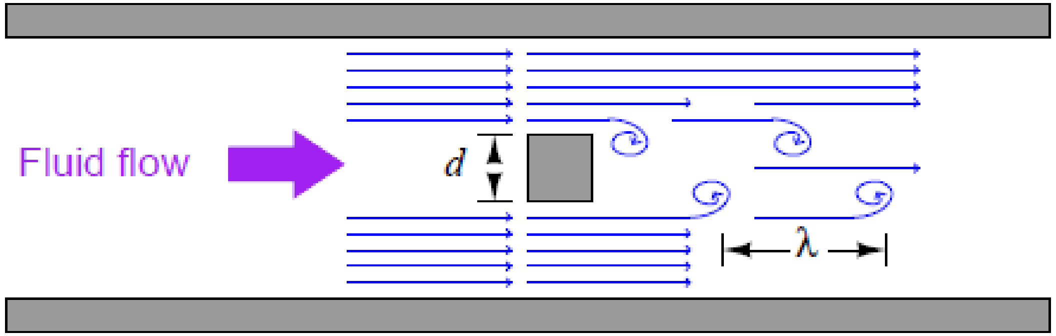




$$Q = k\frac{t_{up} - t_{down}}{(t_{up})(t_{down})}$$

Vortex flowmeter

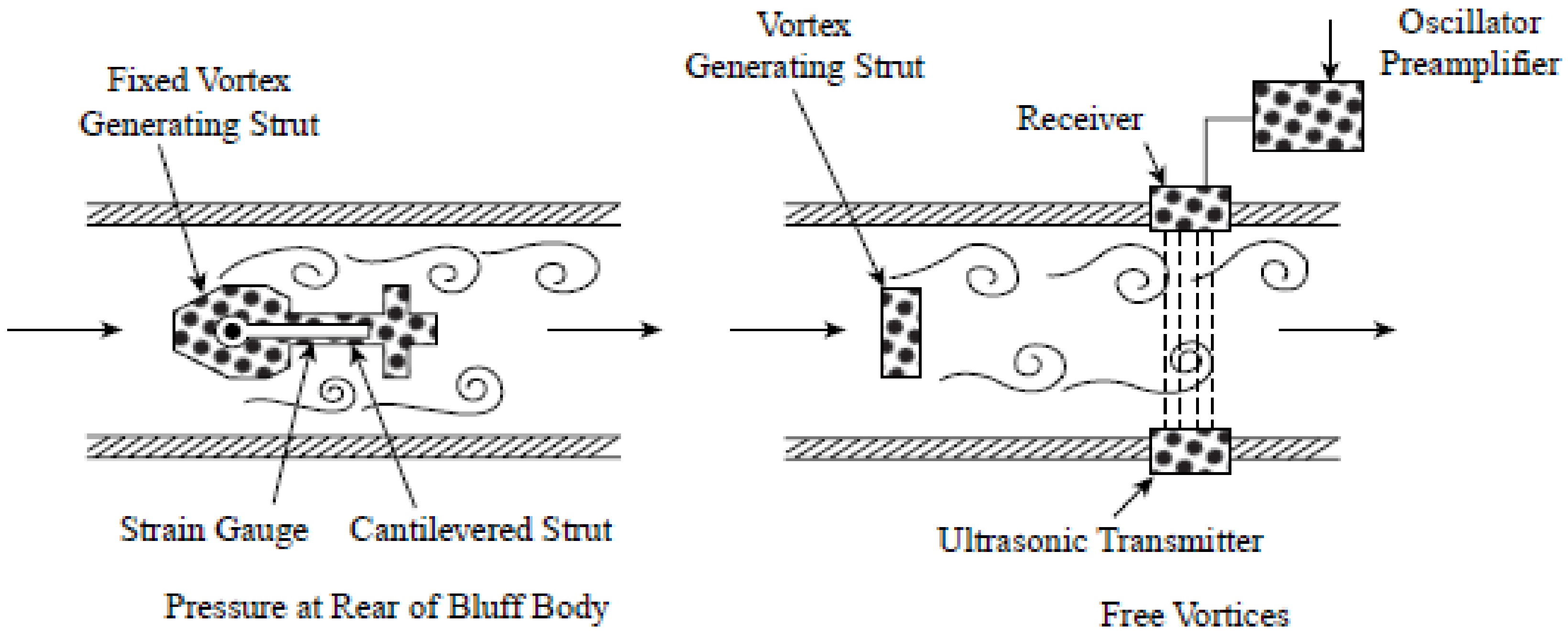
- When an obstruction is placed in the path of a flowing stream, the fluid is unable to remain attached to the object on its downstream sides and will alternately separate (shed) from one side and then the other.
- When a fluid moves with high Reynolds number past a stationary object (a “bluff body”), there is
- a tendency for the fluid to form vortices on either side of the object
- Von Kármán also noticed that the distance between the shed vortices is constant, regardless of flow velocity.



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

Strouhal determined that, as long as the Reynolds number of the flowing stream is between 20,000 and 7,000,000, the ratio between the shedder width and the vortex interval is 0.17. This number is called the Strouhal number

As long as the obstruction is not eroded or coated, as long as the pipe Reynolds number is high enough to produce vortices, and as long as the detector is sensitive enough to detect these vortices ,the result is a flowmeter that is sensitive to flow velocity and insensitive to the nature of the flowing media (liquid, gas, steam), the density, the viscosity, the temperature, the pressure, and any other properties.

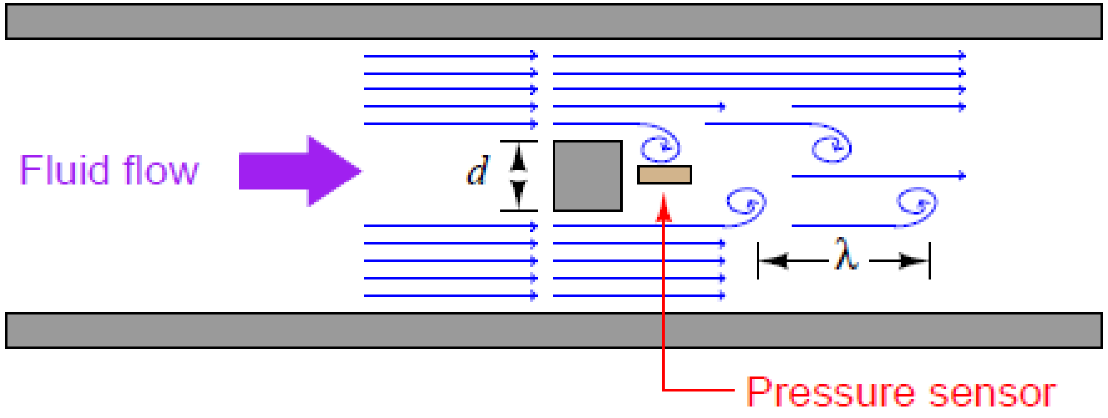


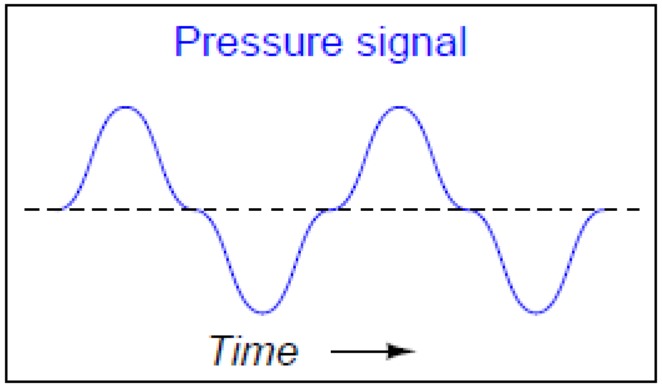
$$v = \lambda f$$

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

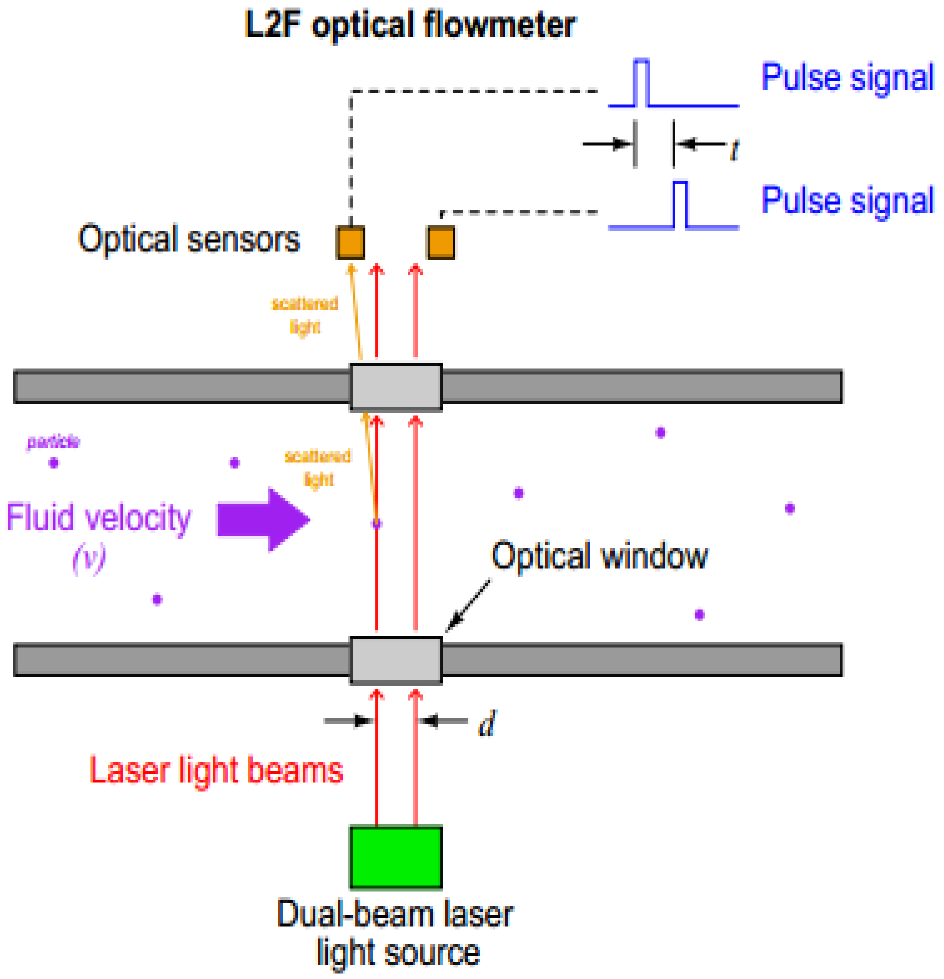
$$v = \frac{df}{0.17}$$

Detection of vortices


Fluid flow
d
λ
Pressure sensor


Pressure signal
Time

Optical flowmeter



Laser-Two-Focus (L2F) uses two laser beams to detect the passage of any light-scattering particles carried along by the moving fluid.

As a particle passes through each laser beam, it redirects the light away from its normal straight-line path in such a way that an optical sensor (one per beam) detects up the scattered light and generates a pulse signal.

As that same particle passes through the second beam, the scattered light excites a second optical sensor to generate a corresponding pulse signal.

The time delay between two successive pulses is inversely proportional to the velocity of that particle.

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

Where,

v = Velocity of particle

d = Distance separating laser beams

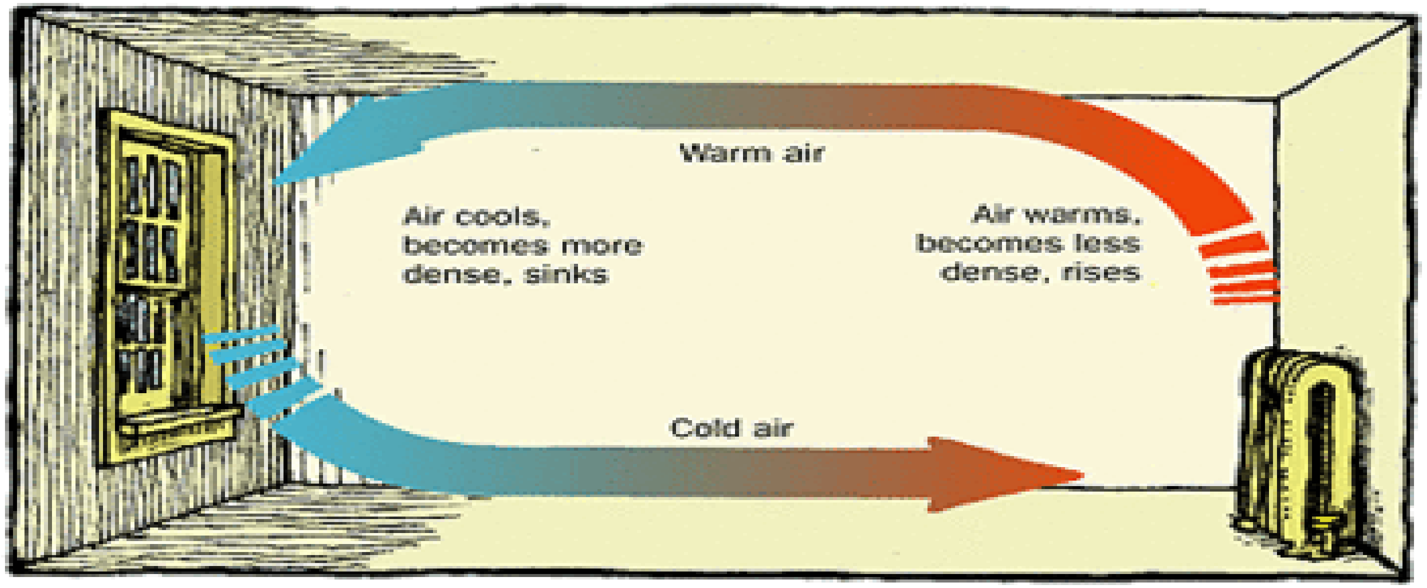
t = Time difference between sensor pulses

