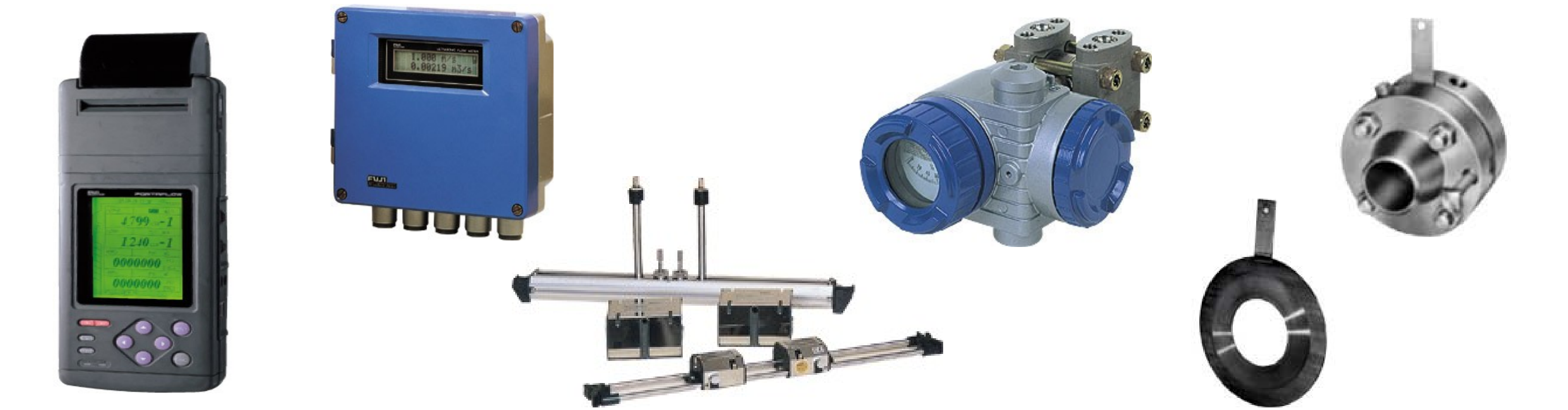


Basic Flow Measurement

Contents

Introduction

Since 1989 there were at least 23 distinct type of technologies available for the measurement of flow in closed conduit. Flow meters selection are part of the basic art of the instrument engineer, and while only handful of these technologies contribute to the majority of installations.

And wide product knowledge is essential to find the most cost effective solution to any flow measurement application.

Types of Flows
Reynolds Number

The performance of flowmeters is also influenced by a dimensionless unit called the Reynolds Number. It is defined as the ratio of the liquid's inertial forces to its drag forces.

The Reynolds number is used for determined whether a flow is laminar or turbulent. Laminar flow within pipes will occur when the Reynolds number is below the critical Reynolds number of 2300 and turbulent flow when it is above 2300.   The value of 2300 has been determined experimentally and a certain range around this value is considered the transition region between laminar and turbulent flow.

$$Re = \frac{v_s L}{\nu} \; . \qquad \text{Or} \qquad Re = \frac{\rho v_s L}{\eta}$$

v_s = Mean Fluid Velocity,

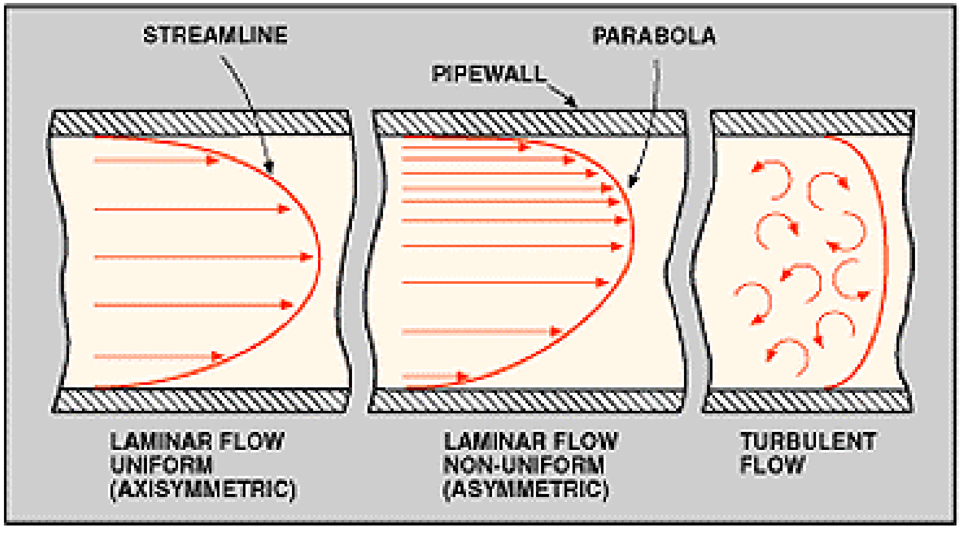
η - (Absolute) Dynamic fluid Viscosity

v = Kinematics Fluid Viscosity (v = η/ρ)

ρ = Fluid Density

L **= Characteristic Length (Equal to diameter, 2*r* if a Cross Section is Circular)**

Types of Flows



Basic Requirements for Flow Measurement

- ❖Ability to Integrate Flow Fluctuation
- ❖Easy Integration with Piping System
- ❖High Accuracy
- ❖High Turn-Down Ratio
- ❖Low Cost
- ❖Low Sensitivity to Dirt Particles
- ❖Low Pressure Loss
- ❖No Moving Parts
- ❖Resistant to Corrosion and Erosion

Definition of Quantities to be measured

Volume Flow Rate

The definition of volume flow rate is the volume of fluid that flows past a given cross sectional area per second. Therefore,

$$V = Av$$

V = Volume Flow Rate

A = Cross Section Area

V = Velocity of Fluid

Standard SI Unit is m^3/hr

Other Common Units :

$1L/s = 10^3\ cm^3/s = 10^{-3}\ m^3/s$

$1gal/s = 3.788\ L/s = 0.003788\ m^3/s$

$1cf/min = 4.719x10^{-4}\ m^3/s$

Definition of Quantities to be Measured

Mass Flow Rate

The definition of mass flow rate is the number of kilograms of mass flow that flows past a given cross sectional area per second. Therefore,

$$m = \rho V = \rho A v$$

m = Mass Flow Rate

ρ = Specific Density

V = Volume Flow Rate

A = Cross Section Area

V = Velocity of Fluid

Standard SI Unit is kg/hr

Types of Measurement

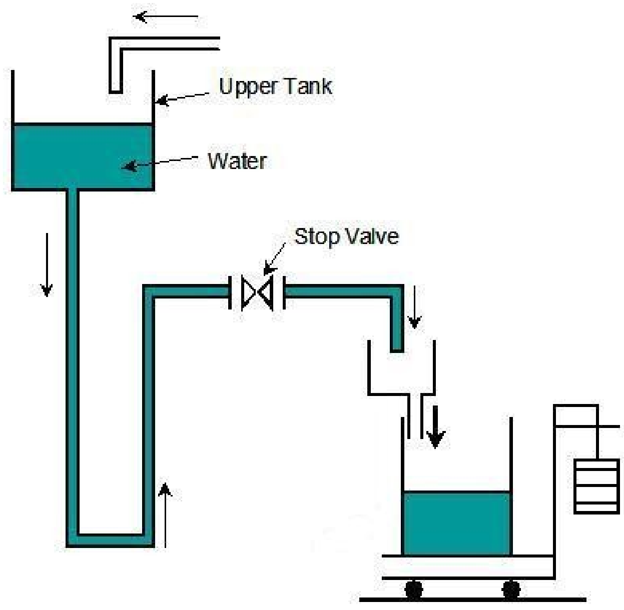
Direct Rate Measurement

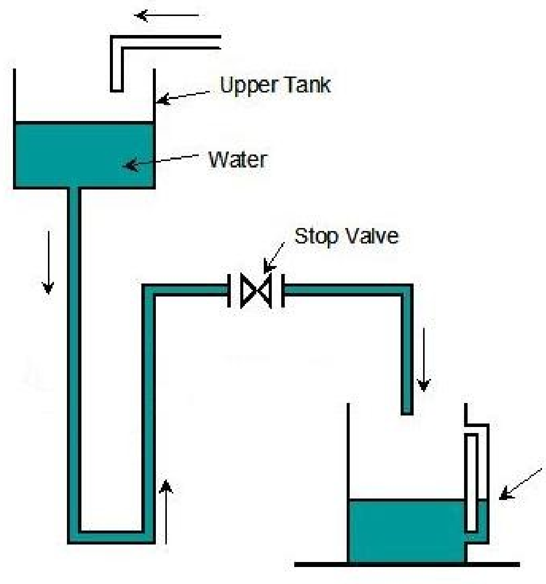
Required large device if the volume rates are high. And in case a smaller device is used then the measured values will not be accurate.

Fluctuations in the measuring values due to the opening/closing of valves during start/stop of the measurements.

Devices that measure the volume/mass of the fluid and the timing may not be concurrent.

Types of Measurement
Direct Rate Measurement





Type of Measurement

Indirect Rate Measurement

For many practical applications, indirect measuring techniques are

employed using various kind of principles.

