Instrumentation & Measurement

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Flow Measurement

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Position-Displacement Measurement

- Source Book:

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Franklyn Kirk, Thomas Weedon,
Philip Kirk

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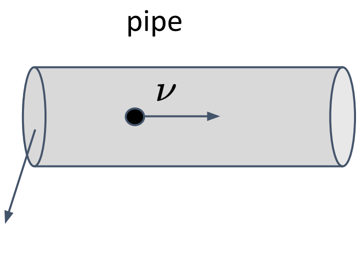
Chapters 18-22

Topics

- Flow Units, Flow velocity, Flow rate and Total volume
- Differential pressure principle + flow meter
- Mechanical Flowmeters
- Magnetic Flowmeters
- Ultrasonic Flowmeters
- Mass Flowmeters
- Flow Switch

Flow Velocity, Rate and Total

Flow rate is the quantity of fluid passing a point at during a time unit.



A is the pipe
cross-sectional area size

$$\text{Flow Velocity} \rightarrow \nu \leftarrow \text{Units} : \frac{m}{s}, \frac{cm}{s}, \frac{ft}{s}, \frac{in}{s}$$

$$\text{Flow Rate} \leftrightarrow Q \leftarrow \text{Units} : \frac{l}{min}, \frac{m^3}{s}, \frac{m^3}{h}, \frac{cm^3}{s}, \frac{gal}{s}, \frac{gal}{m}, \frac{gal}{h}$$

$$\text{Total Flow} \leftrightarrow \text{Volume} \leftarrow \text{Units} : l, m^3, cm^3, gal, ft^3$$

$$Q = \nu \times A \qquad \left(\rightarrow \frac{m^3}{s} = \frac{m}{s} \times m^2\right)$$

$$Total\ Flow = Vol = Q \times t \qquad \left(\rightarrow m^3 = \frac{m^3}{s} \times s\right)$$

Flow Velocity, Rate and Total

Example: A rotameter in your lab measures the water flow rate as 10 l/min (= 0.01 m^3/min) in a 1.27 cm diameter hose.

Find the flow velocity in m/s ?

How much of water in litter would pour into the tank after 10 minutes?

Flow Velocity, Rate and Total

Example: A rotameter in your lab measures the water flow rate as 10 l/min (= 0.01 m^3/min) in a 2 cm diameter hose.
Find the flow velocity in m/s ?
How much of water in litter would pour into the tank after 10 minutes?

$$r = \frac{D}{2} = \frac{0.0127\,m}{2} = 0.00635\,m$$

$$A = \pi . r^2 = \pi \times \ 0.00635 \ \times 0.00635 \ m^2 \ = 1.27 \ \times 10^{-4} \ \ m^2$$

$$Q = \nu \times A \Rightarrow \nu = \frac{Q}{A} \ = \frac{0.01 \ \frac{m^3}{min}}{1.27 \ \times 10^{-4} \ \ m^2} = \frac{100}{1.27} \ \frac{m}{min} \approx 78.74 \ \frac{m}{min} \approx 1.31 \ \frac{m}{s}$$

$$Total\ Flow = \ Vol \ = Q \times t \quad = 10 \ \times \ 10 = 100 \ \ litter$$

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Absolute viscosity is the resistance to flow of a fluid and has units of centipoise (cP). Kinematic viscosity is the ratio of absolute viscosity to fluid density and has units of centistokes (cS). The viscosity of many commercial fluids, like oils, is commonly specified as an allowable range at a certain temperature.

For example, No. 6 fuel oil and motor oil specifications allow a broad range of viscosity at a specified temperature. At 68°F, water has a viscosity of 1.0 cP, SAE 30 oil has a viscosity of approximately 100 cP, and No. 6 fuel oil has a viscosity of approximately 850 cP.

Viscosity is affected by temperature and other factors and normally decreases with increasing temperature. Many fluids must be preheated before being pumped.