Mass flowmeters

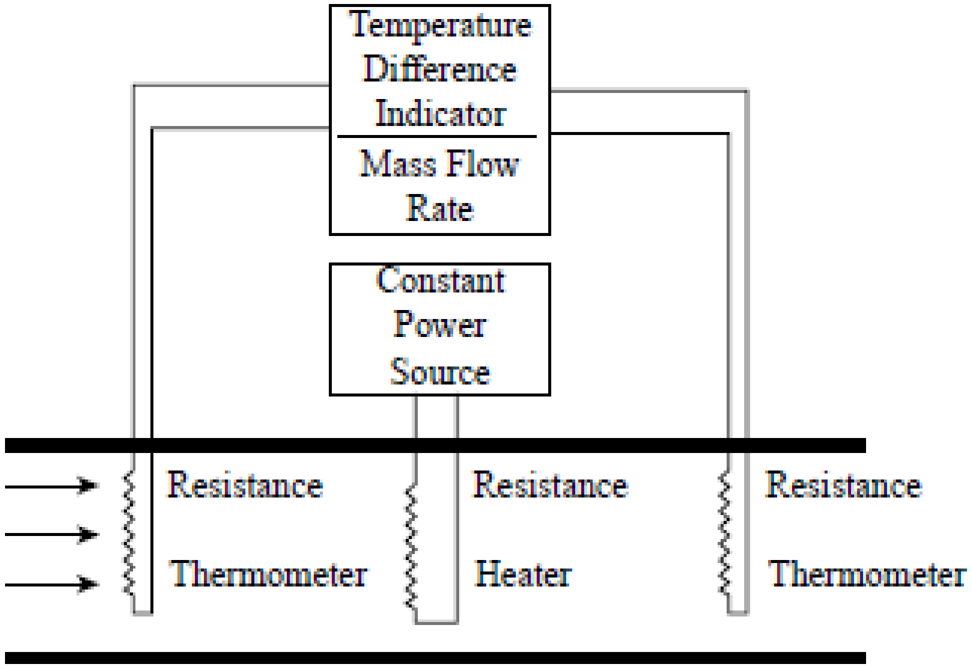
Hot Wire Anemometer/ thermal flowmeters

Thermal flowmeters can be divided into the following two categories:
1. Flowmeters that measure the rise in temperature of the fluid after a known amount of heat has been added to it. They can be called **heat transfer flowmeters**.
2. Flowmeters that measure the effect of the flowing fluid on a hot body. These instruments are sometimes called **hot-wire probes** or heated-thermopile flowmeters

Both types of flowmeters can be used to measure flow rates in terms of mass, which is a very desirable measurement, especially on gas service



HEAT TRANSFER FLOWMETERS



$$Q = Wc_p(T_2 - T_1)$$

where

Q = heat transferred (BTU/h or Cal/h)

W = mass flow rate of fluid (lbm/h or kgm/h)

c_p = specific heat of fluid (BTU/lbm °F or cal/kgm °C)

T_1 = temperature of the fluid before heat is transferred to it (°F or °C)

T_2 = temperature of the fluid after heat has been transferred to it (°F or °C)

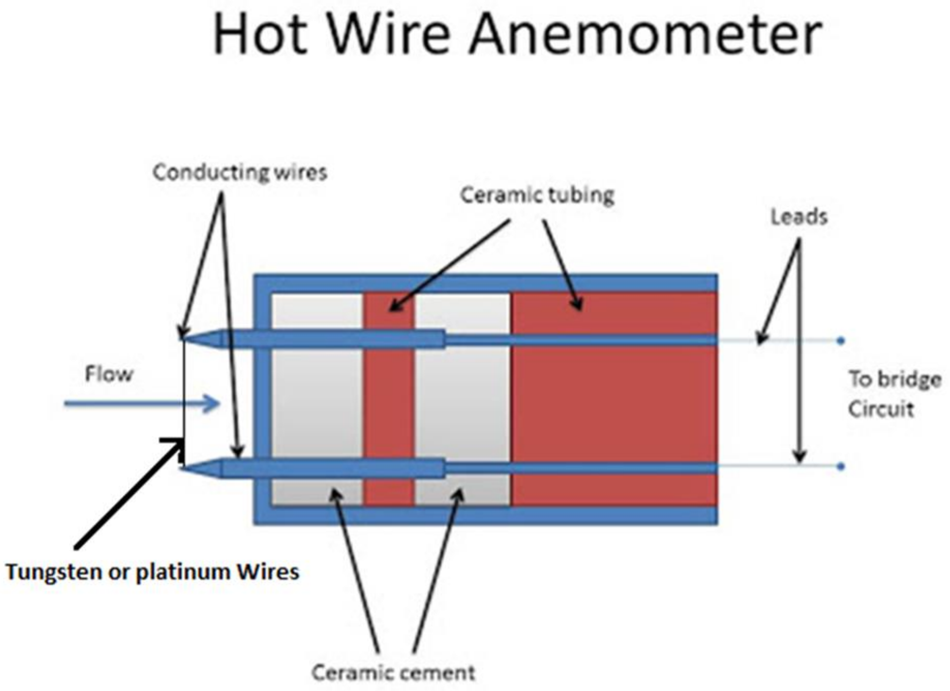
$$W = \frac{Q}{C_p(T_2 - T_1)}$$

Heat is added to the fluid stream with an electric immersion heater. The power to the heater equals the heat transferred to the fluid (Q) and is measured using a wattmeter. T1 and T2 are thermocouples or resistance thermometers. Since we know the fluid, we also know the value of its specific heat. Thus, by measuring Q, T1, and T2, the flow rate (W) can be calculated. T1 and T2 do not have to

be separately detected; they can be connected to each other so that the temperature difference (T1 − T2) is measured directly

Hot wire probes

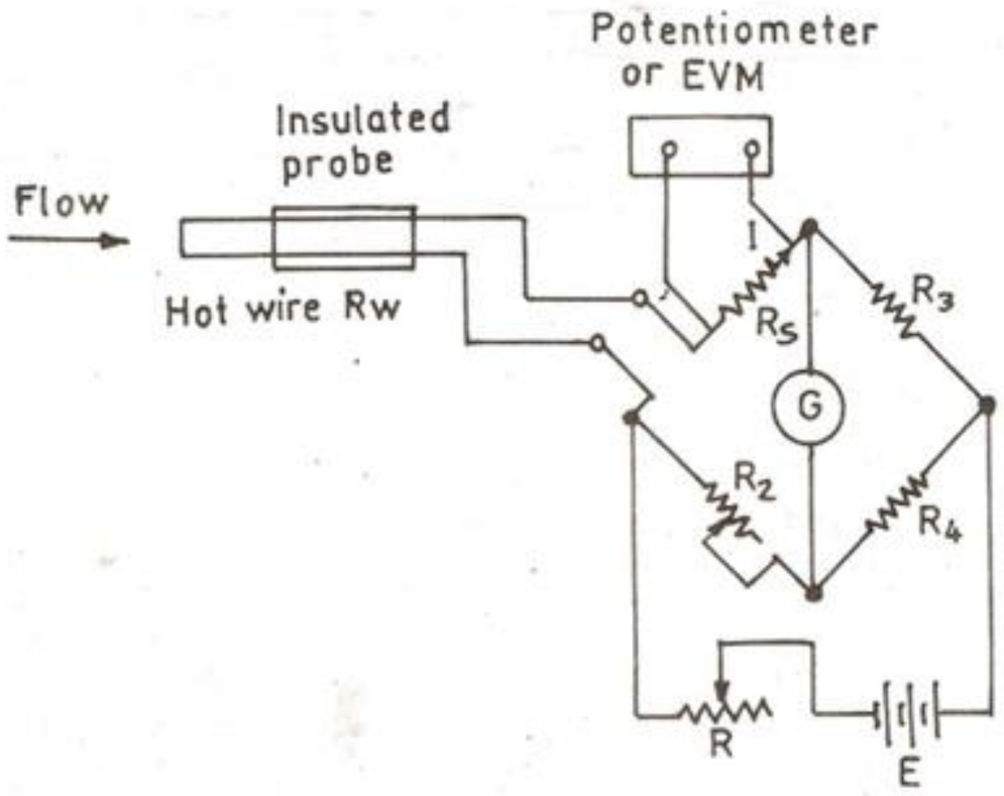
When an electrically heated wire is placed in a flowing gas stream, heat is transferred from the wire to the gas and hence the temperature of the wire reduces, and due to this, the resistance of the wire also changes. This change in resistance of the wire becomes a measure of flow rate



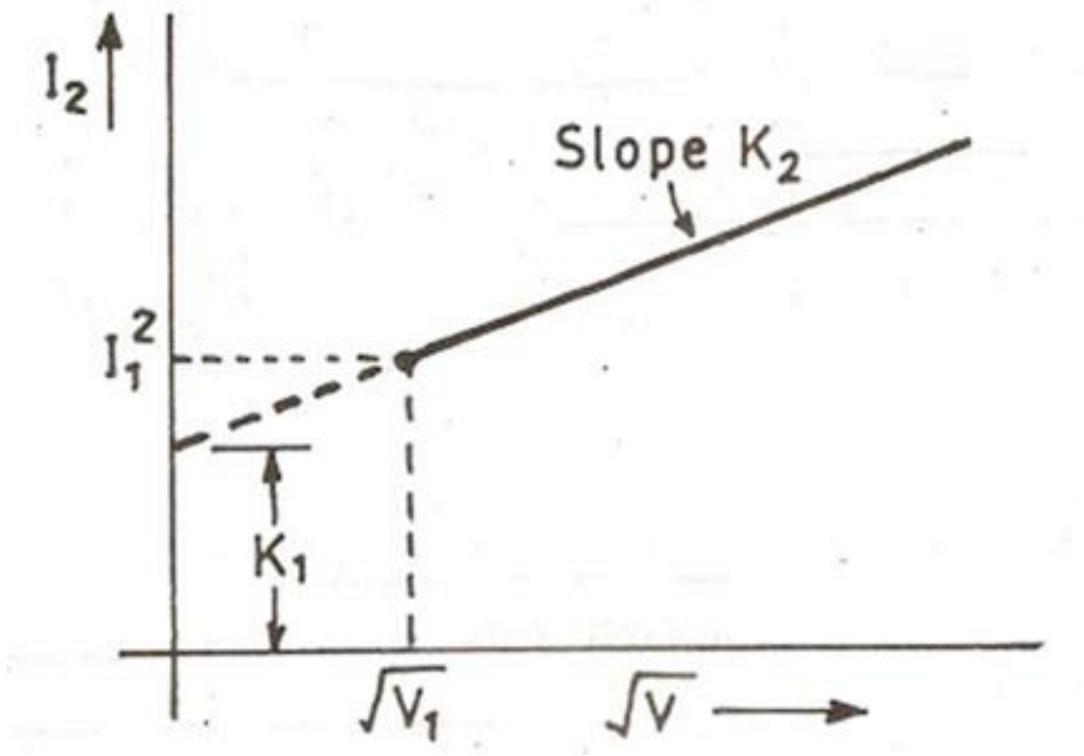
Operation of Hot wire Anemometer
There are two methods of measuring flow rate using a anemometer bridge combination namely:

Constant current method
Constant temperature method

Constant temperature anemometer

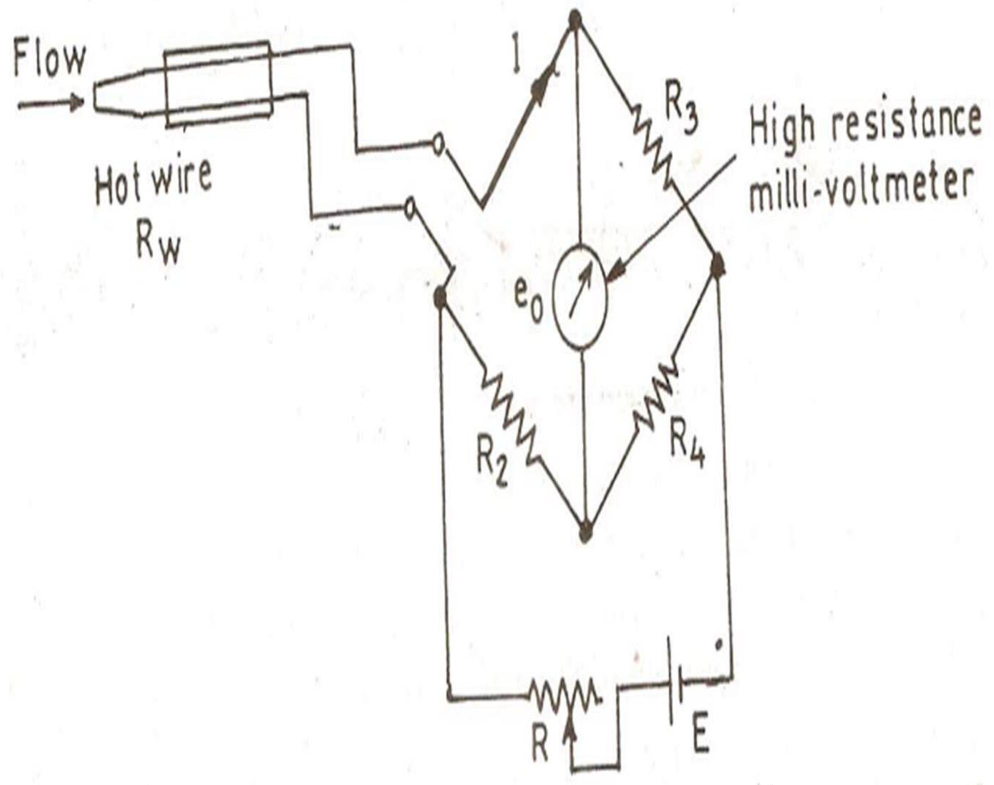


- A current is initially passed through the wire.
- Due to the gas flow, heat transfer takes place from the sensing wire to the flowing gas and this tends to change the temperature and hence the resistance of the wire.
- The principle in this method is to maintain the temperature and resistance of the sensing wire at a constant level. Therefore, the current through the sensing wire is increased to bring the sensing wire to have its initial resistance and temperature.
- The electrical current required in bringing back the resistance and hence the temperature of the wire to its initial condition becomes a measure of flow rate of the gas when calibrated.