Here are some of the basic working principles:

Differential Pressure

Force on Bodies in the Flow

Heat Transfer

Corriolis Force

Magneto-Inductive

Frequency of Vortices

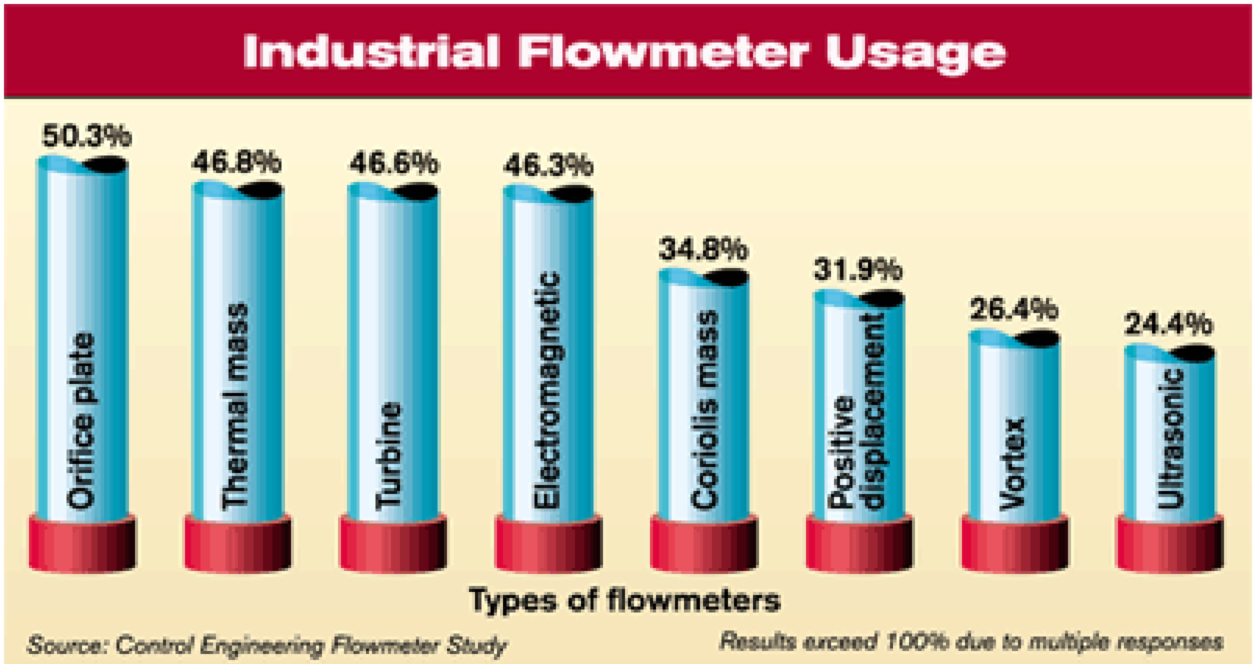
Ultrasonic

Type of Flowmeters

1. Correlation Method
2. Corriolis
3. Elbow Tap “Elbow Meter”
4. Electro-Magnetic
5. Flow Nozzles
6. Flow Tube
7. Nutating Disk
8. Orifices
9. Oval Gear
10. Pitot Tube
11. Positive Mass
12. Reciprocating Piston
13. Rotary Vane
14. Swirl
15. Target
16. Thermal Dispersion
17. Turbine
18. Ultrasonic Doppler
19. Ultrasonic Transit Time
20. Variable Area
21. Venturi Tube
22. Vortex
23. Weir & Flume

Type of Flowmeters

Industrial Flowmeter Usage



Type of Flowmeters

Orifice, Nozzle & Venturi “Differential Pressure”

Basic Equation

$$v = k\sqrt{\frac{h}{p}}$$

$$Q = kA\sqrt{\frac{h}{p}}$$

$$m = kA\sqrt{hp}$$

v = Fluid Velocity

Q = Volume Flow Rate

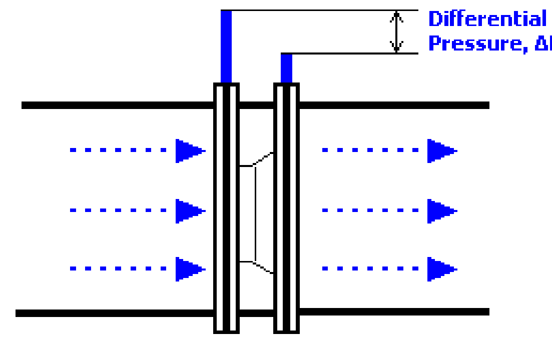
A = Cross Sectional Area of Pipe

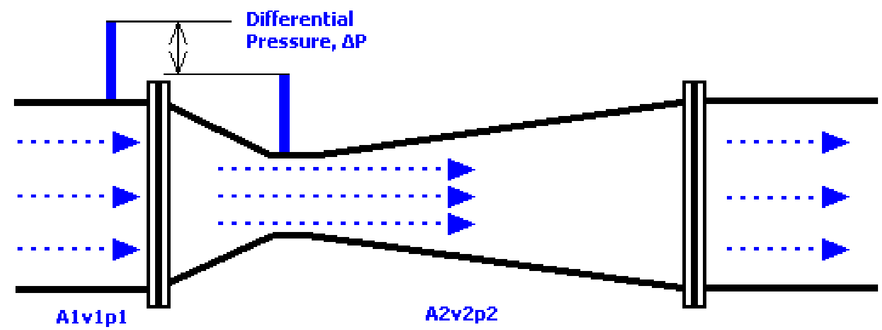
m = Mass Flow Rate

k = Constant

h = Differential Pressure

p = Density of Fluid





The (lateral) pressure exerted by an incompressible fluid varies inversely with the square of the speed of the fluid.

Type of Flowmeters

Orifice, Nozzle & Venturi "Differential Pressure

Basic Equation

A) Liquid Volumetric

$$Flow(Q) = \sqrt{DP} \times \left[\frac{K \times A \times 4.6285}{\sqrt{D}}\right] m^3/hr$$

B) Gas Volumetric

$$Flow(Q) = \sqrt{DP} \times \left[\frac{K \times A \times \sqrt{Tf + 273}}{\sqrt{S} \times 4.0323 \times \sqrt{Pf}}\right] Am^3/hr$$

$$Flow(Q) = \sqrt{DP} \times \left[\frac{K \times A \times 66.839 \times \sqrt{Pf}}{\sqrt{S} \times \sqrt{Tf + 273}}\right] Nm^3/hr$$

C) Liquid/Gas Mass

$$Flow(Q) = \sqrt{DP} \times \left(K \times A \times \sqrt{D} \times 4.6285\right) kg/hr$$

QA = Flow (m^3/hr)

QB = Flow (Nm^3/hr) at 0 ^{0}C & 1.013 bara

QC = Flow (kg/hr)

S = Specific Gravity (Air = 1)

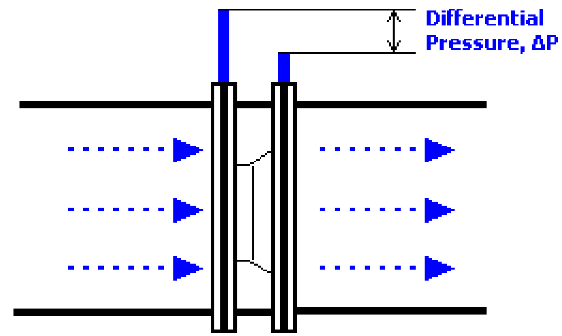
D = Density at actual conditions (kg/m^3)

A = Pipe Internal C.S.A (cm^2)

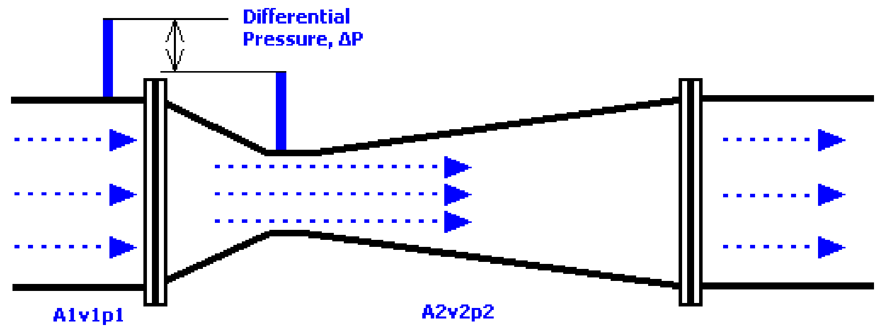
Tf = Actual Temperature (^{0}C)

Pf = Actual Pressure (bara)

K = TORBAR Coefficient (See Table)



The orifice, nozzle and venturi flow meters use the Bernoulli's Equation to calculate the fluid flow rate by using the pressure difference between an obstruction in the flow.



Type of Flowmeters

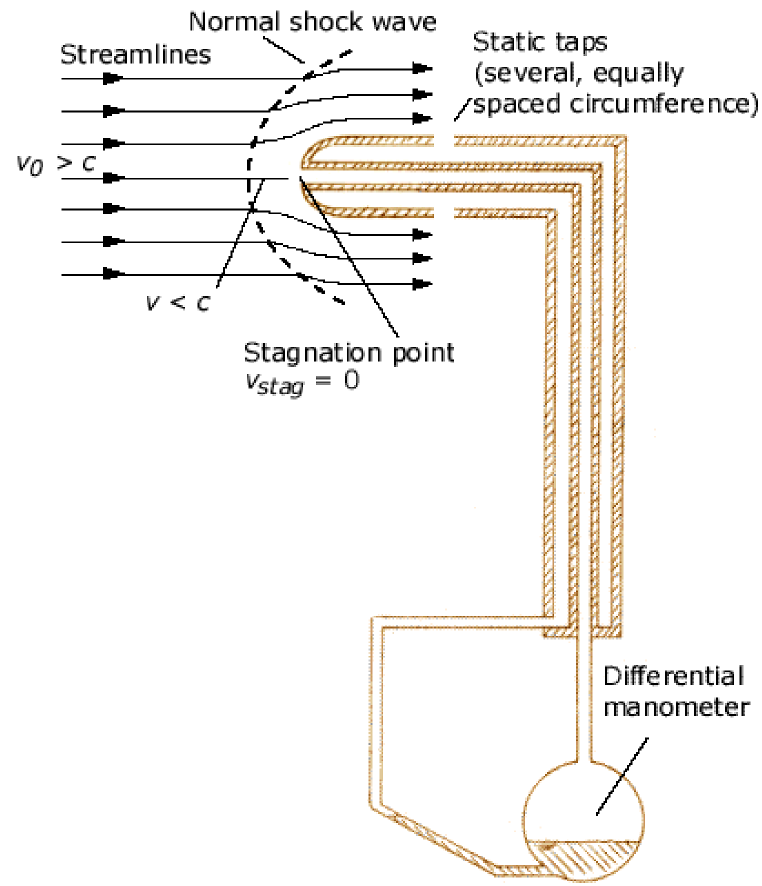
Bernoulli's Equation

For Pitot Tube:

$P + \frac{1}{2}\rho V^2 + \rho g h = \text{Constant}$

If no change in the elevation, $\rho g h = 0 = z$

And point 2 is stagnation point, i.e. $V_2 = 0$



$$\frac{v_1^2}{2g} + z_1 + \frac{p_1}{\rho g} = \frac{v_2^2}{2g} + z_2 + \frac{p_2}{\rho g}$$

$$\frac{v_1^2}{2} + \frac{p_1}{\rho} = \frac{p_2}{\rho}$$

P = Sta

$$v_1 = \sqrt{\frac{2(p_2 - p_1)}{\rho}}$$

ρ = Density of Fluid

v = Velocity of Fluid

g = Gravitational **Acceleration (9.81m/s**

h = Height

Type of Flowmeters

Thermal Mass

$$Q = WCp\ (T_2 - T_1) \text{ and therefore}$$

$$W = Q/Cp\ (T_2 - T_1)$$

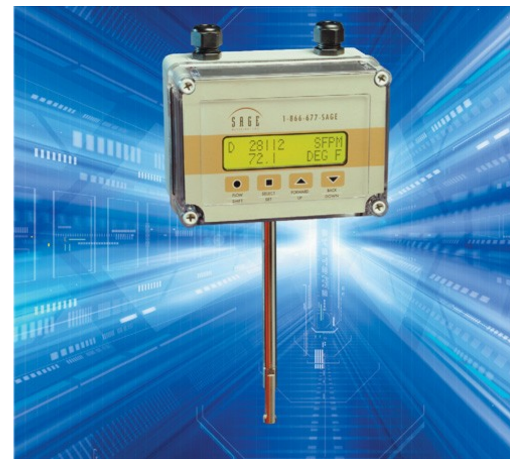
Q = Heat Transfer

W = Mass Flow Rate

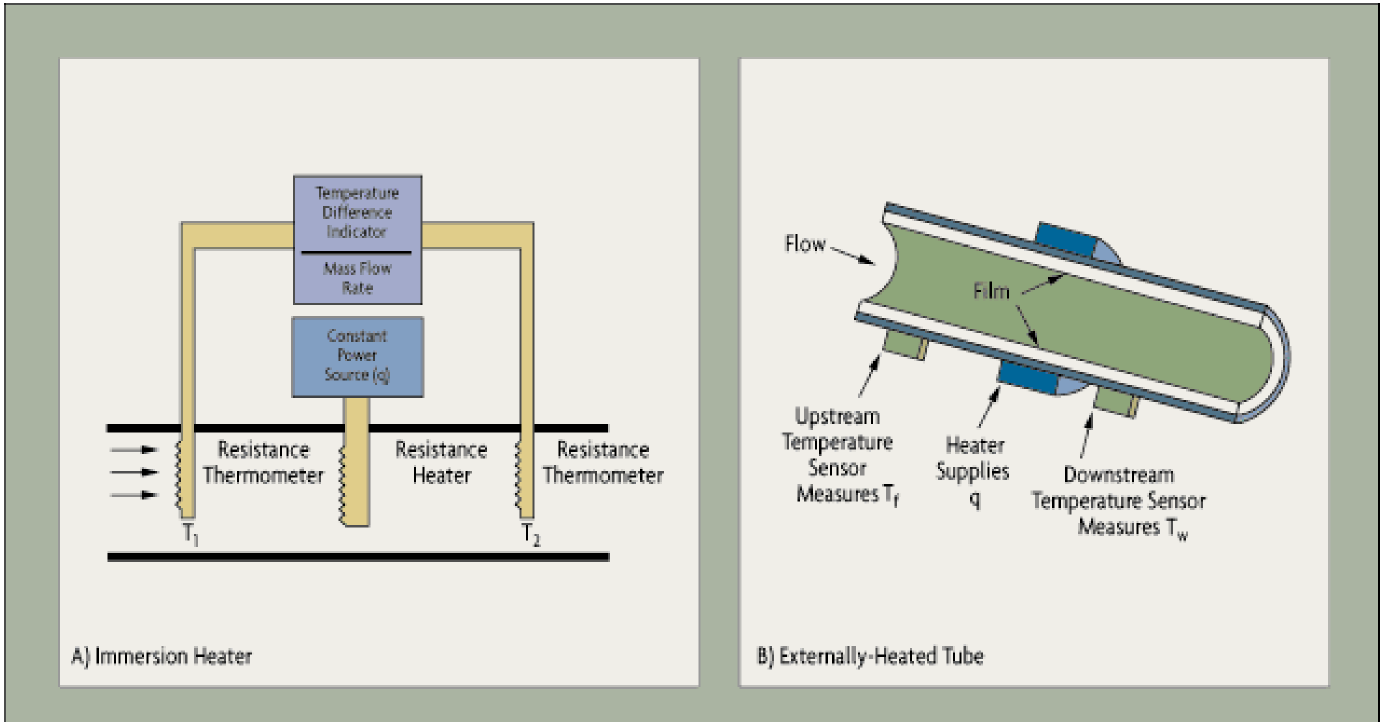
Cp = Specific Heat of Fluid

T_1 = Temperature Upstream

T_2 = Temperature Downstream

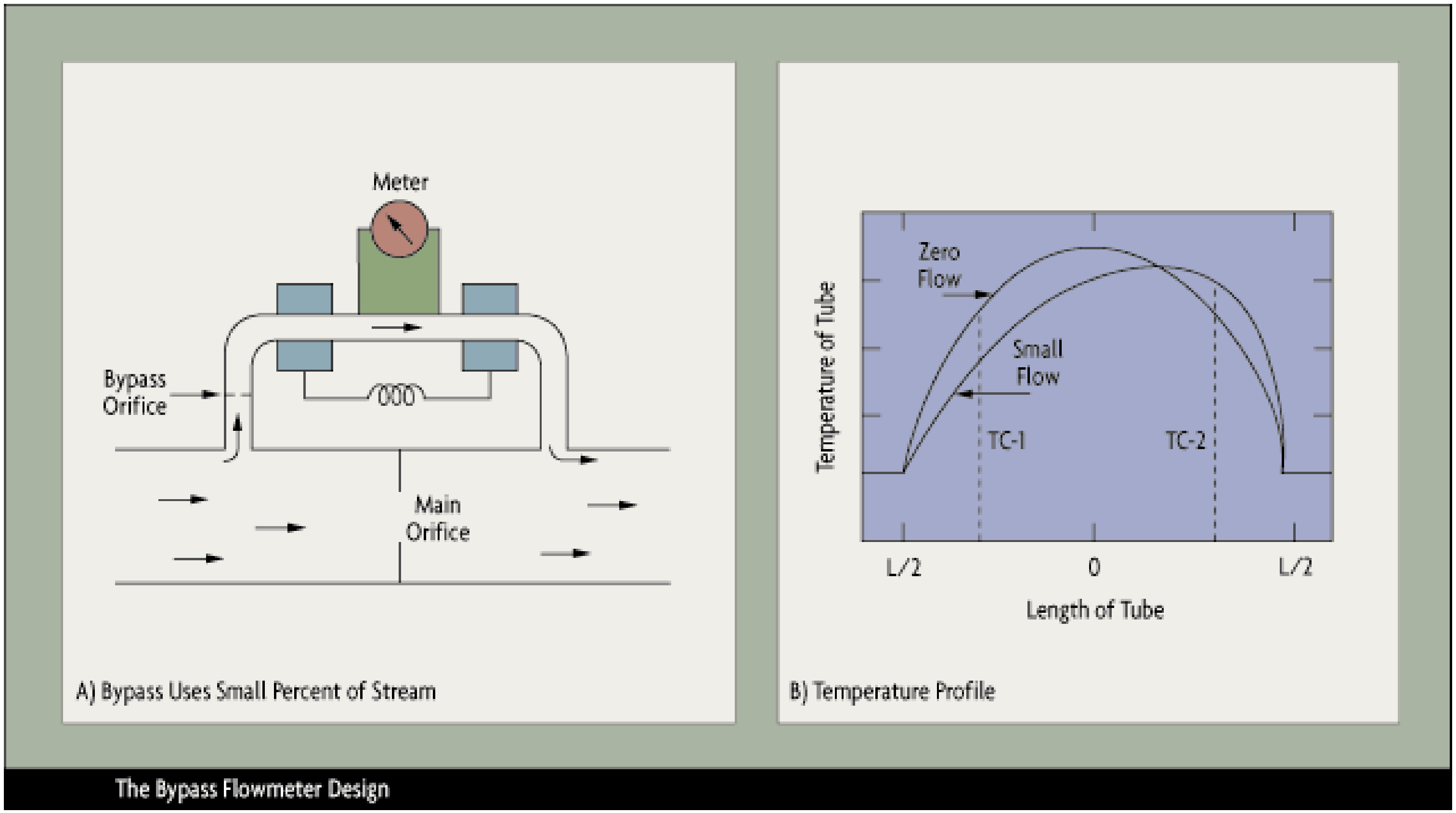


Type of Flowmeters
Thermal Mass



Thermal Mass Flowmeter Designs

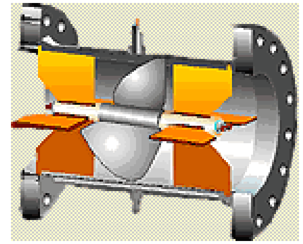
Type of Flowmeters
Thermal Mass

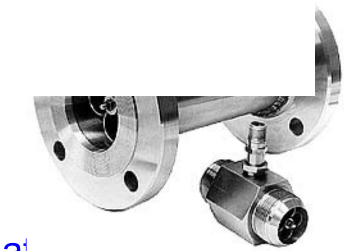


Type of Flowmeters

Turbine

Working Principle





Reluctance

The coil is a permanent magnet and the turbine blades are made of a material a magnets. As each blade passes the coil, a voltage is generated in the coil. Each pulse represents a discrete volume of liquid. The number of pulses per unit volume is called the meter's K-factor.

Inductance

A permanent magnet is embedded in the rotor, or the blades of the rotor are made of permanently magnetized material. As each blade passes the coil, it generates a voltage pulse. In some designs, only one blade is magnetic and the pulse represents a complete revolution of the rotor.