[Understanding Laminar and Turbulent Flow](https://www.youtube.com/watch?v=9A-uUG0WR0w)

https://www.youtube.com/watch?v=9A-uUG0WR0w

Typical Liquid Viscosities*

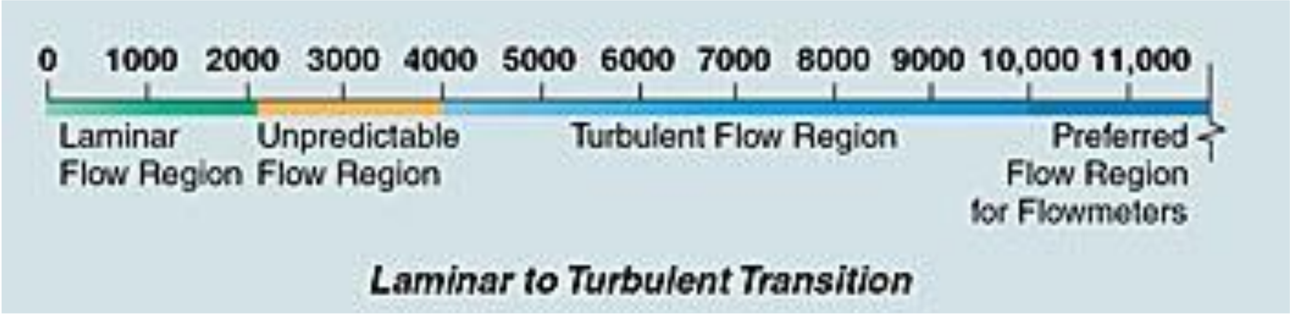
	Specific Gravity, SG	Absolute Viscosity, Centipoise	Kinematic Viscosity, Centistokes
Water	1.0	0.98	0.97
Gasoline	0.71	0.48	0.67
Ethylene glycol	1.1	20	18
SAE 30 motor oil	0.91	96 (100°F)	106 (100°F)
No. 6 Fuel oil	0.88	850 (68°F) 335 (122°F)	966 (68°F) 379 (122°F)
95% Sulfuric acid	1.84	26.6	14.5
25% Sodium chloride	1.2	2.9	2.4
Acetic acid	1.05	1.2	1.15
Glycerin	1.3	1000	770
Acetone	0.79	0.33	0.42
n-Propyl alcohol	0.80	2.2	2.75
Corn oil	0.93	26.5 (130°F)	28.7 (130°F)
Molasses	1.43	430 to 7000 (100°F)	300 to 5000 (100°F)
Freon	1.33	0.20	0.15

*at room temperature unless otherwise noted

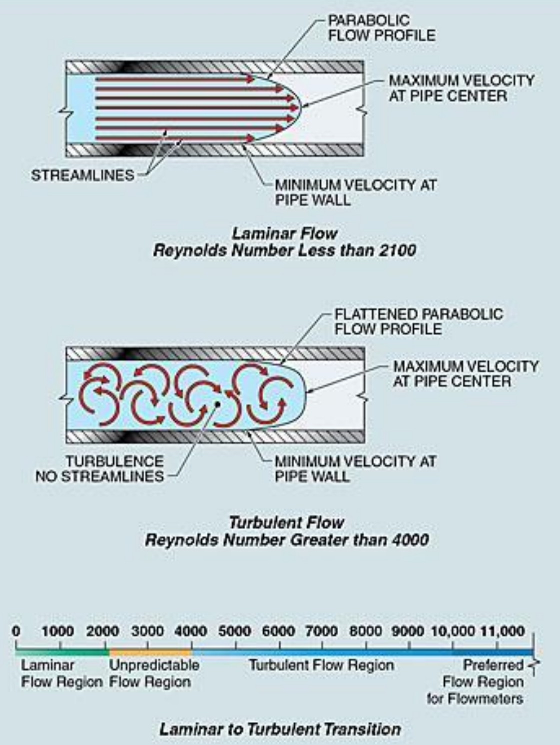
Laminar streamlines are smooth and steady while turbulent flow is chaotic. Laminar flow occurs at Reynolds numbers below 2100.

A Reynolds number is the ratio between the inertial forces moving a fluid and viscous forces resisting that movement. It describes the nature of the fluid flow. The Reynolds number has no units of measure and is calculated from velocity or flow rate, density, viscosity, and the inside diameter of a pipe. Reynolds numbers commonly range from 100 to 1,000,000. However, they can be higher or lower than these values.