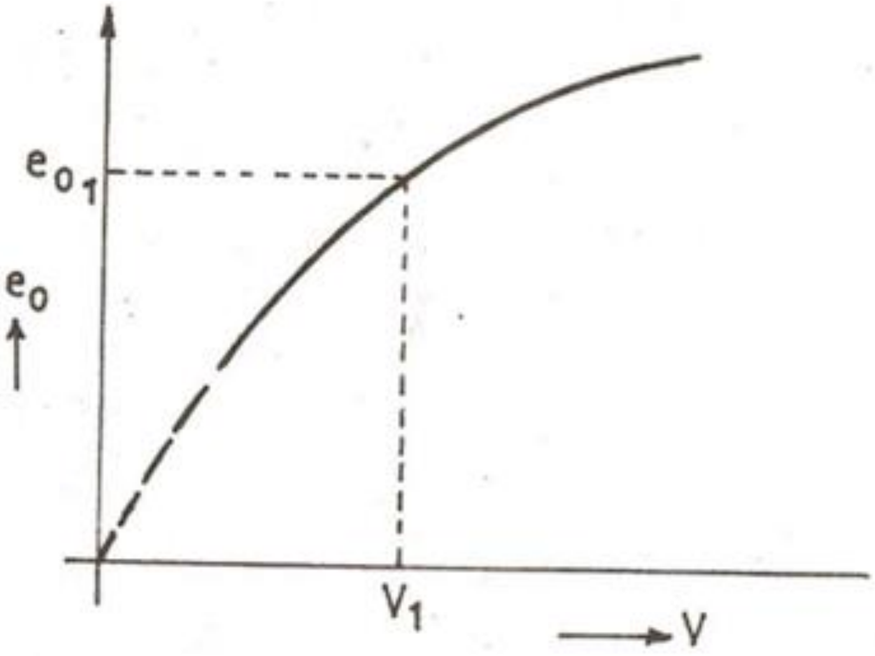


I_2
Slope K_2
I_1^2
K_1
$\sqrt{V_1}$
$\sqrt{V}$

Constant current anemometer

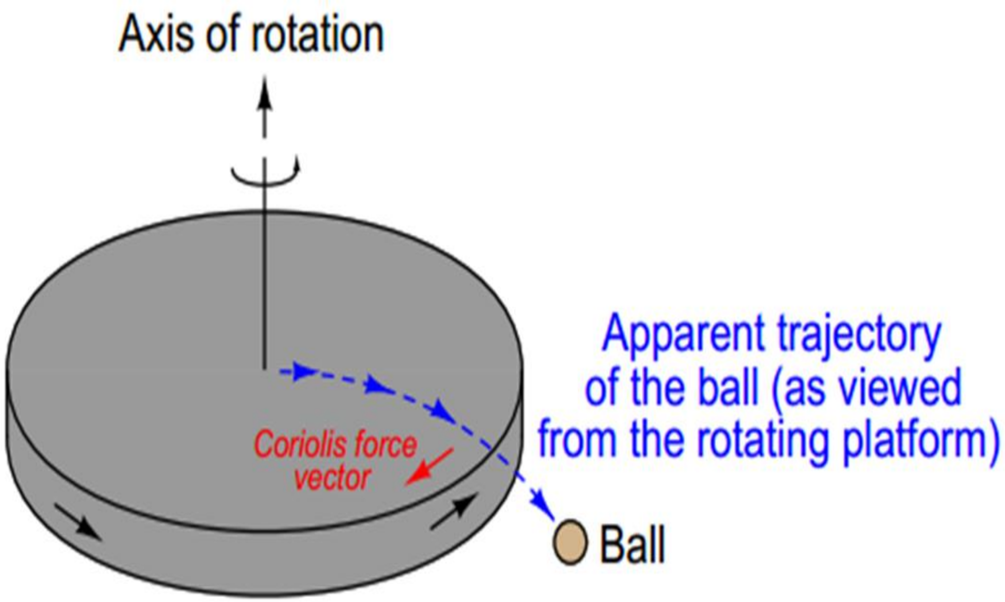


- A constant current is passed through the sensing wire. That is, the voltage across the bridge circuit is kept constant, that is, not varied.
- Due to the gas flow, heat transfer takes place from the sensing wire to the flowing gas and hence the temperature of the sensing wire reduces causing a change in the resistance of the sensing wire. (this change in resistance becomes a measure of flow rate).
- Due to this, the galvanometer which was initially at zero position deflects and this deflection of the galvanometer becomes a measure of flow rate of the gas when calibrated



Relationship between bridge output voltage and velocity of fluid

Coriolis force



$$\vec{F}_c = -2\vec{\omega} \times \vec{v'} m$$

Where,

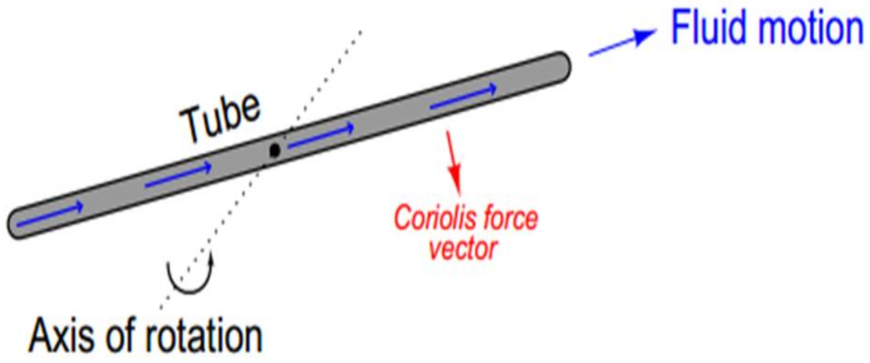
$\vec{F}_c$ = Coriolis force vector

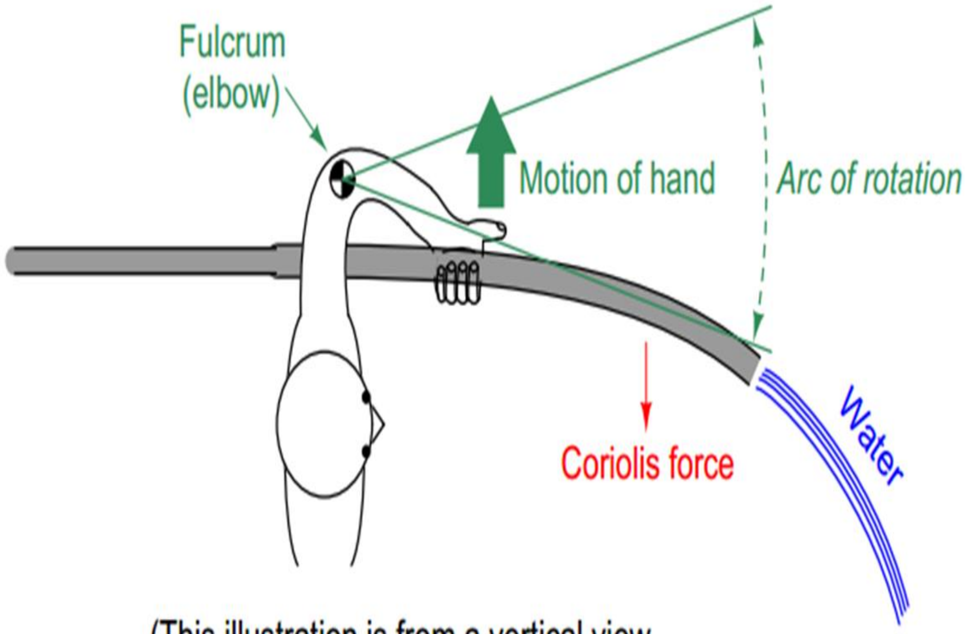
$\vec{\omega}$ = Angular velocity (rotation) vector

$\vec{v'}$ = Velocity vector as viewed from the rotating reference frame

m = Mass of the object

Coriolis force





(This illustration is from a vertical view, looking down. The Coriolis force acts laterally, bending the hose to the side.)

Coriolis Flowmeter

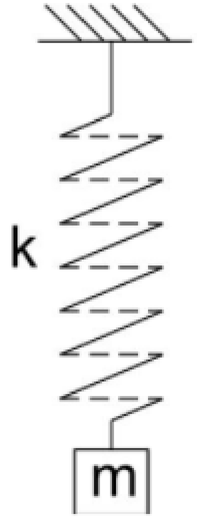
Coriolis flowmeter works by **shaking one or more tubes carrying the flowing fluid**, then precisely measuring the frequency and phase of that shaking.
The back-and-forth shaking is driven by an electromagnetic coil, powered by an electronic amplifier circuit to shake the tube(s) at their **mechanical resonant frequency**.
Since this **frequency depends on the mass of each tube, and the mass of the tubes depends on the density of the fluid filling the fixed volume of the tubes**, the resonant frequency becomes an inverse indication of fluid density.

$$\text{Tube frequency} \propto \frac{1}{\text{Density}}$$

$$f \propto \frac{1}{\rho}$$

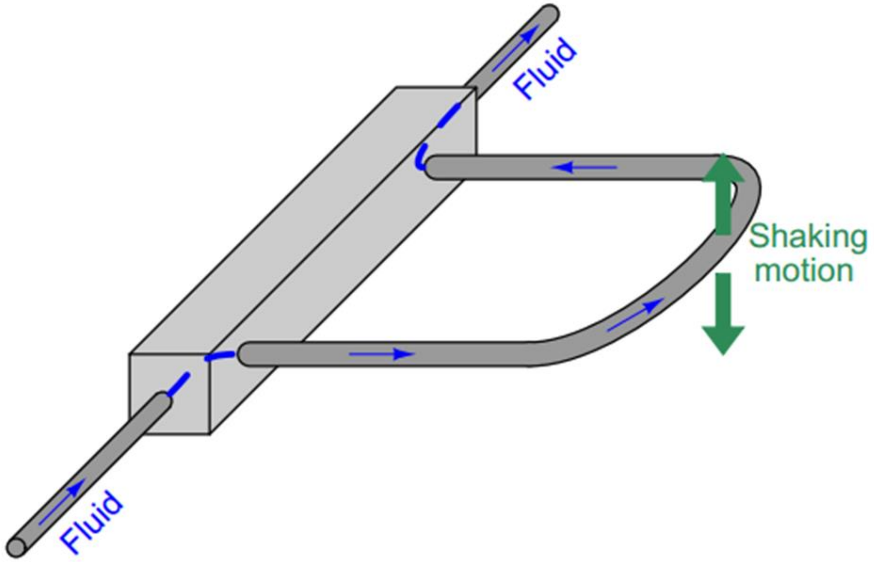
The resonant frequency is

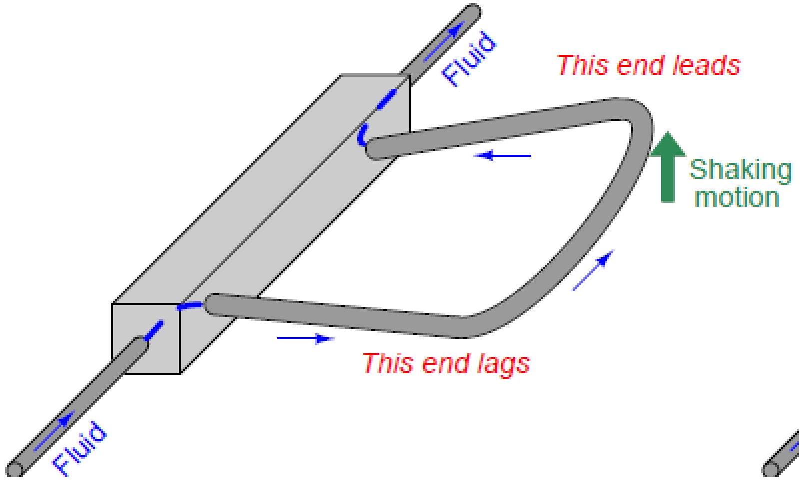
$$\frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

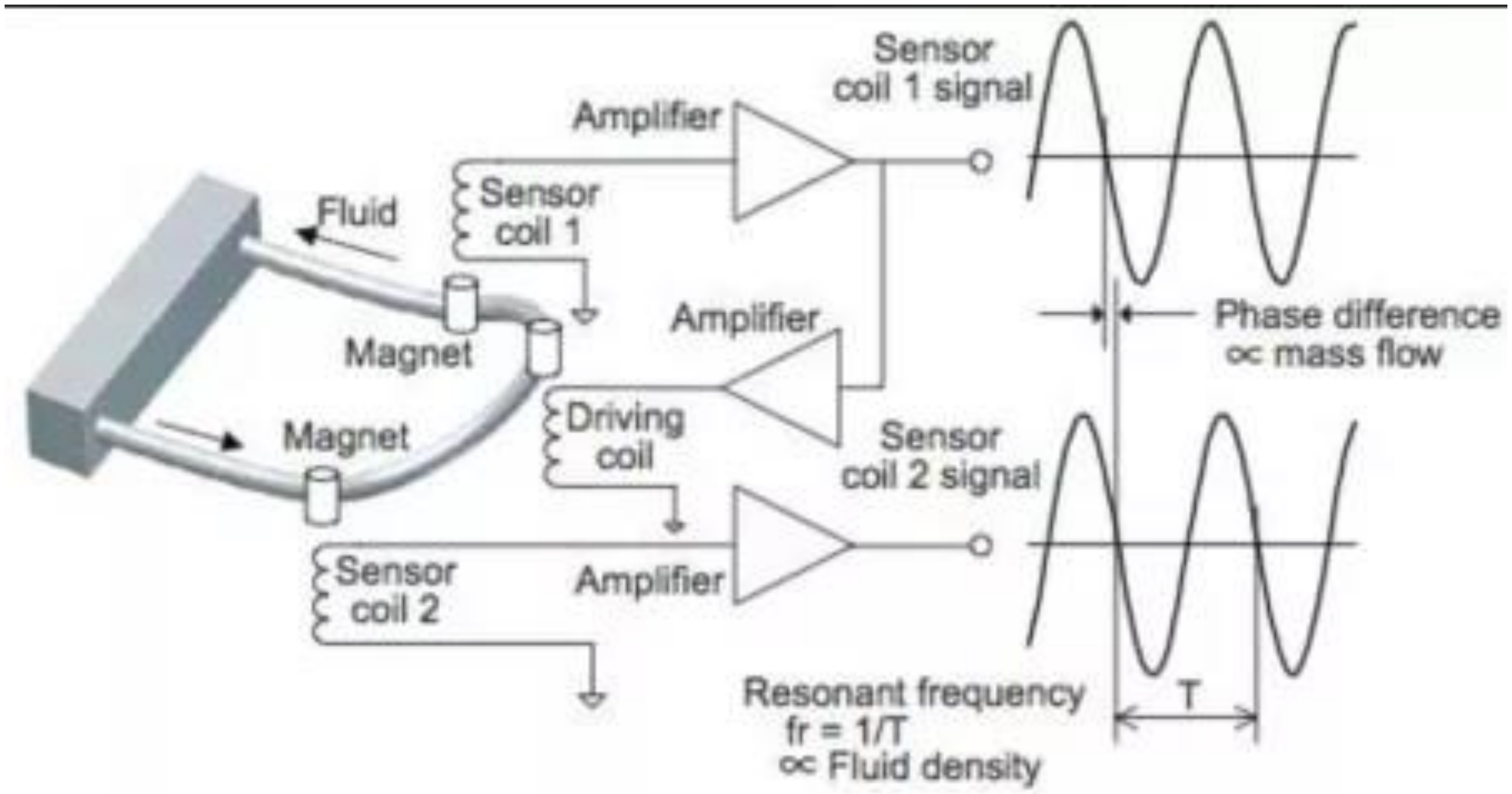


As fluid begins to move through the tubes, the inertia of the moving fluid adds another dimension to the tubes' motion: the tubes begin to undulate, twisting slightly instead of just shaking back and forth. This twisting motion is directly proportional to the mass flow rate, and is internally measured by comparing the phase shift (θ) between motion at one point on the tube versus another point on the tube: the greater the undulation, the greater the phase shift between these two points' vibrations.