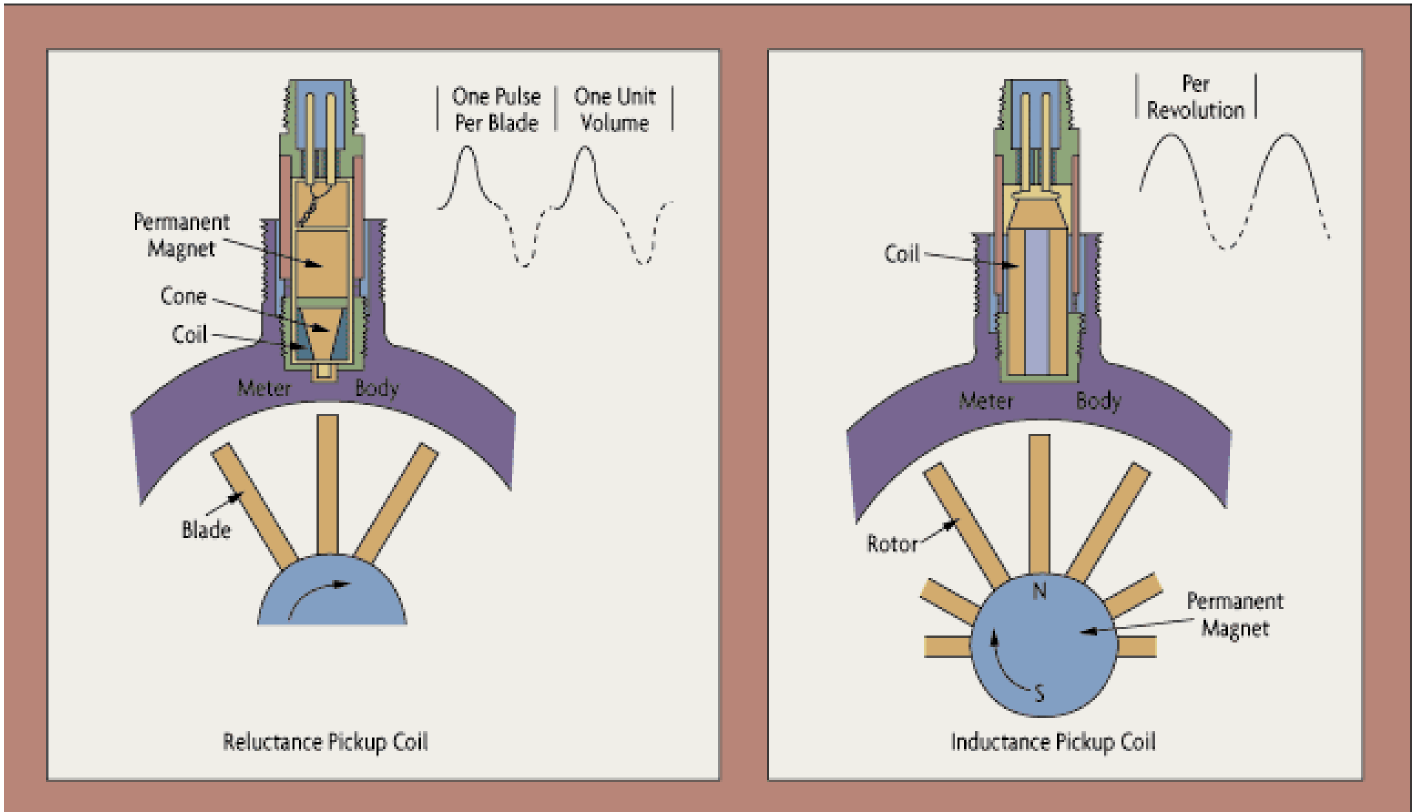
Capacitive

Capacitive sensors produce a sine wave by generating an RF signal that is amplitude-modulated by the movement of the rotor blades.

Hall-Effect

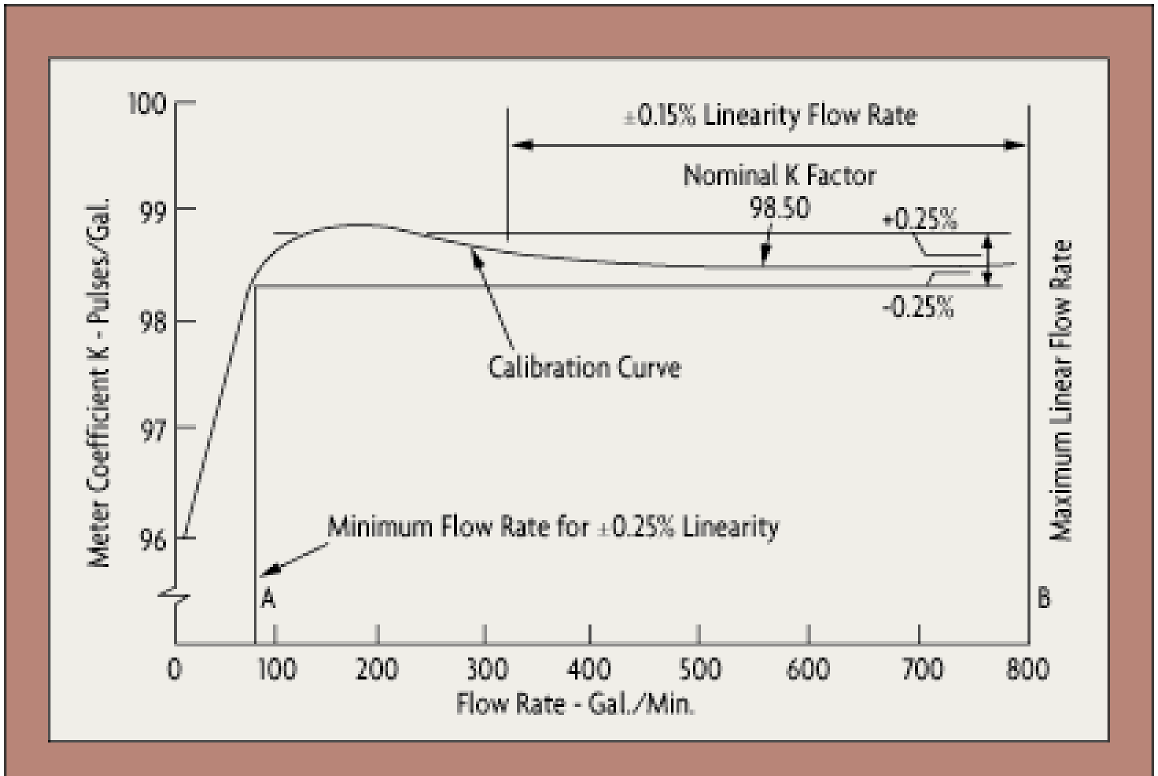
Hall-effect transistors also can be used. These transistors change their state when they are in the presence of a very low strength (on the order of 25 gauss) magnetic field.

Type of Flowmeters
Turbine



Generation of Turbine Flow Signal

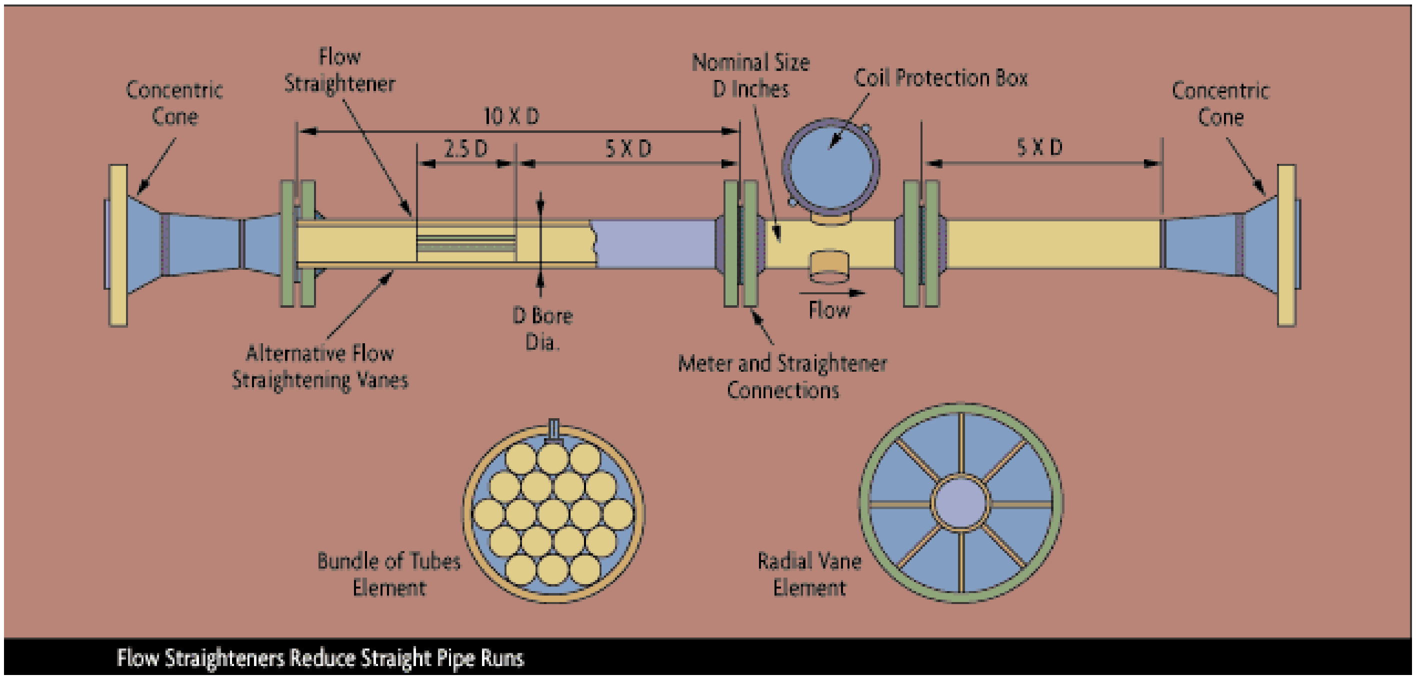
Type of Flowmeters
Turbine



Typical Turbine Flowmeter Calibration Curve

Type of Flowmeters

Turbine



Type of Flowmeters

Electromagnetic

The operation of magnetic flow meters is based on Faraday's law of electromagnetic induction. Magflow meters can detect the flow of conductive fluids only. Early magflow meter designs required a minimum fluidic conductivity of 1-5 microsiemens per centimeter for their operation. The newer designs have reduced that requirement a hundredfold to between 0.05 and 0.1.

$$E = BDV/C$$

E = Induced Voltage

B = Magnetic Field Strength

D = Inner Diameter of Pipe

V = Average Velocity

C = Constant

Type of Flowmeters

Electromagnetic

The magnetic flow meter’s coil can be powered by either alternating or direct current.

In AC excitation, line voltage is applied to the magnetic coils and as a result, the flow signal (at constant flow) will also look like a sine wave. The amplitude of the wave is proportional to velocity. Addition to the flow signal, noise voltages can be induced in the electrode loop. Out-of-phase noise is easily filtered, but in-phase noise requires that the flow be stopped (with the pipe full) and the transmitter output set to zero. The main problem with ac magflow meter designs is that noise can vary with process conditions and frequent re-zeroing is required to maintain accuracy.

And as for DC excitation designs, a low frequency (7-30 Hz) dc pulse is used to excite the magnetic coils. When the coils are pulsed on the transmitter reads both the flow and noise signals. In between pulses, the transmitter sees only the noise signal. Therefore, the noise can be continuously eliminated after each cycle.

Type of Flowmeters

Electromagnetic

Today, DC excitation is used in about 85% of installations while AC types claim the other 15% when justified by the following conditions:

- When air is entrained in large quantities in the process stream.
- When the process is slurry and the solid particle sizes are not uniform.
- When the solid phase is not homogeneously mixed within the liquid.
- When the flow is pulsating at a frequency under 15 Hz.

Type of Flowmeters
Electromagnetic

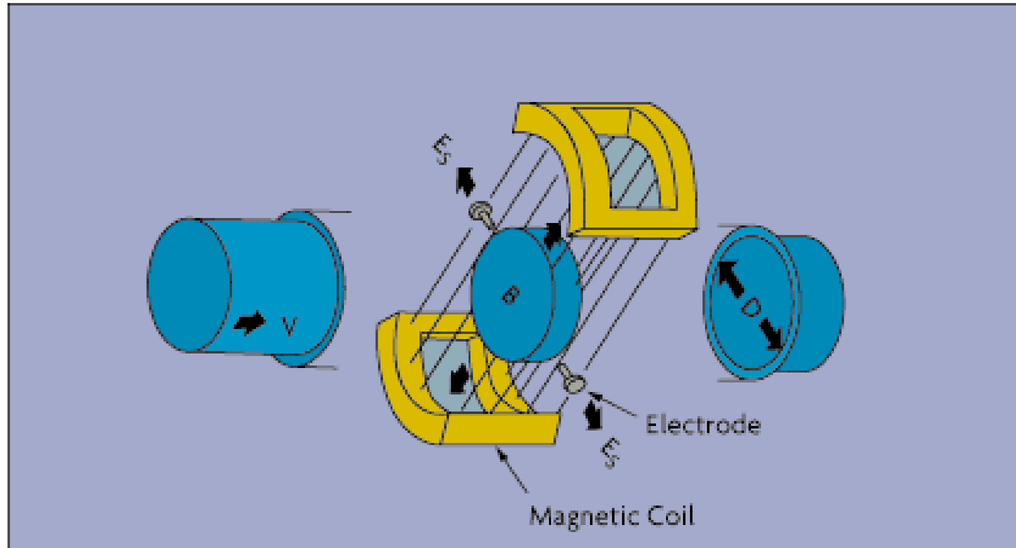
E = Induced Voltage

B = Magnetic Field Strength

D = Inner Diameter of Pipe

V = Average Velocity

C = Constant

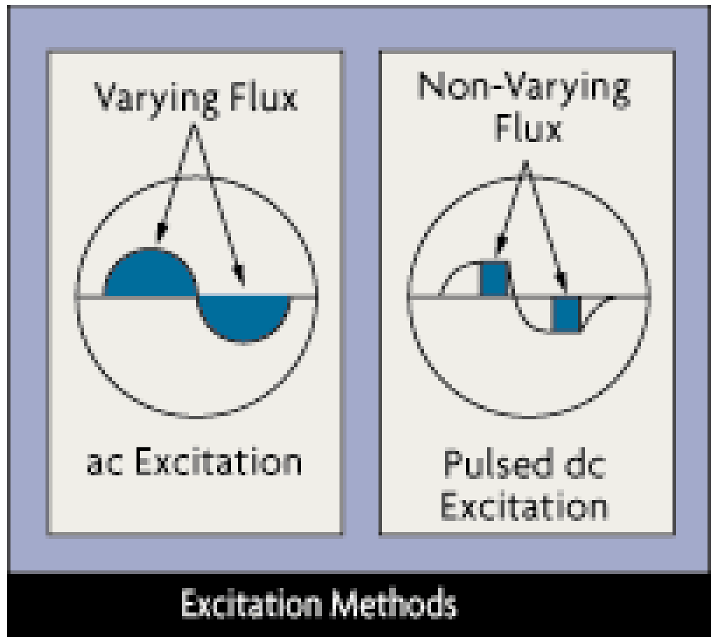


The Magmeter and Its Components

E = BDV/C

C is a constant to take care of the engineering proper units

Type of Flowmeters
Electromagnetic



Type of Flowmeters

Corriolis

The principle of angular momentum can be best described by Newton's 2nd Law of angular motion and the definitions using these following notations:

Newton's 2nd Law of angular motion states that

$\gamma = I\alpha$ and defines that $H = I\omega$ and since by definition $I = mr^2$

Then $\gamma = mr^2\alpha$ and then $H = mr^2\omega$

Since $\alpha = \omega/t$ then becomes $\gamma = mr^2 * \omega/t$ and solving mass flow rate, m/t we get

$m/t = \gamma/r^2\omega$ also divide $H = mr^2\omega$ by t then $H/t = m/t * r^2\omega$