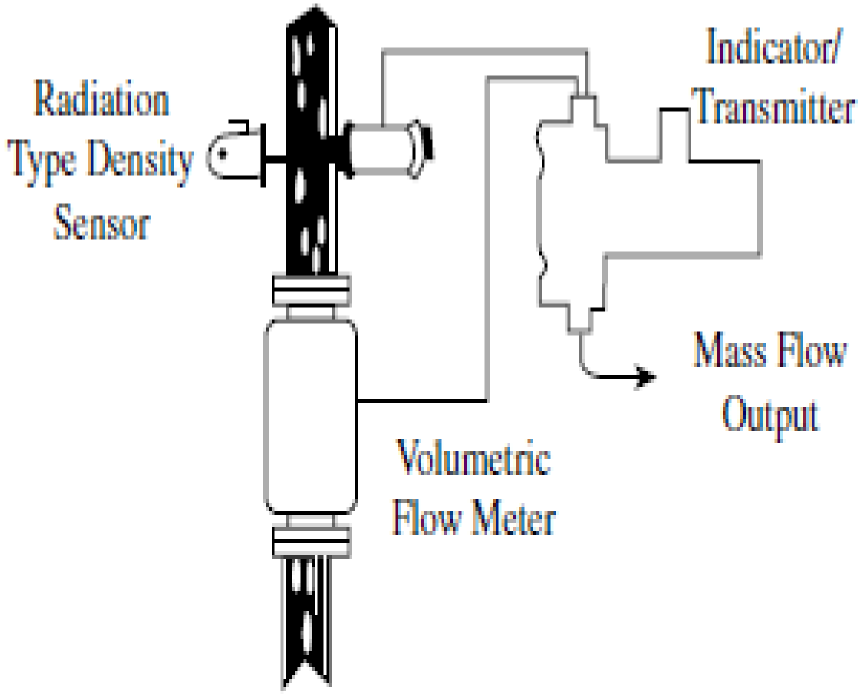
$$\text{Tube twisting} \propto \text{Mass flowrate} \qquad \theta \propto W$$



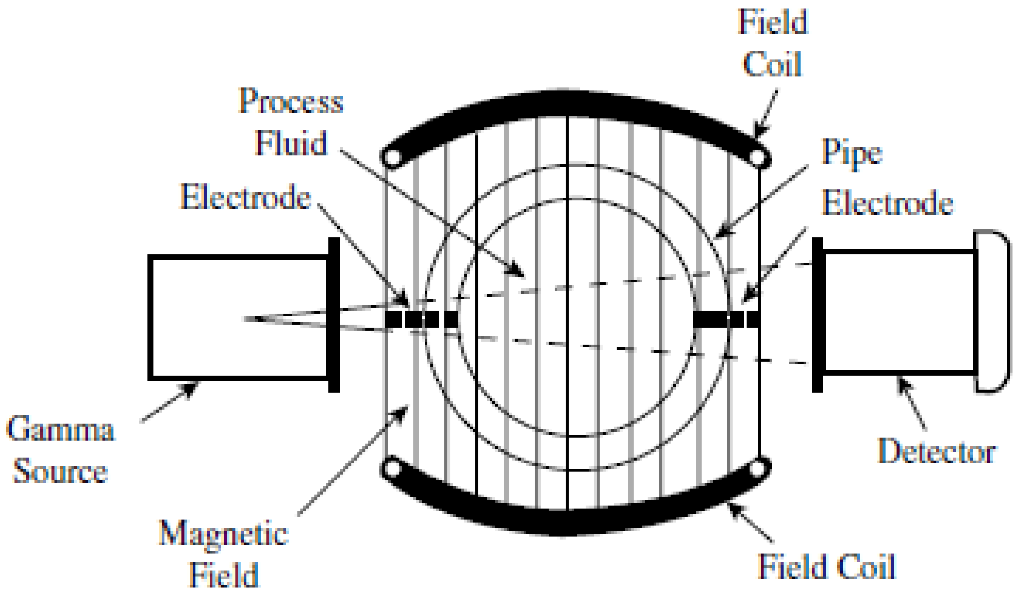



Sensor
coil 1 signal
Amplifier
Sensor
coil 1
Fluid
Magnet
Amplifier
Phase difference
∝ mass flow
Magnet
Driving
coil
Sensor
coil 2 signal
Sensor
coil 2
Amplifier
Resonant frequency
fr = 1/T
∝ Fluid density
T

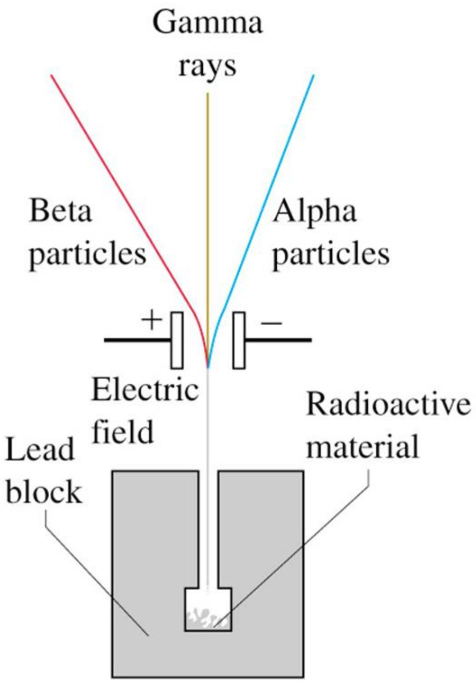
Radiation type mass flow meters



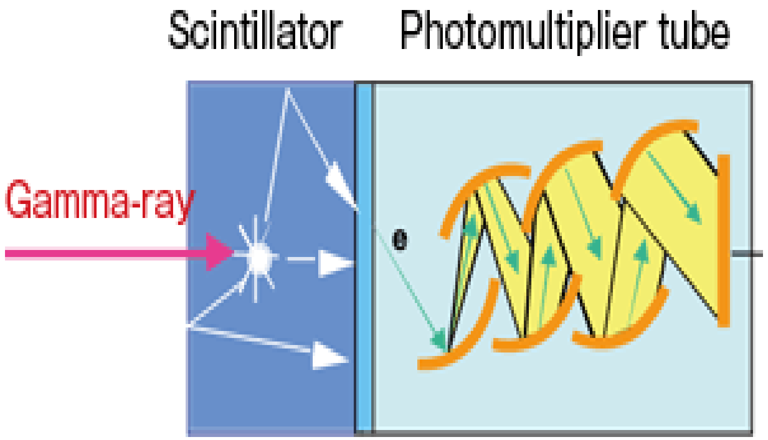
- Two separate sensors—one to measure the volumetric flow and the other to detect the density of the flowing stream—and then to use the two transmitter signals as inputs into a mass flow computing module
- Units are composed of a either a **Doppler ultrasonic flowmeter** or a **magnetic flowmeter** and a **gamma-radiation-based densitometer**



Radioactive emissions



Gamma Rays detector



ANGULAR MOMENTUM-TYPE MASS FLOWMETERS

H = angular momentum (lbf-ft-sec)
I = moment of inertia (lbf-ft^2)
ω = angular velocity (rad/sec)
α = angular acceleration (rad/sec^2)
Y = torque (ft-lbf)
r = radius of gyration (ft)
m = mass (slugs)
t = time (sec)

The mass flow of fluid can be determined if an angular momentum is introduced into the fluid stream and measurements are made of the torque produced by this angular momentum and of the fluid's angular velocity

Newton's second law of angular motion states that

$$Y = I\alpha$$

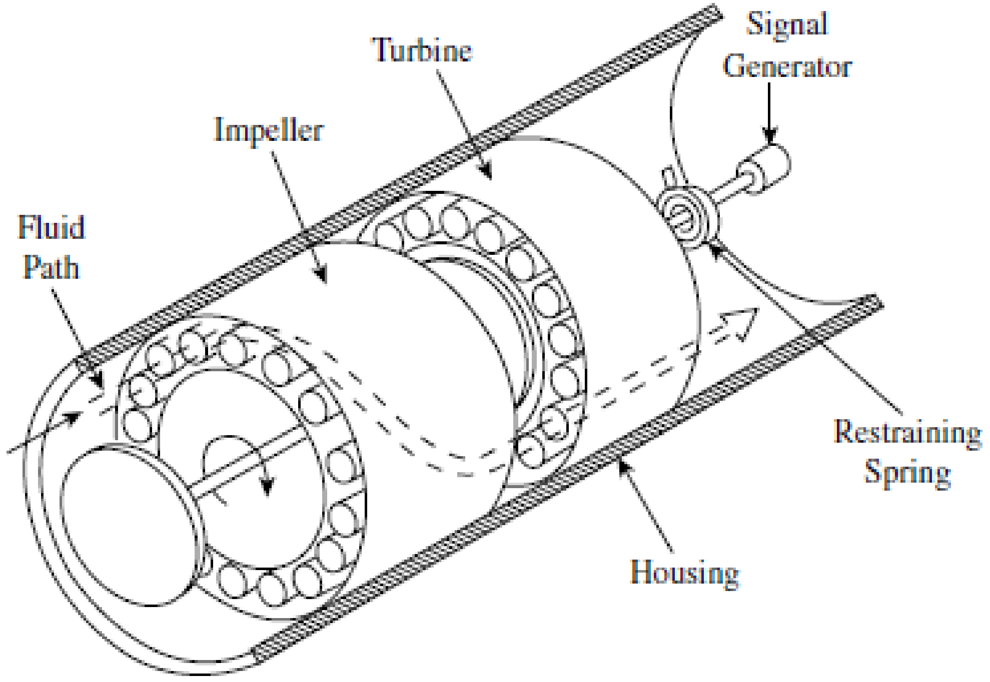
$$H = I\omega$$

$$I = mr^2$$

$$Y = mr^2\alpha \qquad H = mr^2\omega \qquad \alpha = \frac{\omega}{t}$$

$$Y = \frac{m}{t}r^2\omega \qquad \frac{m}{t} = \frac{Y}{r^2\omega} \qquad \frac{H}{t} = \frac{m}{t}r^2\omega$$

Impeller-Turbine Flowmeter



- The impeller-turbine-type mass flowmeter uses two rotating elements in the fluid stream, an impeller and a turbine .
- Both elements contain channels through which the fluid flows.

- The impeller is driven at a constant speed by a synchronous motor through a magnetic coupling and imparts an angular velocity to the fluid as it flows through the meter.
- The turbine located downstream of the impeller removes all angular momentum from the fluid and thus receives a torque proportional to the angular momentum.
- This turbine is restrained by a spring that deflects through an angle that is proportional to the torque exerted upon it by the fluid, thus giving a measure of mass flow

Constant Torque-Hysteresis Clutch

Another angular-momentum type mass flowmeter eliminates the necessity of making a torque measurement after imparting a constant torque to the fluid stream. The relationship between mass flow and torque is

$$\frac{m}{t} = \frac{Y}{r^2\omega}$$

Therefore, if Y is held at a constant value, and since r^2 is a physical constant of any given system,

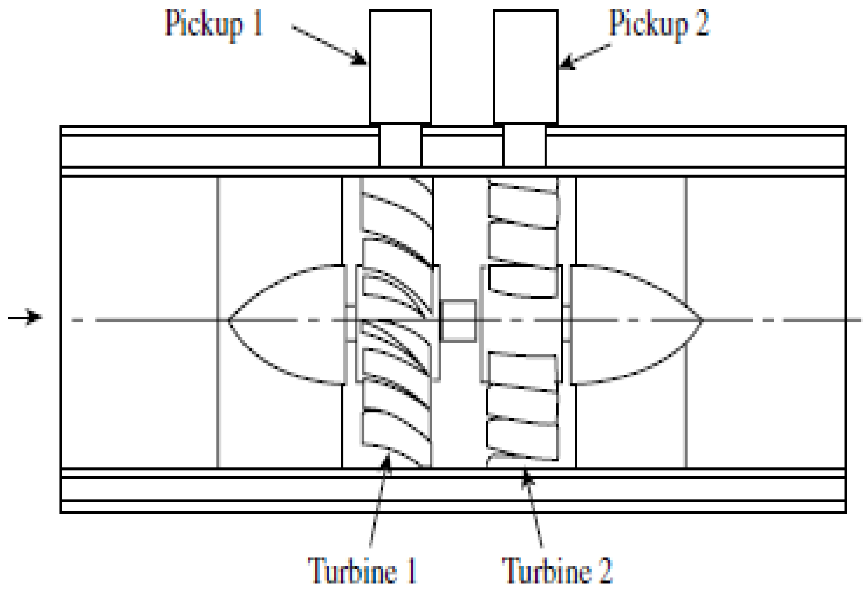
$$\frac{m}{t} = \frac{k}{\omega}$$

This relationship is used in designing a mass flowmeter as follows:

1. A synchronous motor is placed in the center of the flowmeter assembly.
2. This motor is magnetically coupled to an impeller that is located within the flowing process stream.
3. The magnetic coupling between the motor and the impeller is provided by means of a hysteresis clutch that transmits a constant torque from the motor to the impeller.

Thus, a measurement of the rotational speed of the impeller is inversely proportional to the mass flow rate.

Twin-Turbine Flowmeter



In this instrument, two turbines are mounted on a common shaft .

They are connected with a calibrated torsion member.

A reluctance-type pickup coil is mounted over each turbine, and a strong magnet is located in each turbine within the twin-turbine assembly.

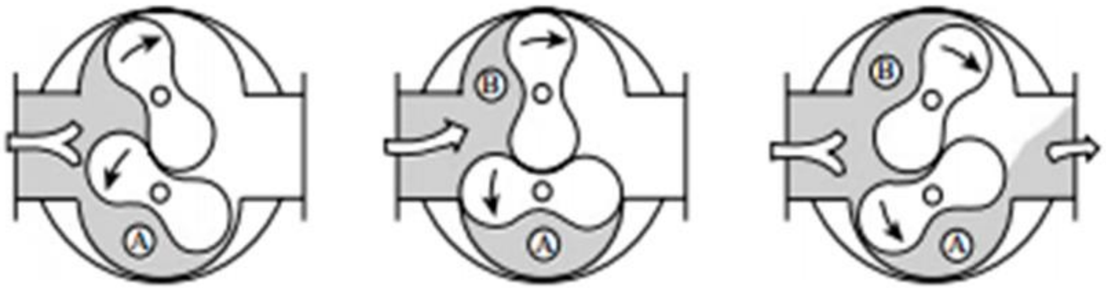
Each turbine is designed with a different blade angle; therefore, there is a tendency for the turbines to turn at different angular velocities.

However, because the motion of the turbines is restricted by the coupling torsion member, the entire assembly rotates in unison at some average velocity, and an angular phase shift is developed between the two turbines. This angle is a direct function of the angular momentum of the fluid

As each turbine magnet passes its own pickup coil, the coil generates a pulse. The pulse from the upstream turbine is used to open a so-called electronic gate, while the pulse from the downstream turbine closes this gate. An oscillator is placed in the electronic circuit, and the oscillations are counted while the gate is opened. The number of oscillations is thus a function of the angle between the two turbines.

Positive displacement meters

Positive-displacement meters measure by internally passing isolated volumes of fluid that successively fill and empty compartments with a fixed quantity of fluid. The filling-and emptying process is controlled by suitable valving and is translated into rotary motion to operate a calibrated register or index that indicates the total volume of fluid passed through the meter.