H = Angular Momentum

I = Moment of Inertia

ω = Angular Velocity

Y = Torque

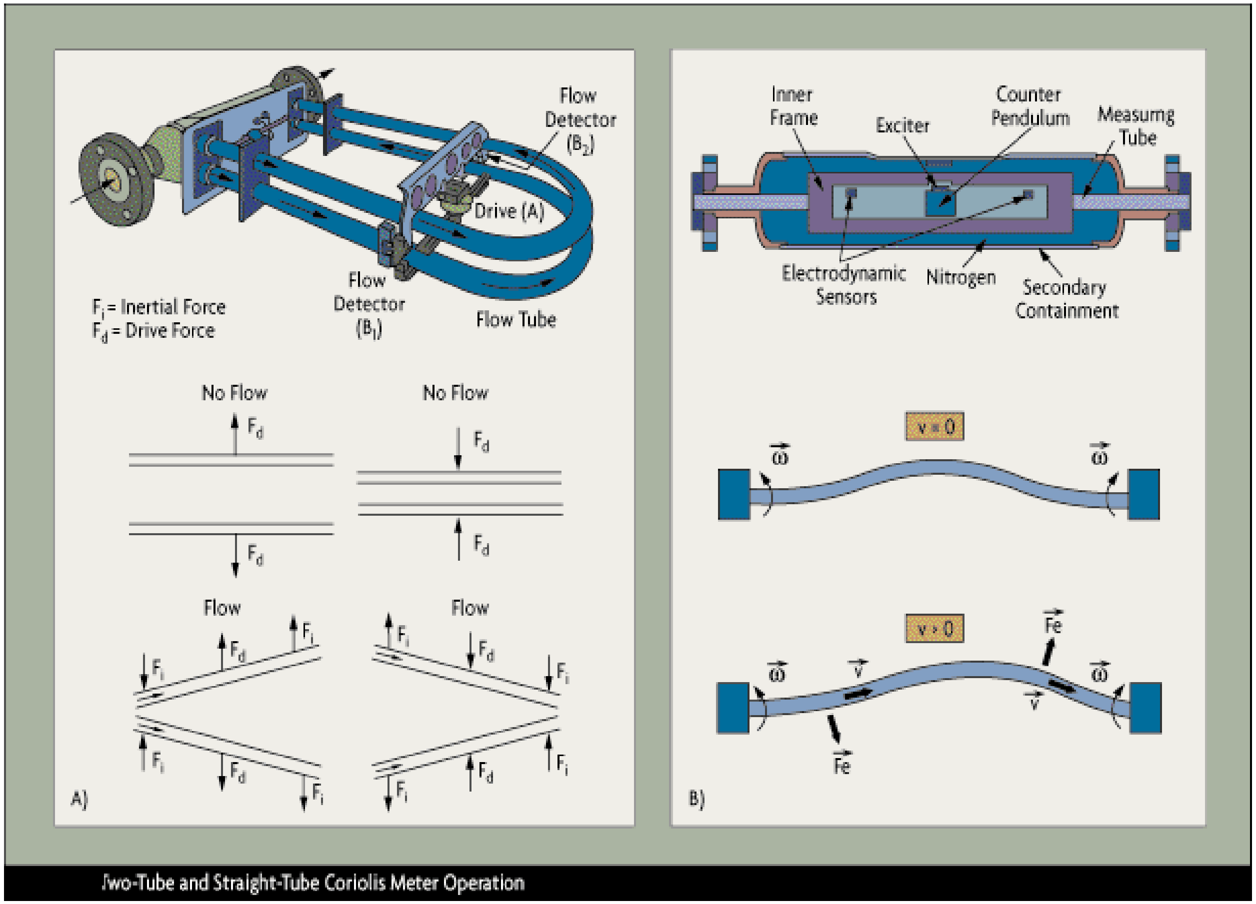
α = Angular Acceleration

r = Torque of Gyration

m = Mass

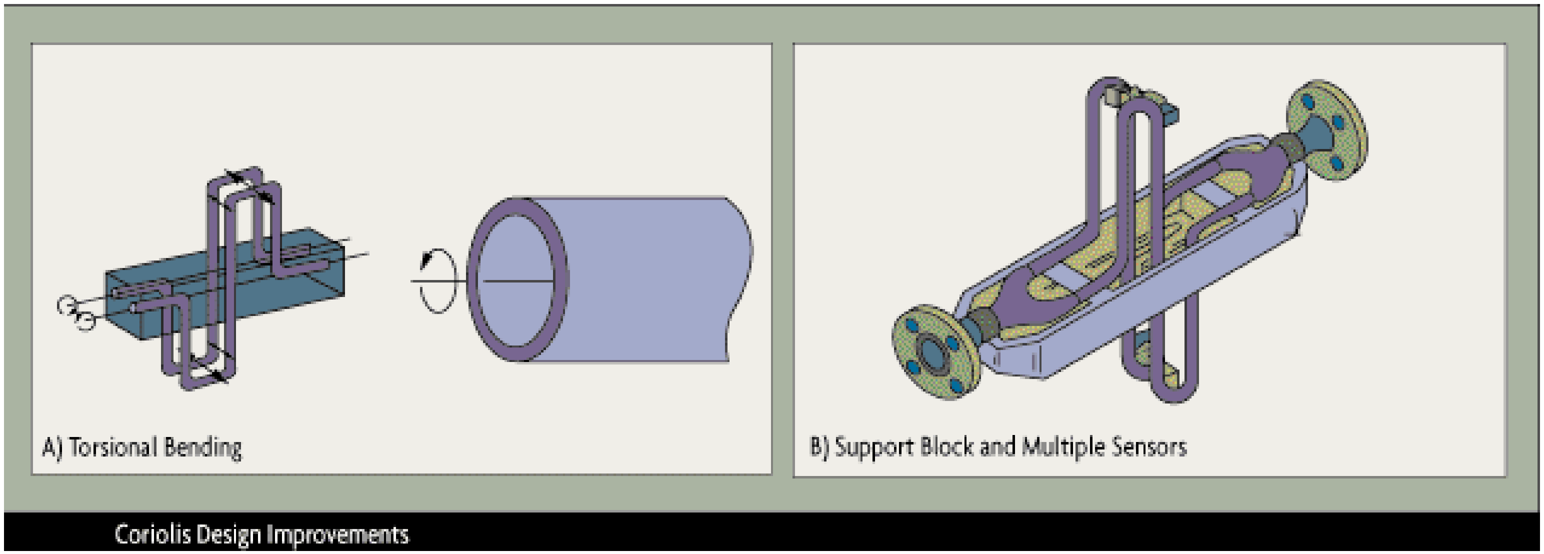
t = Time

Type of Flowmeters
Corriolis

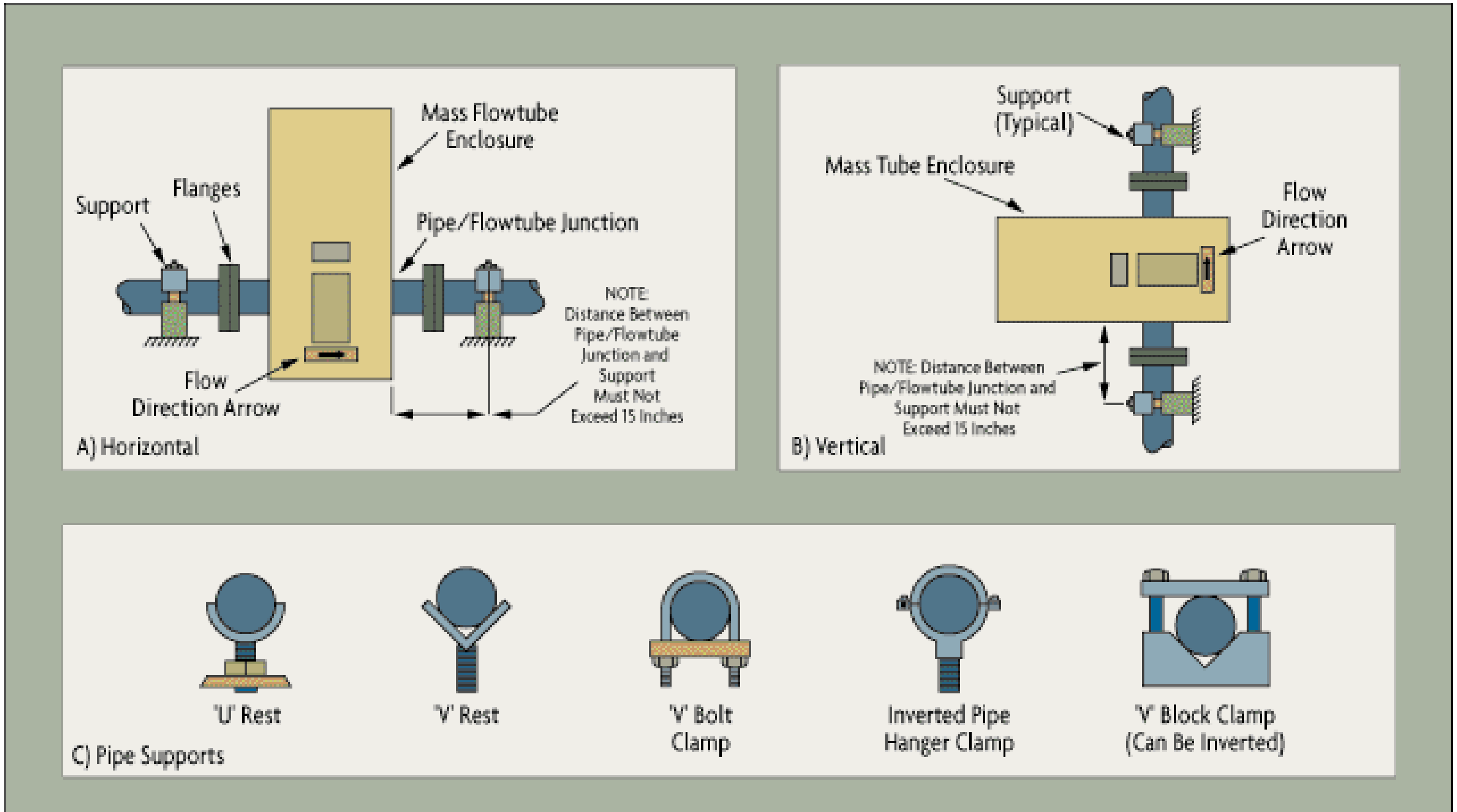


FUJI TECHNOLOGIES

Type of Flowmeters
Corriolis



Type of Flowmeters
Corriolis



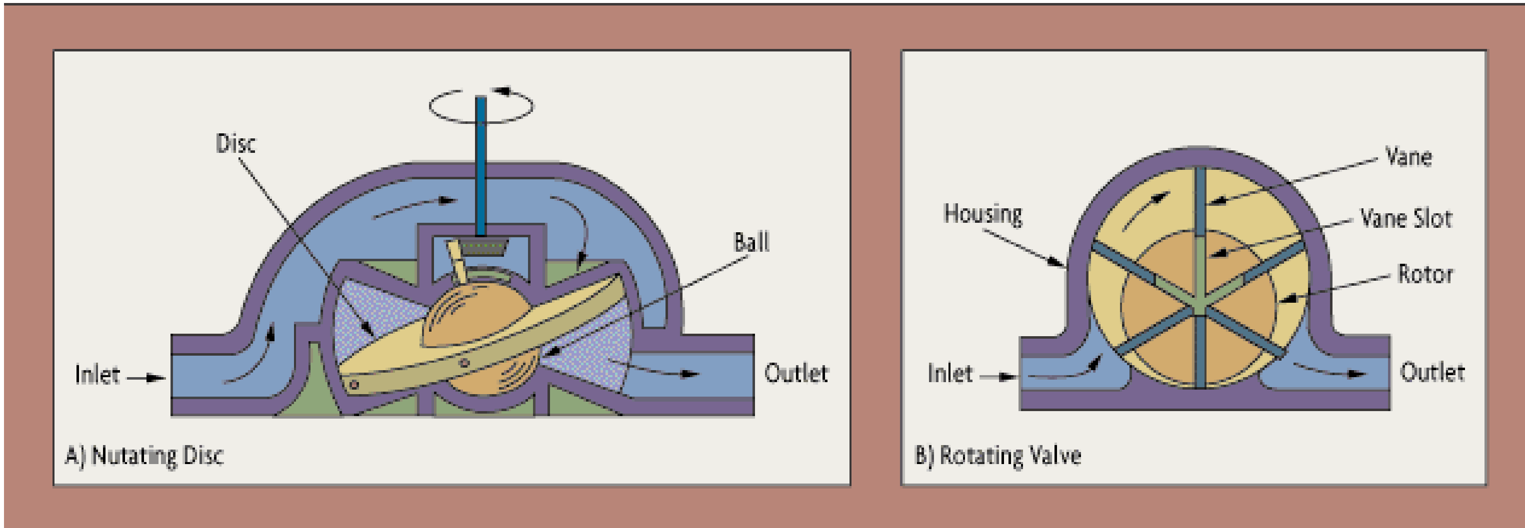
Installation Variations of the Coriolis Meter

Type of Flowmeters
Positive Displacement

Positive displacement meters provide high accuracy, ±0.1% of actual flow rate in some cases and good repeatability as high as 0.05% of reading. Accuracy is not affected by pulsating flow unless it entrains air or gas in the fluid. PD meters do not require a power supply for their operation and do not require straight upstream and downstream pipe runs for their installation. Typically, PD meters are available 1” up to 12” in size and can operate with turndowns as high as 100:1, although ranges of 15:1 or lower are much more common. Slippage in the flowmeter is reduced and metering accuracy is therefore increased as the viscosity of the process fluid increases.

The process fluid must be clean. Particles greater than 100 microns in size must be removed by filtering. PD meters operate with small clearances between their precision-machined parts; wear rapidly destroys their accuracy. For this reason, PD meters are generally not recommended for measuring slurries or abrasive fluids. In clean fluid services, however, their precision and wide rangeability make them ideal for custody transfer and batch charging. They are most widely used as household water meters. Millions of such units are produced annually at a unit cost of less than US$50. In industrial and petrochemical applications, PD meters are commonly used for batch charging of both liquids and gases.

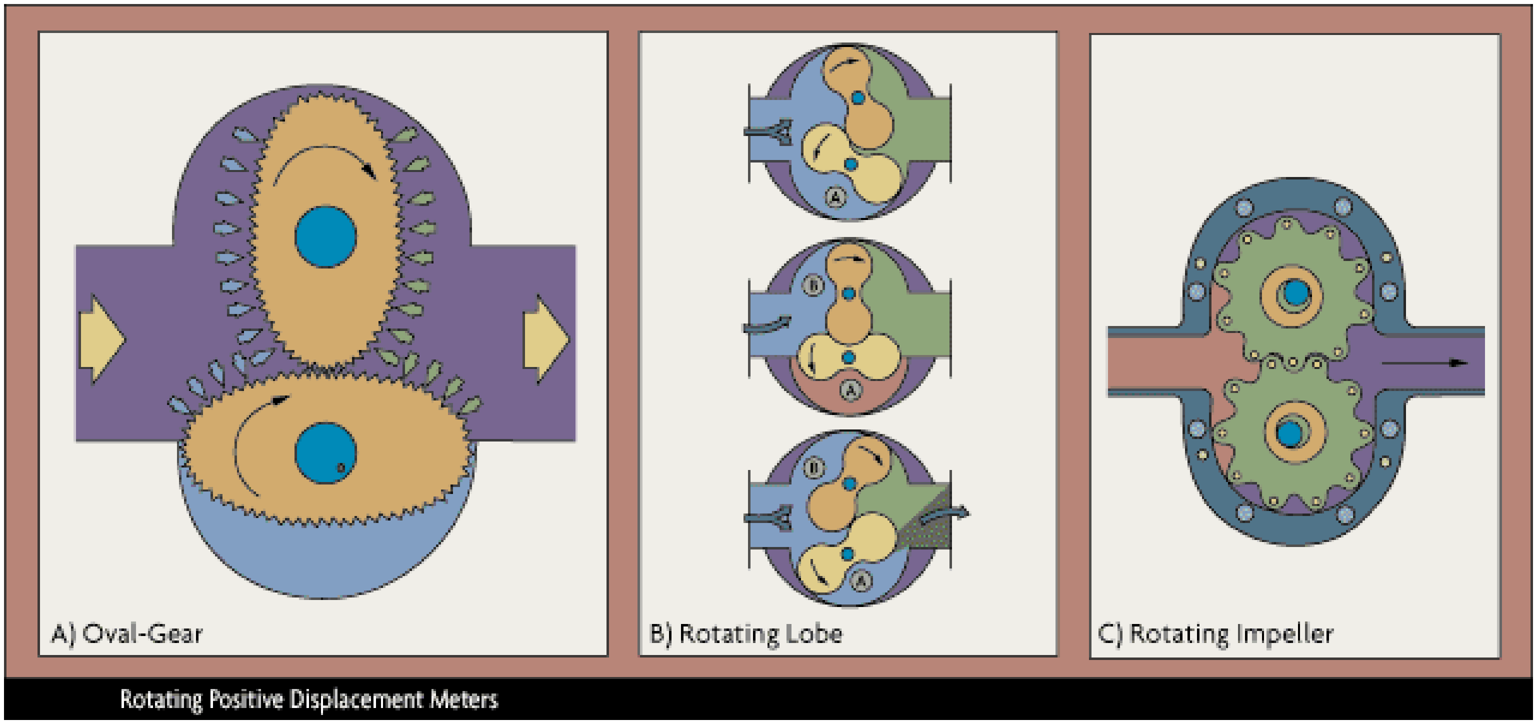
Type of Flowmeters
Positive Displacement