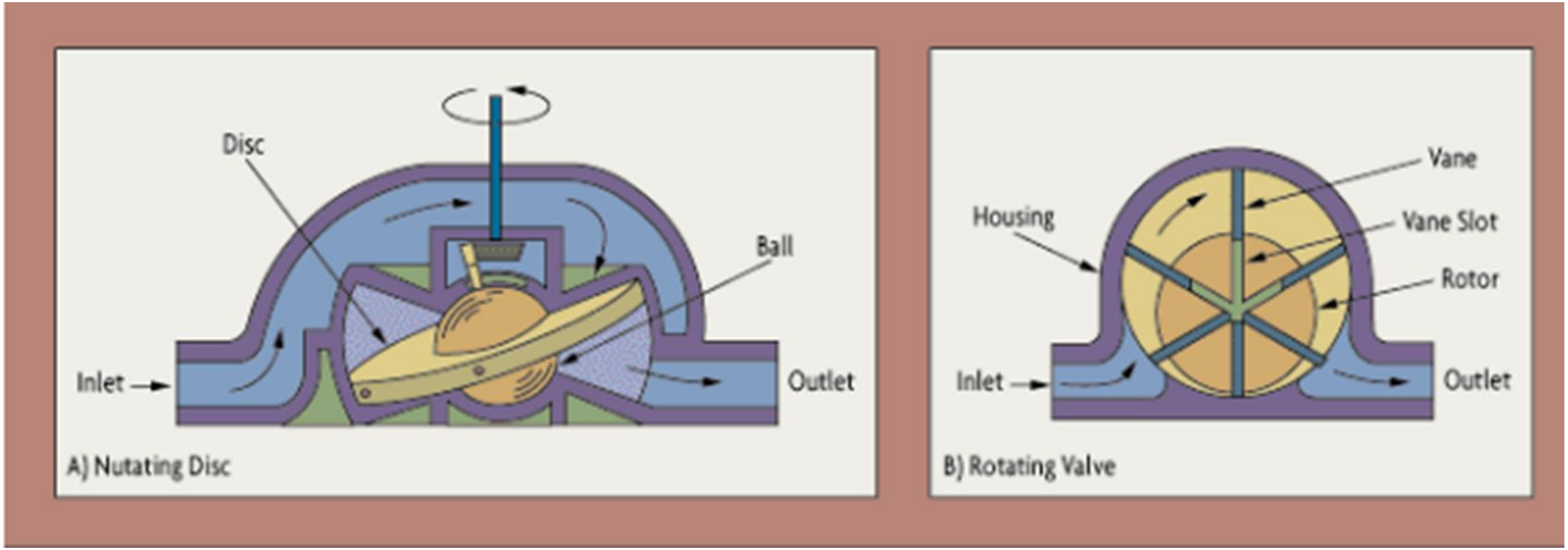


Rotating lobe meter

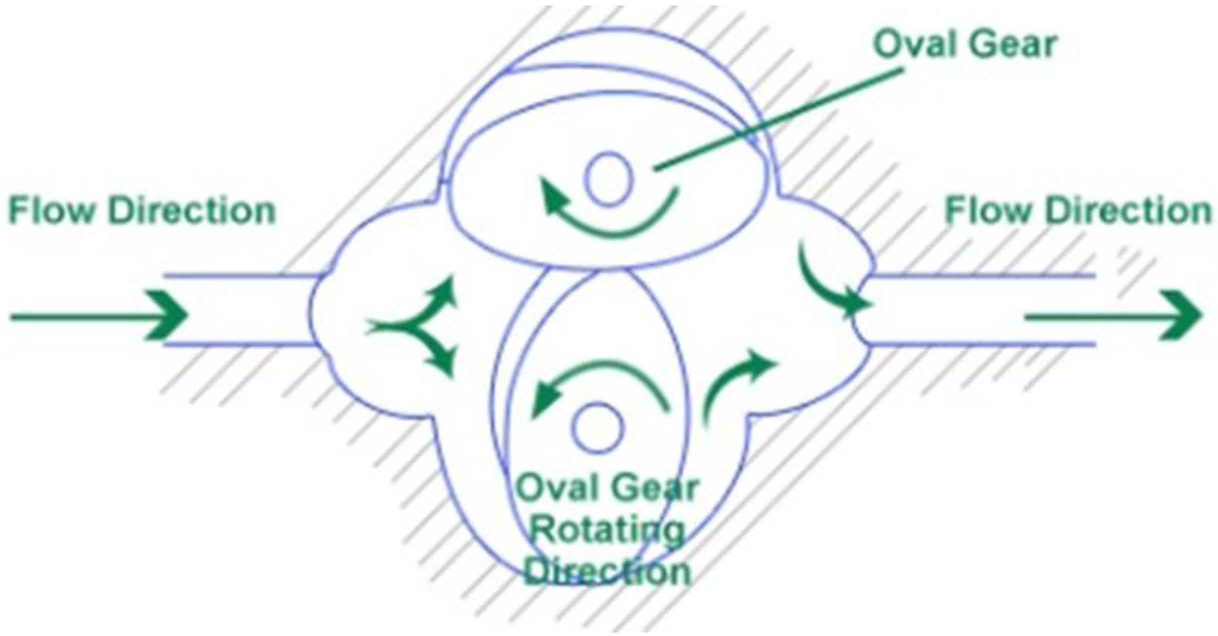
- A positive displacement flowmeter is a cyclic mechanism built to pass a fixed volume of fluid through with every cycle.
- Every cycle of the meter's mechanism displaces a precisely defined ("positive") quantity of fluid, so that a count of the number of mechanism cycles yields a precise quantity for the total fluid volume passed through the flowmeter

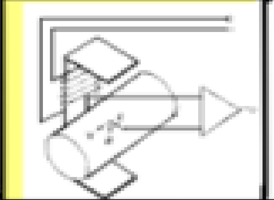
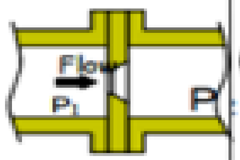
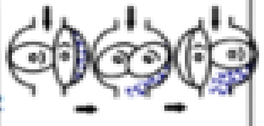
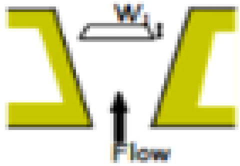
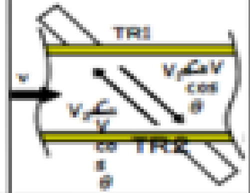
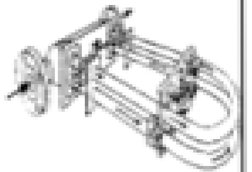
-Applicable only to clean fluid flow streams

Positive displacement flowmeters are also very linear, since mechanism cycles are directly proportional to fluid volume


Disc
Ball
Inlet
Outlet
A) Nutating Disc
Vane
Vane Slot
Housing
Rotor
Inlet
Outlet
B) Rotating Valve

Gear based positive displacement flowmeter



	Magnetic (w/ electrode)	DP	Turbine	Variable area	Ultrasonic	Coriolis (Mass)	Vortex
Measurement Principle							
Meas. objects	Conducting Liquid 5 μS／cm～	Liquid & Gas	Liquid	Liquid & Gas	Liquid & Gas	Liquid & Gas	Liquid & Gas
Moving Parts	E	E	NG	NG	E	E	E
Obstruction inside pipe	E	NG	NG	NG	E	E	NG
Pressure Loss	E	NG	NG	NG	E	G	NG
Effect of Uneven flow	E	NG	E	E	NG	G	NG
Accuracy	E	G	E	G	G	G	G
Range Ability	1:100	1:10	1:20	1:10	1:20	1:100	1:50
Effect of solids	E	NG	NG	NG	G	NG	NG
Effect of adhesion	G	NG	NG	NG	G	NG	NG

E: Excellent G: Good NG: Not Good

Flowmeter	Pipe/size	Gas/Liquid	Accuracy	Ideal for measuring	Principle
Orifice	1" – 48"	Liquid/Gas	1%	Mass flow / velocity	Diff. Pressure
Venturi	6" – up	Liquid/Gas	0.50%	Mass flow / velocity	Diff. Pressure
Turbine	0.5" – 2"	Liquid/Gas	0.30%	Mass flow / velocity	Rotating blades produce pulses
Positive Displacement	1" – 24"	Liquid	0.50%	Mass flow	Traps a specific volume
Magnetic	1" – 120"	Liquid	0.2 – 1 %	Mass flow	Faraday's Law
Ultrasonic	0.5" – 48"	Liquid/Gas	1%	Mass flow	Speed of sound
Vortex	0.5" – 16"	Liquid/Gas	1%	Velocity	Eddies produce pulses
Variable area	0.5" – 3"	Liquid/Gas	1%	Velocity	Diff. Pressure
Coriolis	2" – 150"	Liquid	0.50%	Mass flow	Coriolis principle
Pitot	3" – up	Liquid/Gas	2%	Mass flow / velocity	Diff. Pressure

Multiphase fluid flow measurement

Multiphase flow consist of the simultaneous passage in a system of a stream composed o two or more phases.

Examples

- The flow of blood in the human body,
- bubbles rising in a glass of soda,
- steam condensation on window

Two phase flows

1)Gas-solid flows
2)Liquid-Liquid flows
3)Liquid -Solid flows
4)Gas –Liquid flows

Three phase flows

1)Gas-Liquid-solid
2)Gas-Liquid-liquid
3)Solid-Liquid-liquid

Flow patterns

- The behavior and the shape of the interface between phases in a multiphase mixture is referred as the flow regime or the Flow pattern
- There are competing forces or mechanisms occurring within the multiphase fluid at the same time.

the balance between these forces determines the flow pattern

The several factors that dictate the flow pattern are

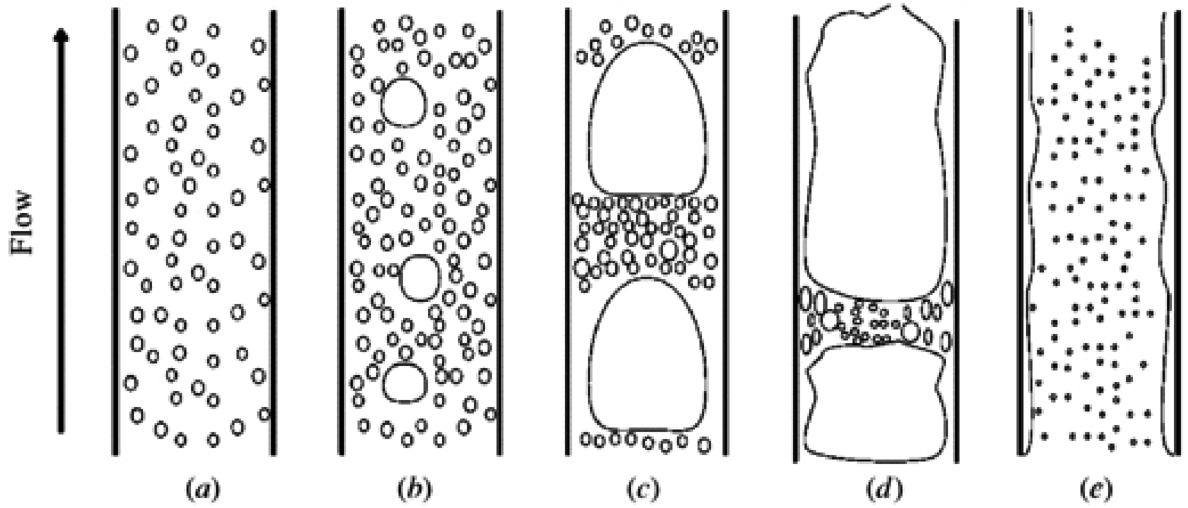
1)Phase properties, velocities, fractions

2)Operating pressure and temperature

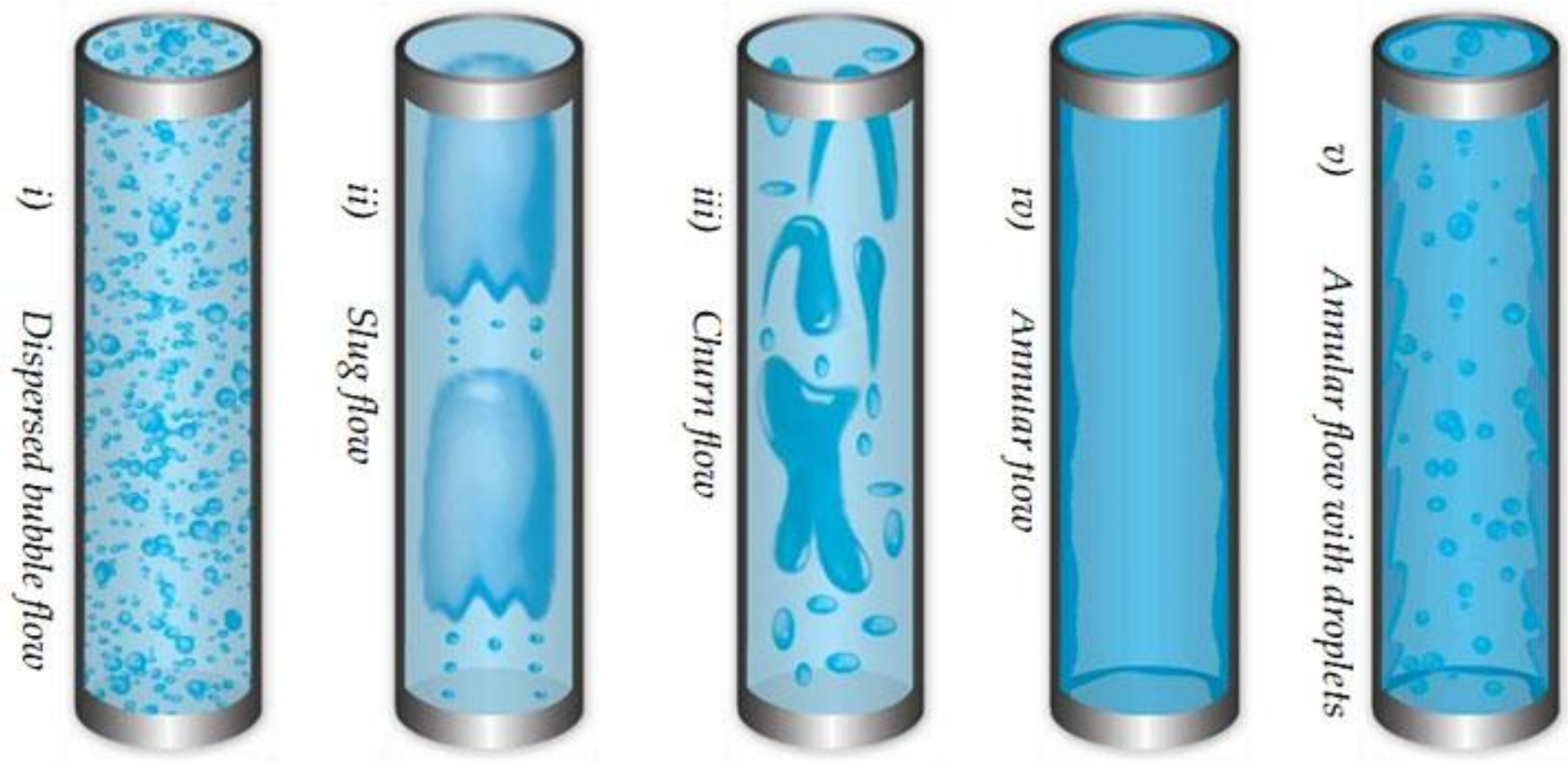
3)Conduit diameter,shape,inclination and roughness

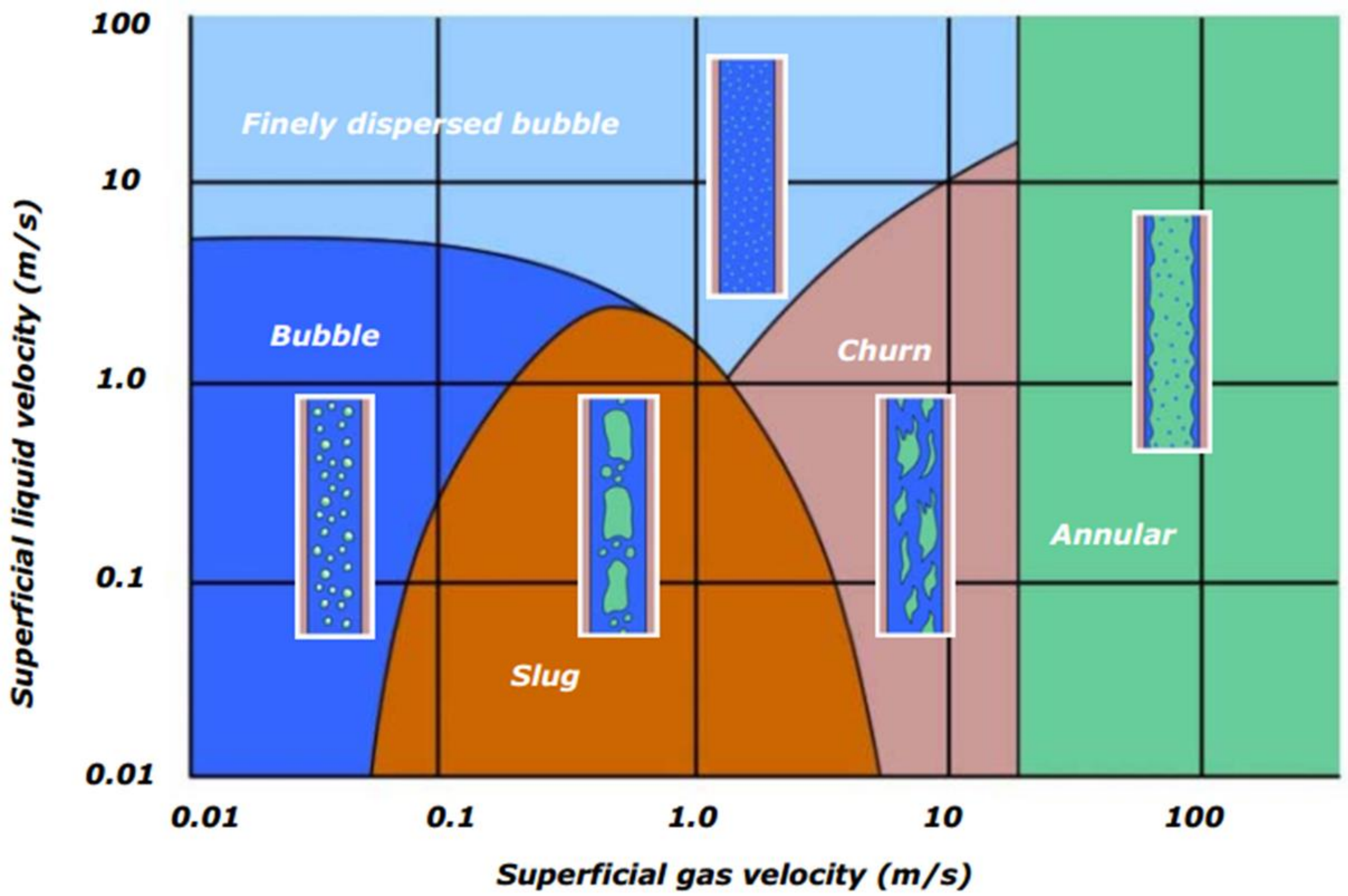
4)Presence off any upstream or downstream pipe work

(bends, valves)



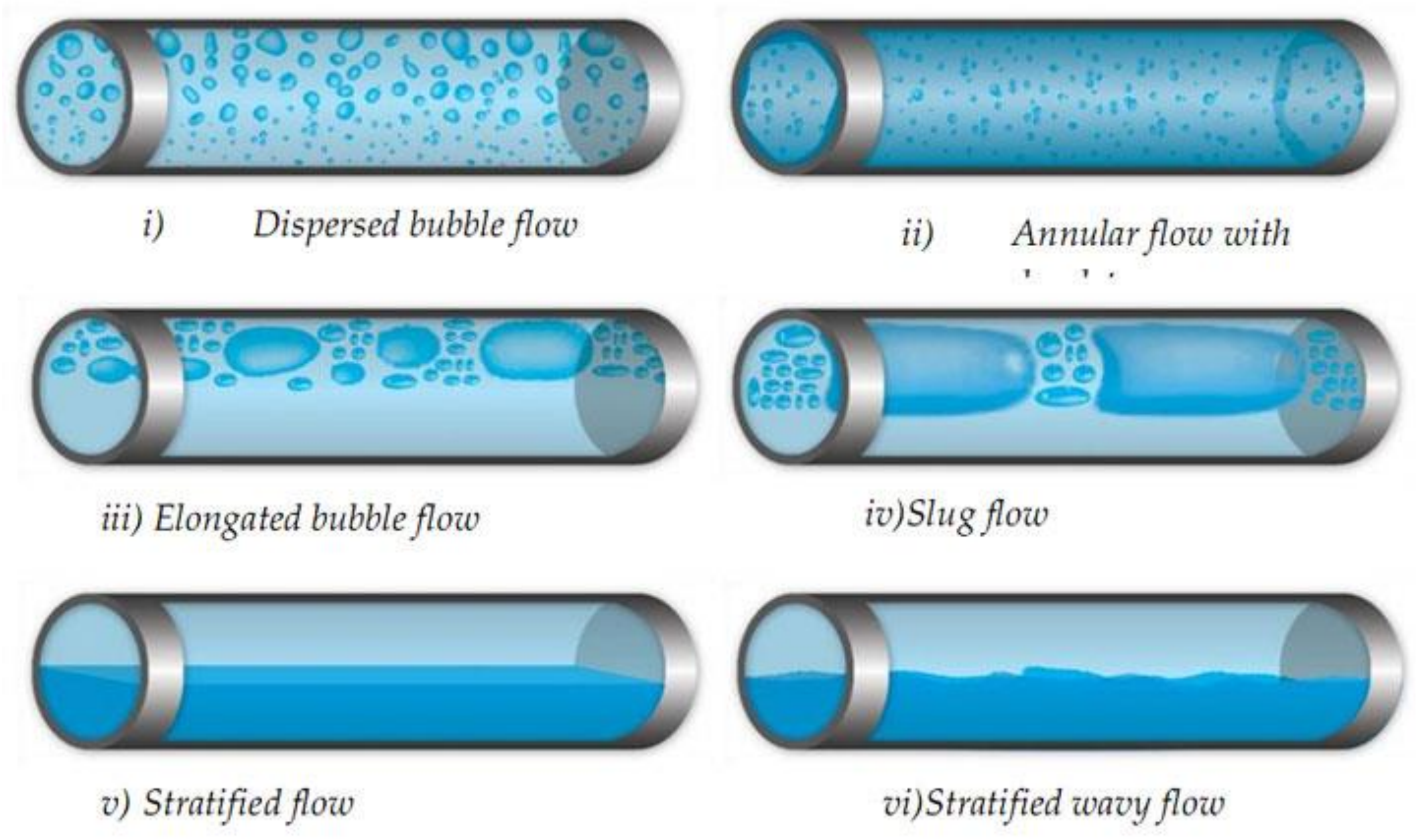
Flow pattern: Gas-liquid flows vertical view

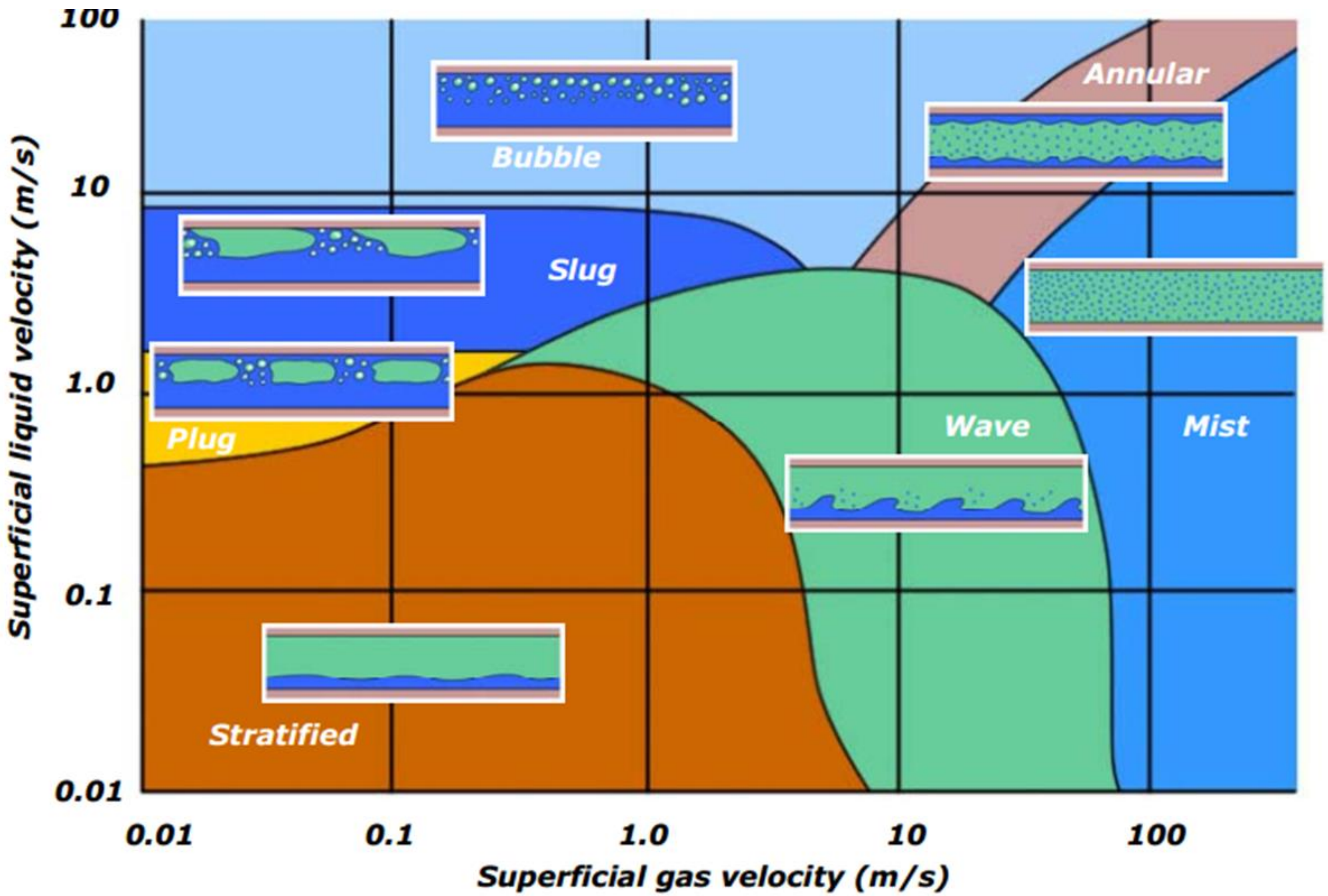




Superficial velocity (or superficial flow velocity), in engineering of multiphase flows and flows in porous media, is a hypothetical (artificial) flow velocity calculated as if the given phase or fluid were the only one flowing or present in a given cross sectional area.