Positive Displacement Flowmeter Designs

Type of Flowmeters

Positive Displacement

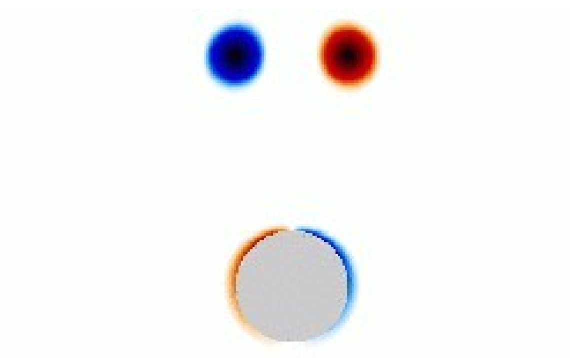


Type of Flowmeters

Vortex

Types of Working Principles

1. Vortex Shedding
2. Vortex Precession
3. Fluidic Oscillation (Coanda Effect



Type of Flowmeters

Vortex

Vortex shedding frequency is directly proportional to the velocity of the fluid in the pipe and therefore to volumetric flow rate. The shedding frequency is independent of fluid properties such as density, viscosity, conductivity, etc., except that the flow must be turbulent for vortex shedding to occur. The relationship between vortex frequency and fluid velocity is:

$$St = f\,(d/v)$$

$$Q = AV = (AfdB)/St$$

$$Q = fK$$

St = Strouhal Number

f = Vortex Shedding Frequency

d = Width of the Bluff Body

A = Cross Sectional Area

V = Average Fluid Velocity

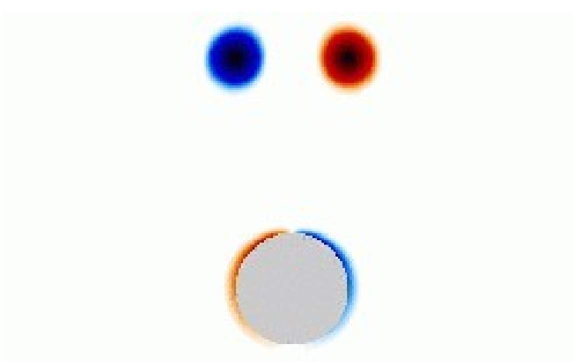
B = Blockage Factor

K = Meter Coefficient

Type of Flowmeters

Vortex

The value of the Strouhal number is determined experimentally, and is generally found to be constant over a wide range of Reynolds numbers. The Strouhal number represents the ratio of the interval between vortex shedding (l) and bluff body width (d), which is about six. The Strouhal number is a dimensionless calibration factor used to characterize various bluff bodies. If their Strouhal number is the same, then two different bluff bodies will perform and behave similarly.



Type of Flowmeters
Vortex Shedding

St = Strouhal Number

f = Vortex Shedding Frequency

d = Width of the Bluff Body

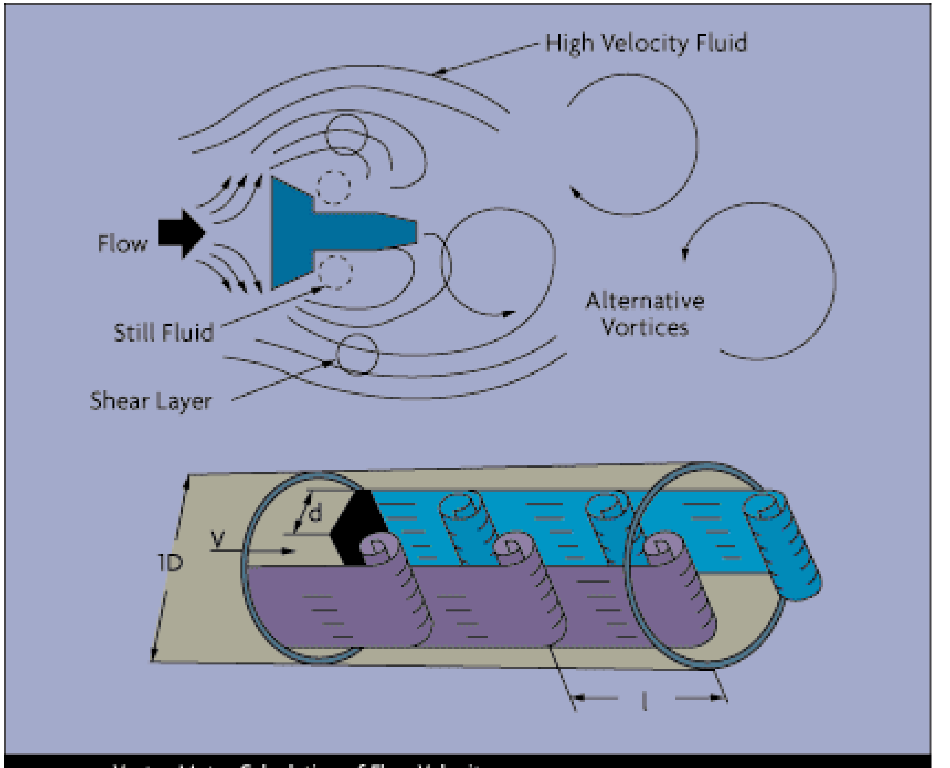
A = Cross Sectional Area

V = Average Fluid Velocity

B = Blockage Factor

K = Meter Coefficient

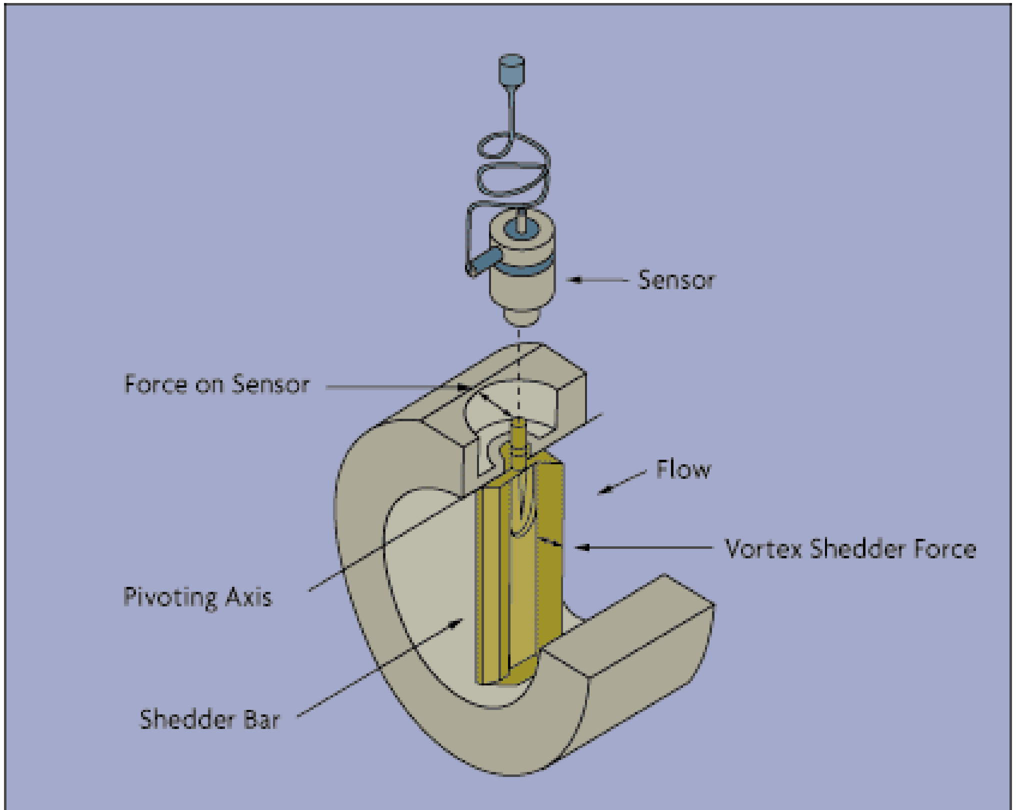
Q = AV = (AfdB)/St



Vortex Meter Calculation of Flow Velocity

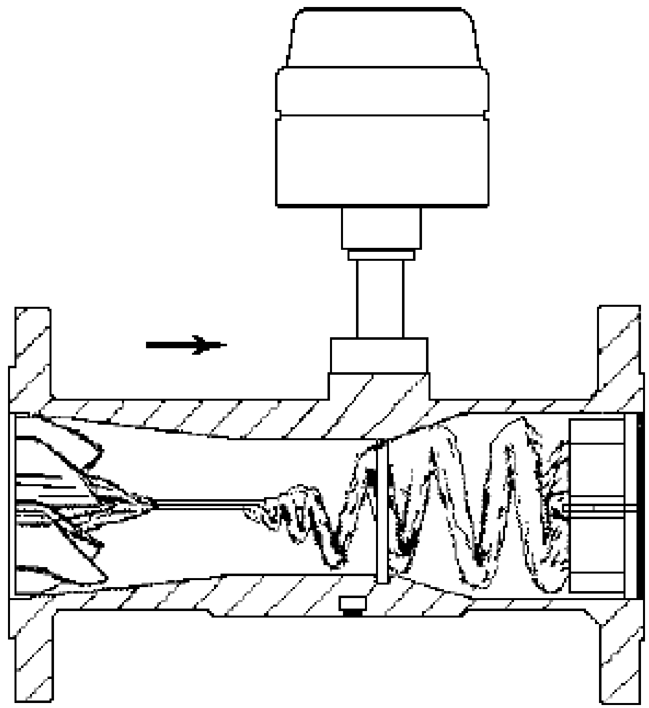
Type of Flowmeters

Vortex Shedding



Vortex Detecting Sensor

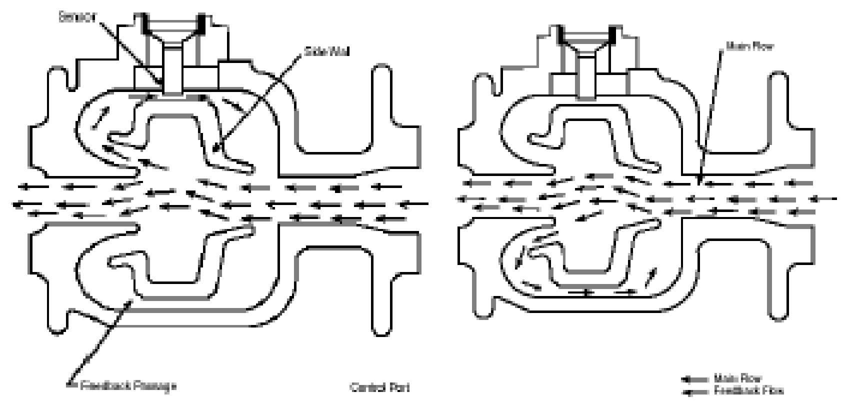
Type of Flowmeters
Vortex Precession



Vortex Precession

Type of Flowmeters
Fluidic Oscillation (Coanda Effect)

Coanda Effect Flowmeter



1. Fluidic Oscillation (Coanda Effect)

Type of Flowmeters

Ultrasonic

Ultrasonic waves travel in the same manner as light or microwaves however being an Elastic waves, they can propagates through any substance like solid, liquid and gases. And by utilizing the properties of ultrasonic waves, clamp on flowmeters with unique feature of being able to measure fluid flow in the pipe externally was developed.