Gas –liquid flow: Horizontal view





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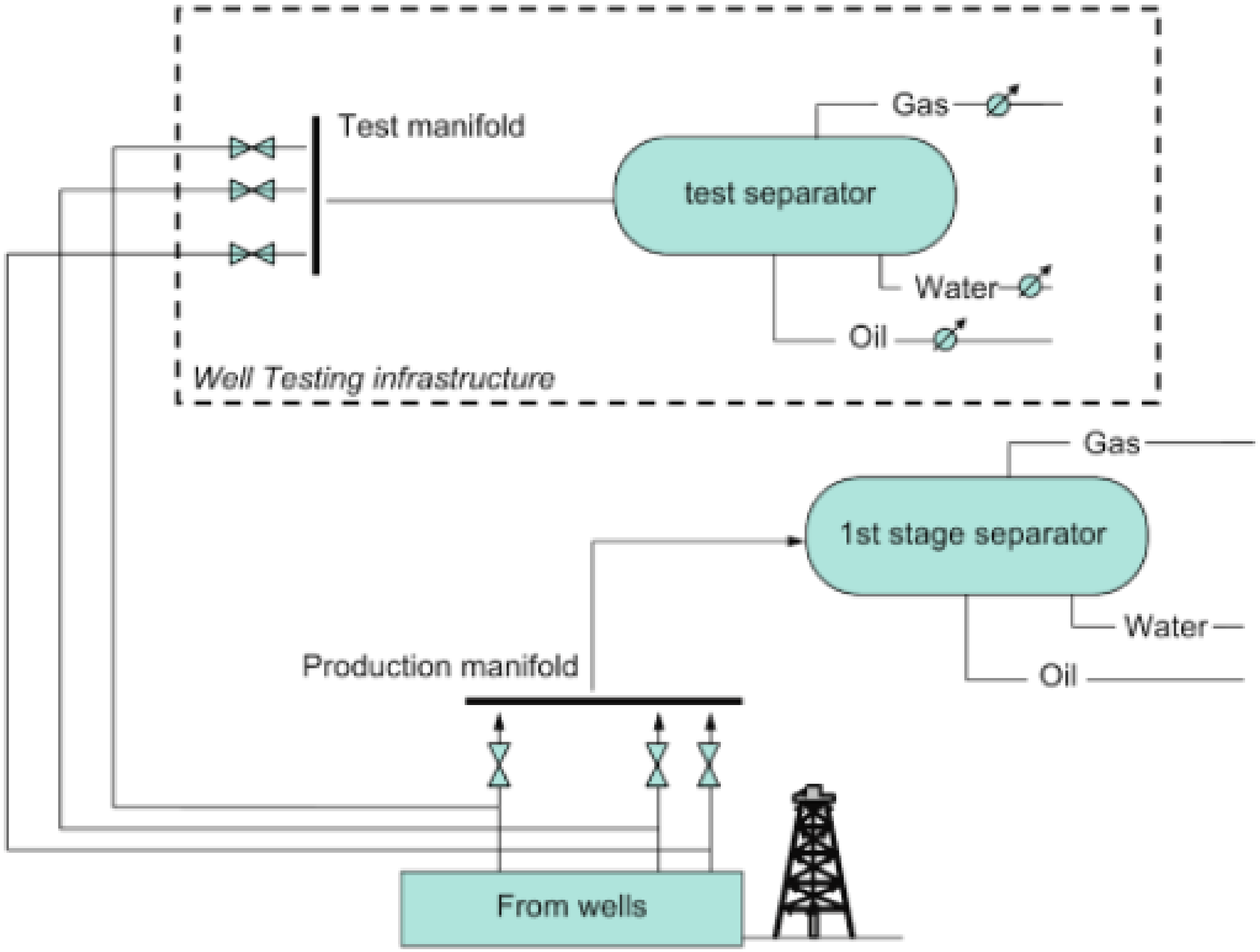
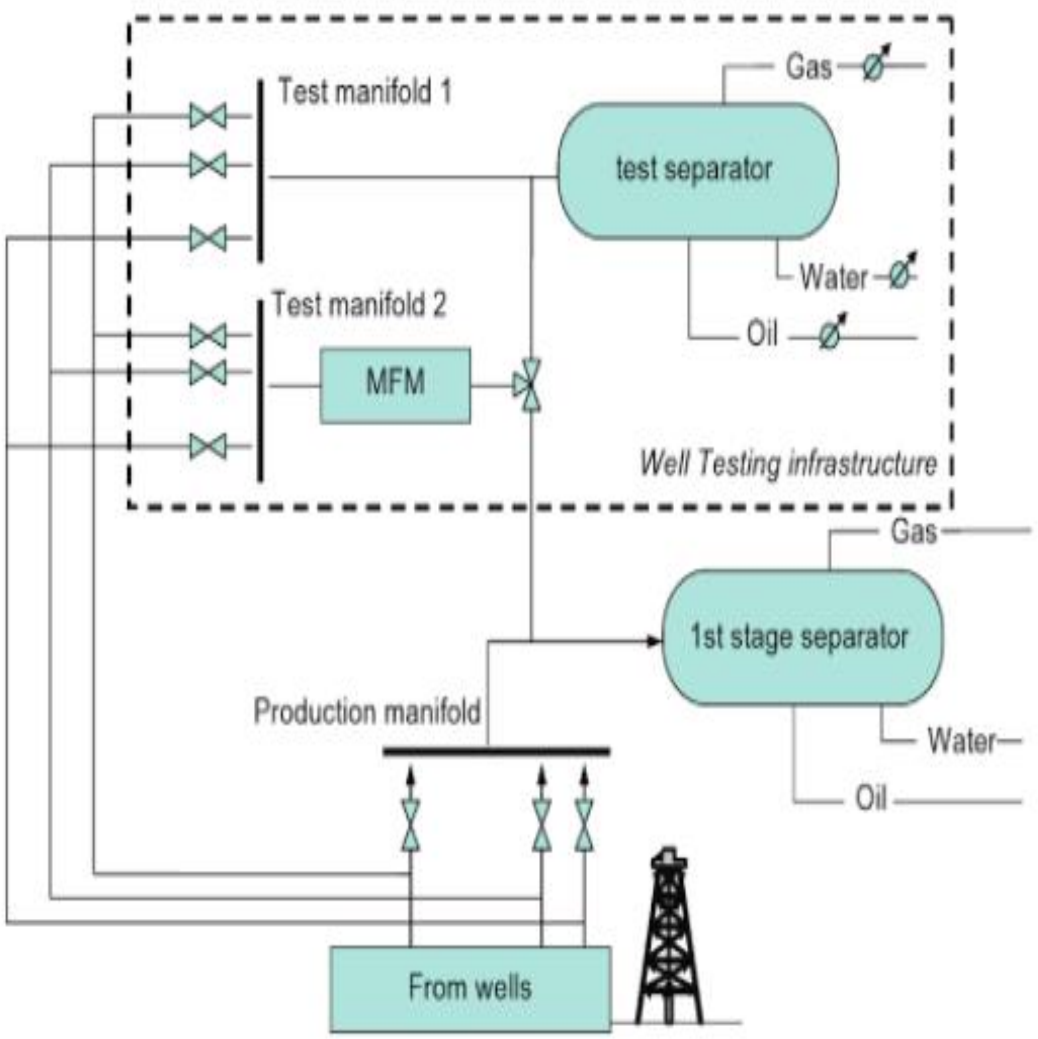
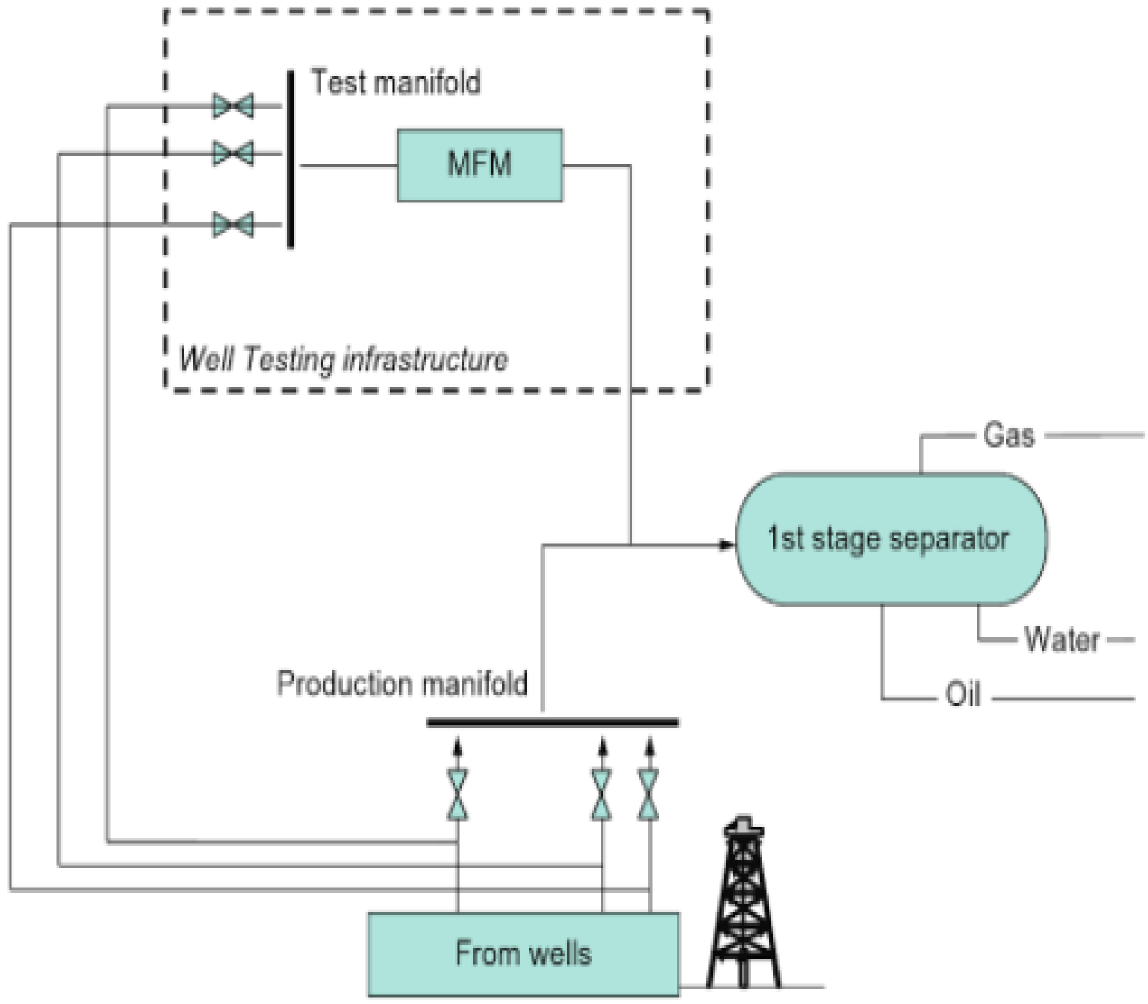
Applications of MFM(multiphase flow meter) in oil and gas industry



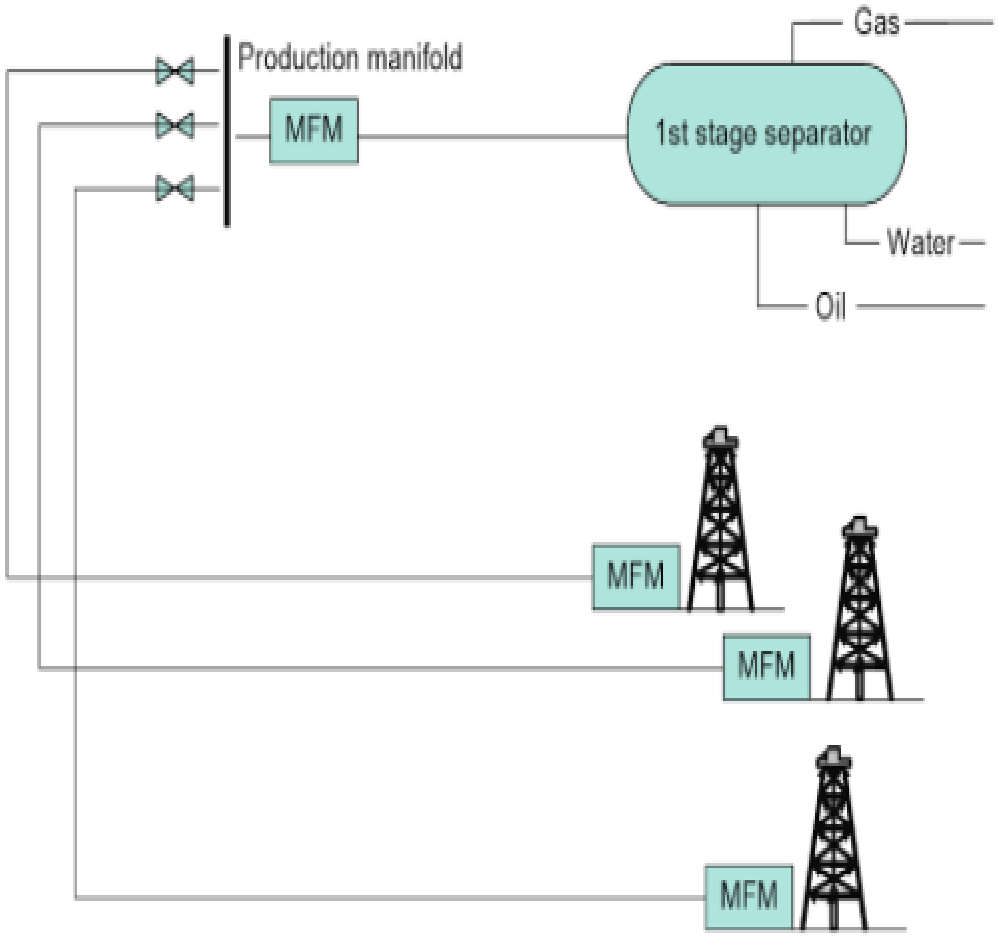
Conventional process

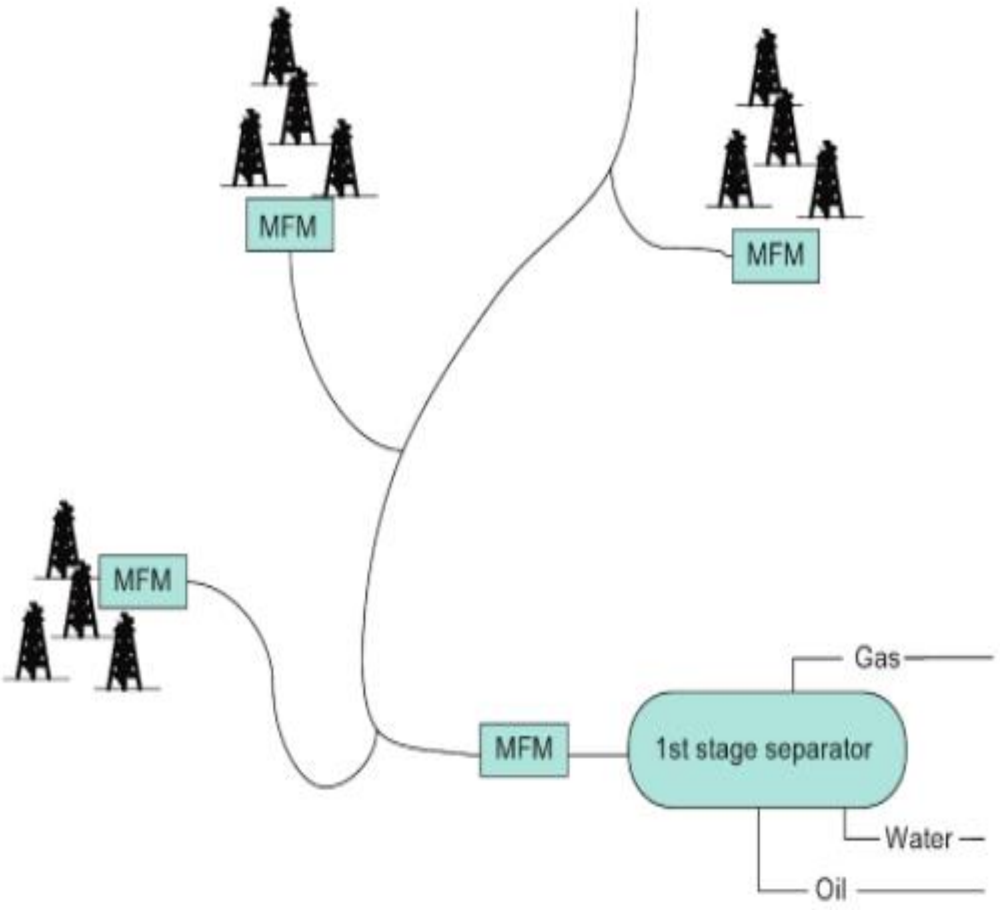
Applications of MFM(multiphase flow meter) in oil and gas industry





Applications of MFM(multiphase flow meter) in oil and gas industry





Desired qualities of Multiphase metering

- Repeatability and accuracy of the measurement.
- Applicability to a wide range of flow rates phase fractions, fluids properties and operating pressure and temperature conditions.
- Ease of installation and intervention
- Low capital expenditure and operation costs
- High mean time before failure

Multiphase flow metering principles

- The objective of multiphase flow metering(MFM) is to determine the flow rates of the individual components .
- The number of instruments depends upon whether or not the three components can be mixed together upstream of the instrumentation.

Homogenous flow

1. The fluids are uniformly mixed and moving as a pseudo fluid at the mixture velocity.
2. The slip velocity between the phases negligible which implies that both the fluids are moving at an average velocity.
3. Attainment of thermodynamics equilibrium between the phases.

If the homogeneity of flow can be achieved, number of measurements can be reduced.

IN PRINCIPLE:
responses R_1, R_2, R_3 are measured

$$R_1 = f_1\left(\dot{M}_G, \dot{M}_O, \dot{M}_W\right)$$
$$R_2 = f_2\left(\dot{M}_G, \dot{M}_O, \dot{M}_W\right)$$
$$R_3 = f_3\left(\dot{M}_G, \dot{M}_O, \dot{M}_W\right)$$

$$\boxed{f_1, f_2, f_3}$$

$\xrightarrow{\text{established by calibration}}$

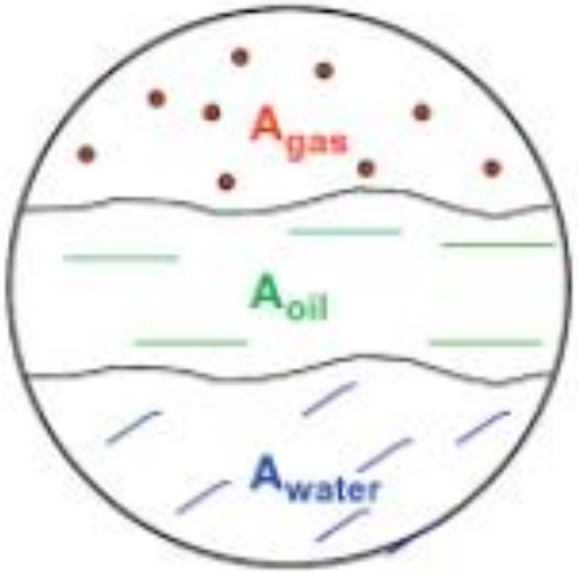
$$\dot{M}_G \quad \dot{M}_O \quad \dot{M}_W$$

IN PRACTICE:
f_1, f_2, f_3 depend on (unknown) upstream conditions
impossible to calibrate for real fluids over full range.

The first MFM approach.

$$\text{Mass flow rate}_{(i)} = \text{Area}_{(i)} * \text{Density}_{(i)} * \text{Velocity}_{(i)}$$

for the $(i)^{th}$ phase



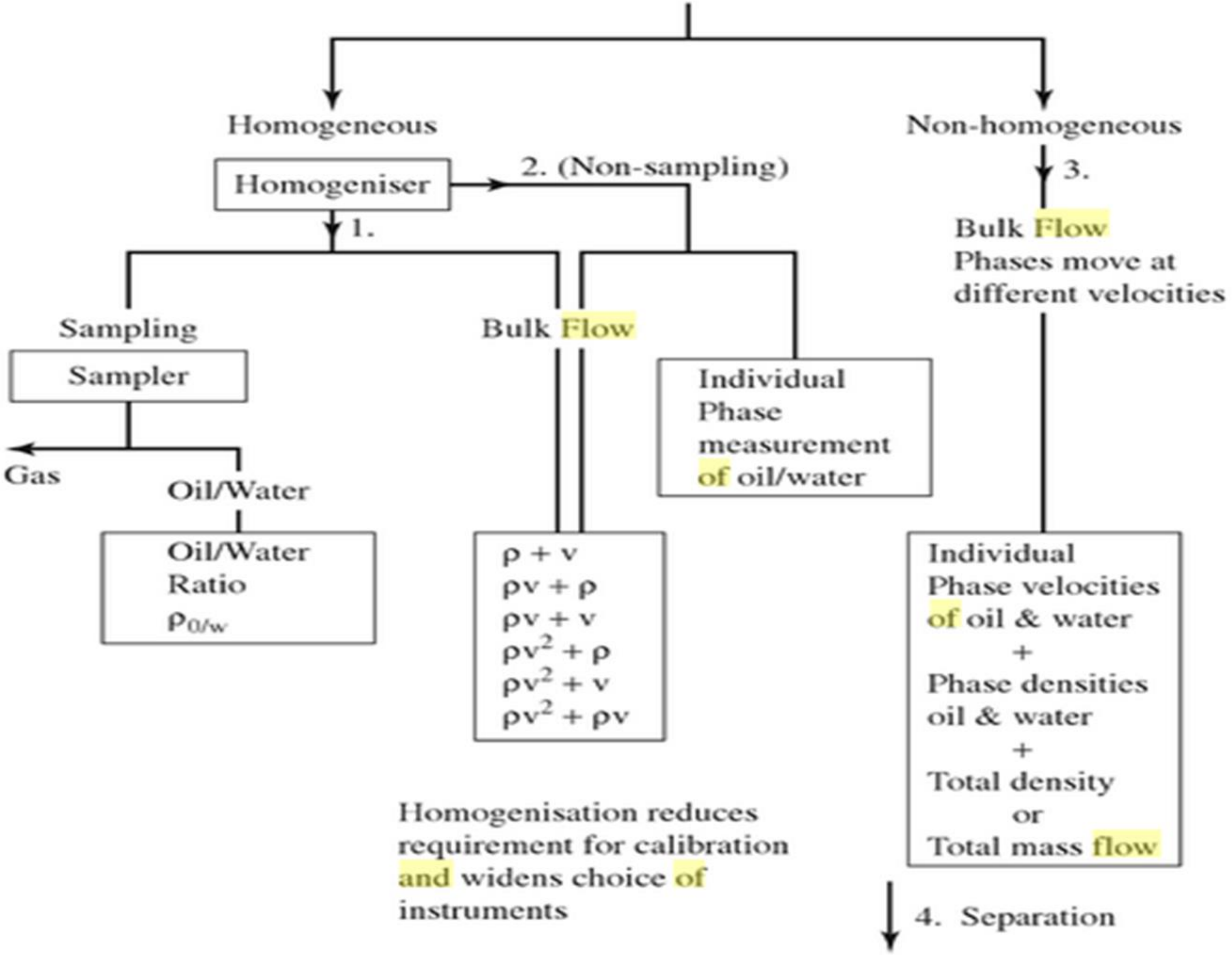
Need to measure only 2 areas.

Need to measure only 1 velocity
if flow is homogenised.

: The second MFM approach.

There are five basic parameters that can be measured by MFM devices

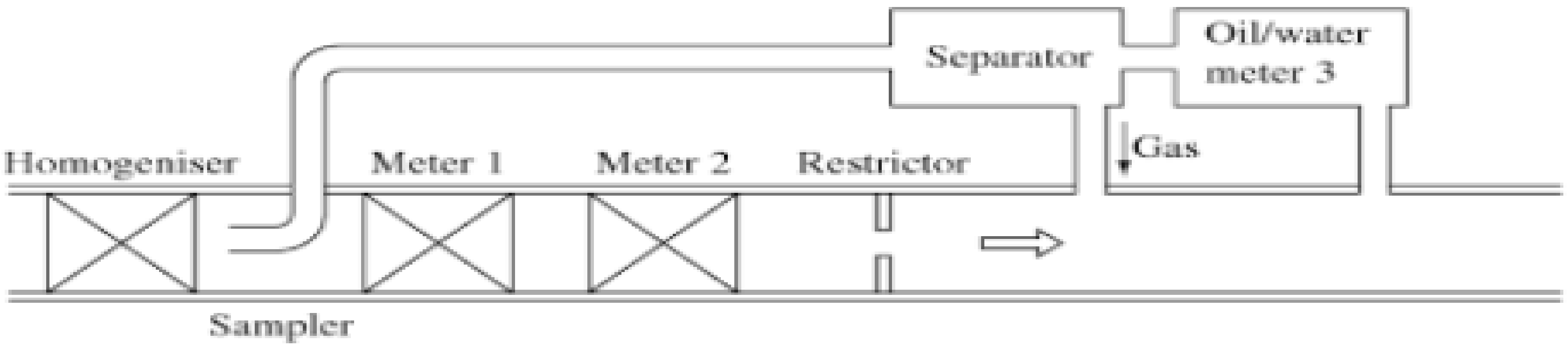
- Density(gamma ray absorption)
- velocity(turbine flow meter)
- Momentum (venture and orifice meters
- Mass flow(Coriolis flowmeter)
- Elemental analysis


Homogeneous
Non-homogeneous
Homogeniser
2. (Non-sampling)
3.
1.
Bulk Flow
Phases move at
different velocities
Sampling
Bulk Flow
Sampler
Individual
Phase
measurement
of oil/water
Gas
Oil/Water
Oil/Water
Ratio
$\rho_{0/w}$
$\rho + v$
$\rho v + \rho$
$\rho v + v$
$\rho v^2 + \rho$
$\rho v^2 + v$
$\rho v^2 + \rho v$
Individual
Phase velocities
of oil & water
+
Phase densities
oil & water
+
Total density
or
Total mass flow
Homogenisation reduces
requirement for calibration
and widens choice of
instruments
4. Separation

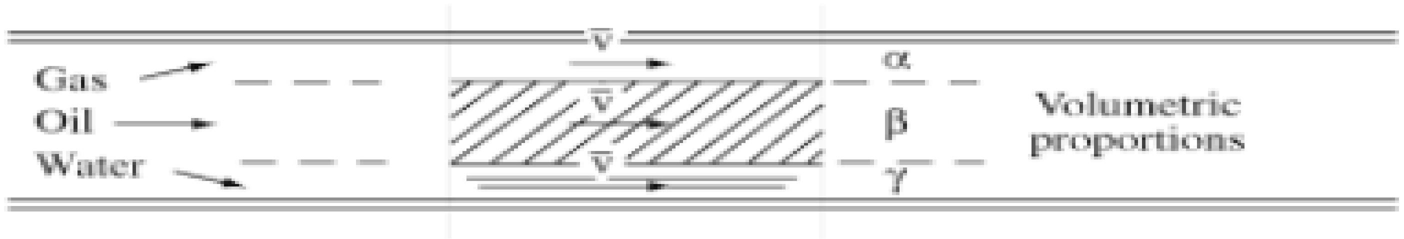
The 4 Routes

1. Homogenisation + Sampling: 2 Homogeneous flow measurements
   + 1 sample measurement
2. Homogenisation without Sampling: 2 Homogeneous flow measurements
   + 1 phase measurement
3. Non-homogeneous Flow: 4 Individual phase measurements
   + 1 bulk flow measurement
4. Separation: 3 Individual stream measurements

Route 1   Homogenisation and sampling of oil/water



Assumptions: Meter 1 and meter 2 measure mean velocity and mean density

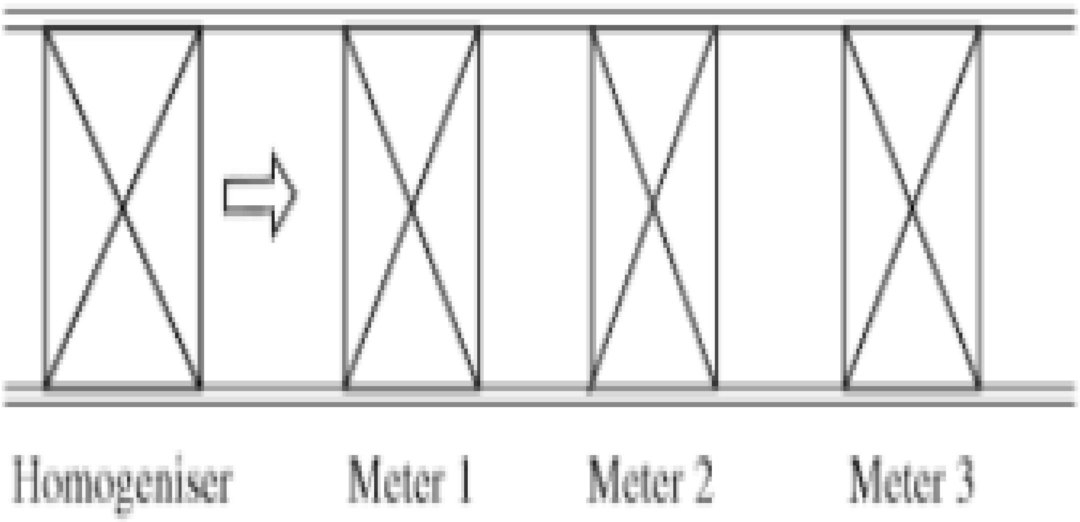


$$\bar{\rho} = \alpha\rho_g + \beta\rho_o + \gamma\rho_w \qquad \text{(i)}$$

$$= (1 - \beta - \gamma)\rho_g + \beta\rho_o + \gamma\rho_w \qquad \text{(ii)}$$

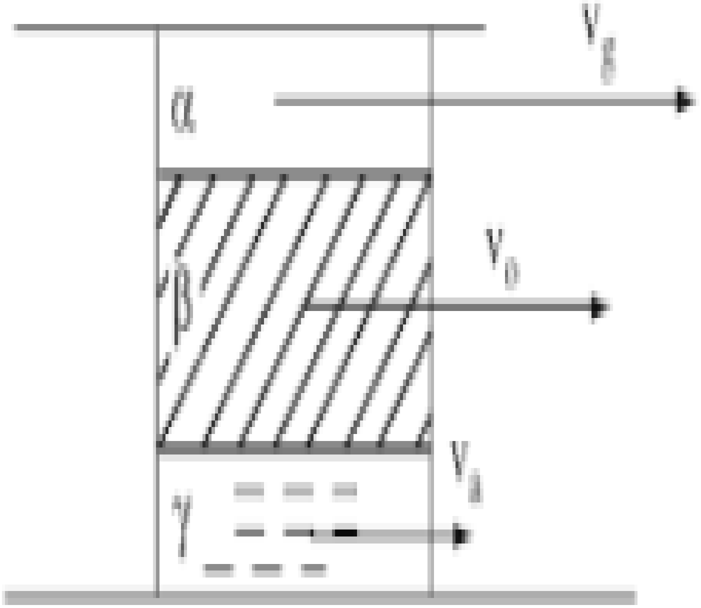
Meter 3 determines the density of the oil/water part of the mixture and provides a measure of the ratio ρ/γ which can be substituted in Equation (ii) to solve for α, β & γ. It is assumed that the phase densities are known or separately measured.

Route 2 Homogenisation without sampling



As in route 1, meter 1 and meter 2 provide a measure of mean velocity and mean density: the third meter is needed for additional information

Route 3 Non-homogenous flow



Key factors for the selection of multiphase flow metering

- Confidence in particular technique
- Health ,safety and environment issues
- Gas void fraction - the fraction of the flow-channel volume that is occupied by the gas phase .
- Operating envelope
- Tool dimensions
- Calibration over field life
- Costs
- Assistance from manufacturers
- Meter orientation and location