Generally, ultrasonic flowmeters works in 2 different kind of principles:

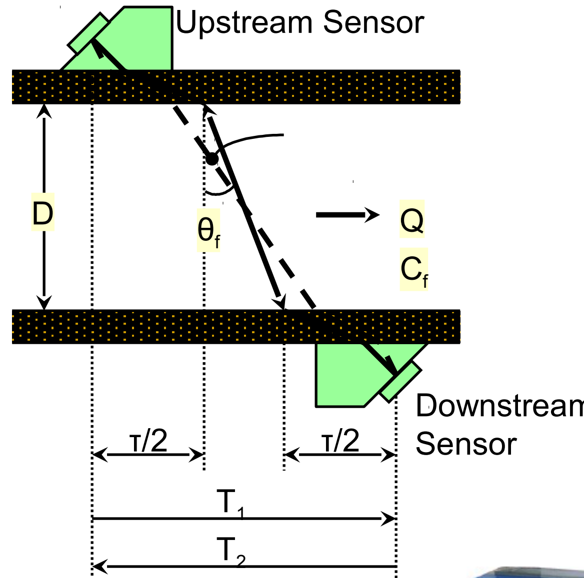
1) Doppler Effect Ultrasonic Flowmeter
   The Doppler Effect Ultrasonic Flowmeter uses reflected ultrasonic sound to measure the fluid velocity. By measuring the frequency shift between the ultrasonic frequency source, the receiver and the fluid carrier. In this the relative motion are measured. The resulting frequency shift is named the ”Doppler Effect”.

2) Transit Time Difference Ultrasonic Flowmeter
   With the Time of Flight Ultrasonic Flowmeter the time for the sound to travel between a transmitter and a receiver is measured. This method is not dependable on the particles in the fluid.

Type of Flowmeters

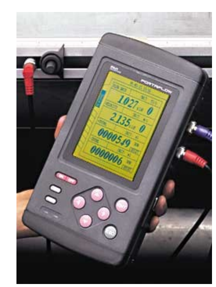
Ultrasonic

$$V_f = \frac{Kdt}{TL}$$



Cross Sectional Area — Average Velocity on C.S.A — Average Velocity on Propagation Path

$$Q = \frac{\pi D^2}{4} \times \frac{1}{K} \times \frac{D}{\sin 2\theta_f} \times \frac{\Delta T}{(T_0 - \tau)^2}$$

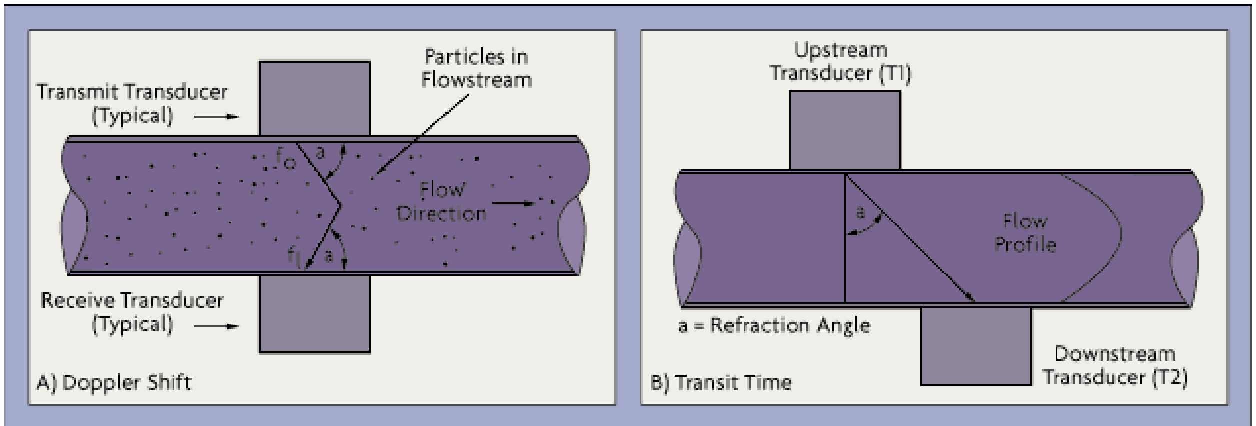


Q = Flow Rate
D = Inner Pipe Diameter
K = Conversion Factor of Average Velocity
Θ_f = Incident angle into liquid
T_1 & T_2 = Transit time
T_0 = Transit time between sensors when flow is at rest ≒ $(T_1 + T_2)/2$
τ = Transit time in pipe walls and sensors = $\Delta T = T_2 - T_1$

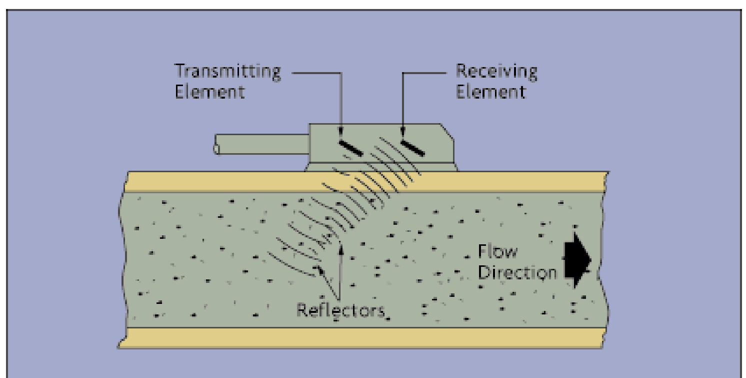
Note that ultrasonic waves are carried with the motion of fluid

Type of Flowmeters

Ultrasonic

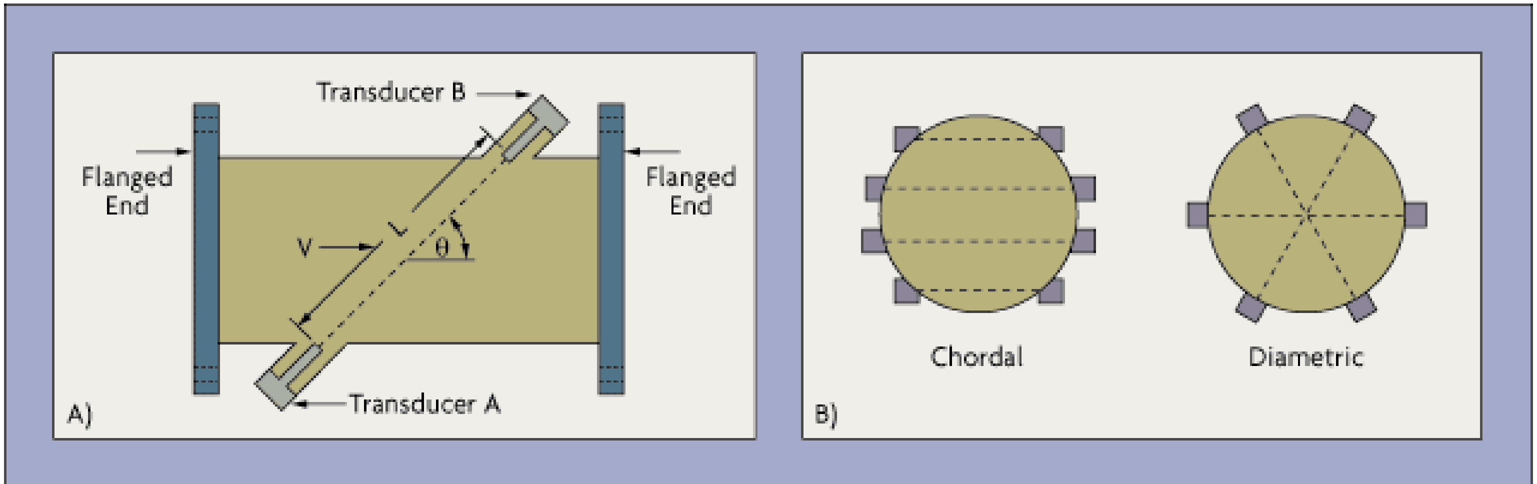


Ultrasonic Flowmeter Designs



Clamp-On Ultrasonic Flowmeter

Type of Flowmeters
Ultrasonic



Spool-Piece Designs for High Accuracy Ultrasonic Flowmetering

Selection of Flowmeters

		Ultrasonic	Electromagnetic	Differential Pressure	Vortex
	Fluid	□	□	□	□
	Gas	X	X	□	□
Measuring Media	Vapor	X	X	□	□
	Slurry	X	O	X	X
	Control	□	□	□	□
Application	Monitor	□	□	□	□
	Supply	X	□	X	X
	Temperature	-40 to 200 °C	-20 to 120 °C	-40 to 600 °C	-10 to 200 °C
Operating Condition	Pressure	-	-1 to 2MPa	-0.1 to 42MPa	5MPa
	Pressure Loss	None	None	Yes	Yes
	Rangeability	Large	Large	Large	Large
	Bore ∅	13 ~ 6,000mm	2.5 ~ 300mm	25 ~ 3,000mm	4 ~ 100mm
Installation Condition	Upstream/Downstream	10D/5D	5D/2D	10D/5D	7D/3D
	Piping Works	Not Required	Required	Required	Required
	Explosion Proof	□	X	□	X
	Accuracy	± 0.5 % of Rate	± 0.5 % of Rate	± 2.0 % of FS	± 1.0 ~ 3. 0 % of Rate
Performance	Velocity Range	-32 to 32m/s	0 to 15m/s	-	0.3 to 4m/s

Flow Measurement Information

Useful links:

a) http://www.iceweb.com.au/Technical/flow_measurements_info_notes.htm
b) http://www.engineeringtoolbox.com/49.html
c) http://www.engineeringtoolbox.com/49_530qframed.html
d) http://www.torbar.co.uk/calcdata.htm
e) http://thcentral.com/fluiddynamicscalcs.htm

Questions & Answers

The End