Velocity is the speed of fluid in the direction of flow. A streamline can be drawn to show the direction and magnitude of smooth flow at every point across a pipe profile. A flow profile can be drawn to represent the velocity of a fluid at different points across a pipe or duct.



Reynolds Number and Flow Profiles



$$Re = 1488 \times \frac{v \times d \times \rho}{\mu}$$

$$Re = 1488 \times \frac{1.0 \times 0.25 \times 62.4}{1.0}$$

$$Re = 1488 \times 15.6$$

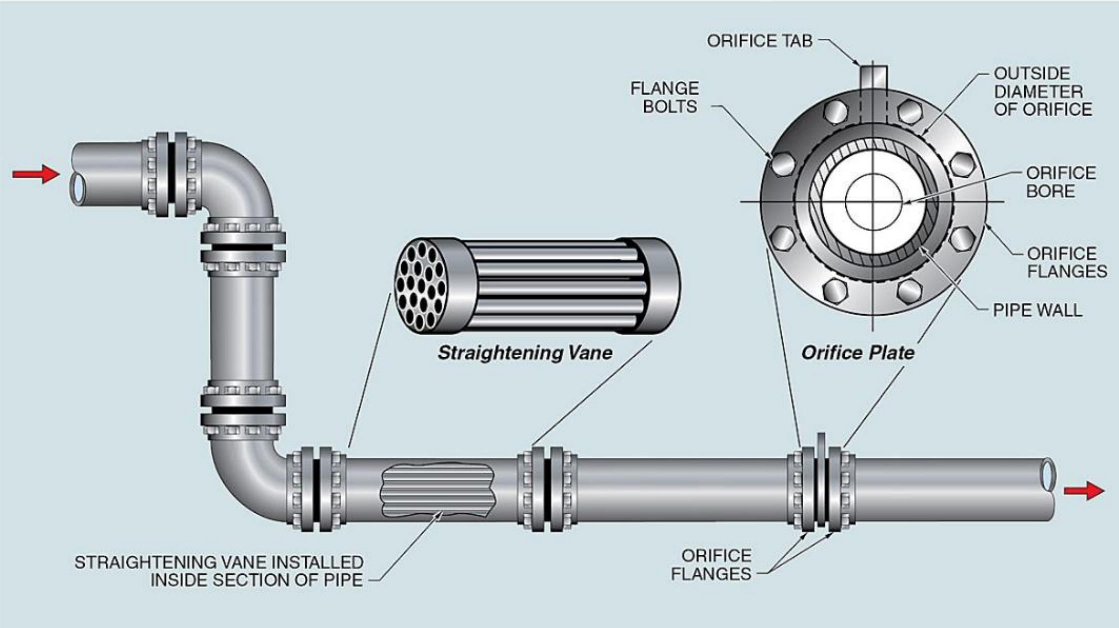
$$Re = 23{,}213$$

$v = 1.0$ ft/sec
$d = 0.25$ ft
$\rho = 62.4$ lb/ft^3
$\mu = 1.0$ cP

Reynolds Number Calculations for Water at 1.0 ft/sec Through a 3" Pipe

Straightening vanes remove flow disturbances upstream of an orifice.

Orifice Flow Elements and Straightening Vanes



Chapter 19

Differential Pressure Flowmeters

Primary Flow Elements • Orifice Plates • Flow Nozzles • Venturi Tubes • Low-Loss Flow Tubes • Pitot Tubes • Operating Principles • Differential Pressure Measurements

Bernoulli's Equation

$$\overbrace{P + \underbrace{\rho g h}_{\text{Due to elevation}}}^{\text{Static}} + \overbrace{\frac{1}{2}\rho V^2}^{\text{Dynamic}} = \text{Constant} \quad \text{along a streamline}$$

[Understanding Bernoulli's Equation](https://www.youtube.com/watch?v=DW4rItB20h4)

V → Flow Velocity

ρ → flow density

https://www.youtube.com/watch?v=DW4rItB20h4

Bernoulli’s Equation assumptions and limitations

Underlying assumptions:

- Applies along the streamline
- No energy is used to overcome the friction. It means the fluid viscosity is low , the flow is laminar (Reynolds number small).
- Higher reynold’s number makes the calculation less accurate.
- The fluid density is constant at two points of calculation (fluid is incompressible)
- This equation can be adapted to compressible and non-laminar flow by some changes
- Fluid should be incompressible like liquid , gas is compressible

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

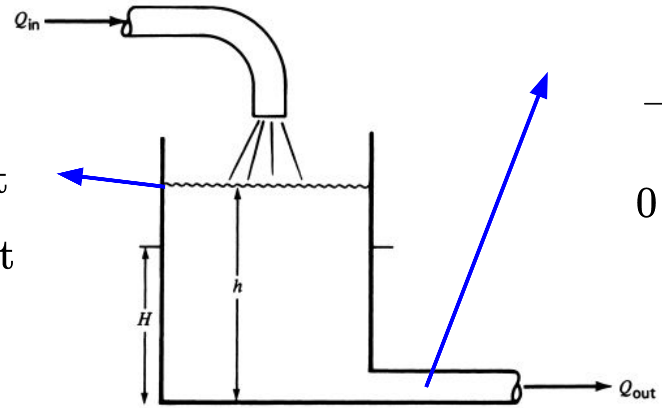
Fluid Speed

At point1 (reference point)

$$P_1 + \rho g h_1 + \frac{1}{2}\rho V_1^2 = \text{Constant}$$

$$0 + 0 + 0 = \text{Constant}$$

$$\Rightarrow \ \text{Constant} = 0$$



At point2

$$\rightarrow P_2 + \rho g h_2 + \frac{1}{2}\rho V_2^2 = \text{Constant}$$

$$0 + \rho g(0 - h) + \frac{1}{2}\rho V^2 = \text{Constant}$$

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

At point1 = At point2

$$0 = -\rho g h + \frac{1}{2}\rho V^2$$

$$\frac{1}{2}\rho V^2 = \rho g h$$

$$\boxed{V = \sqrt{2gh}}$$

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Flow Measurement by Mechanical Obstruction

$$P_1 + \rho g h_1 + \frac{1}{2}\rho V_1^2 = P_2 + \rho g h_1 + \frac{1}{2}\rho V_2^2$$

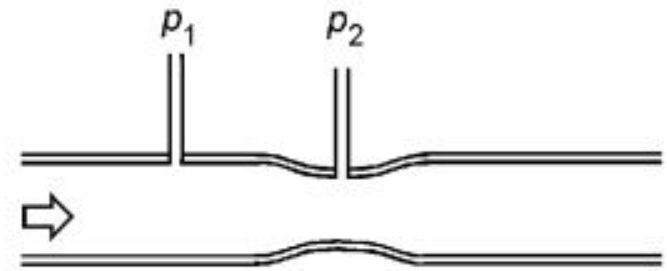
$$\left.\begin{array}{ll} P_2 - P_1 = & \frac{1}{2}\rho V_1^2 - \frac{1}{2}\rho V_2^2 \\ Q_1 = Q_2 = Q & V_1 A_1 = V_2 A_2 \end{array}\right\} \Rightarrow P_2 - P_1 = \frac{1}{2}\rho V_1^2 \left(1 - \left(\frac{A_1}{A_2}\right)^2\right)$$

$$V_1^2 = \frac{1}{1-\left(\frac{A_1}{A_2}\right)^2} \times \frac{2(P_2 - P_1)}{\rho} \quad (\Rightarrow \Delta P \,\alpha\, V^2)$$

$$V_1 = \frac{1}{\sqrt{\frac{1}{1-\left(\frac{A_1}{A_2}\right)^2}}} \times \sqrt{\frac{2}{\rho}} \times \sqrt{P_2 - P_1} \quad \left(\Rightarrow V \alpha \sqrt{\Delta P}\right)$$

$$V_1 = C \times \sqrt{\Delta P} \qquad (Q_1 = V_1 A_1)$$

$$\boxed{\Rightarrow Q = K \times \sqrt{\Delta P}}$$



$$Q = K \times \sqrt{\Delta P}$$

K is constant and its value depends on

- Density of fluid
- the diameter of the pipe in narrow and wide area
- type of obstruction
- Units of measurement

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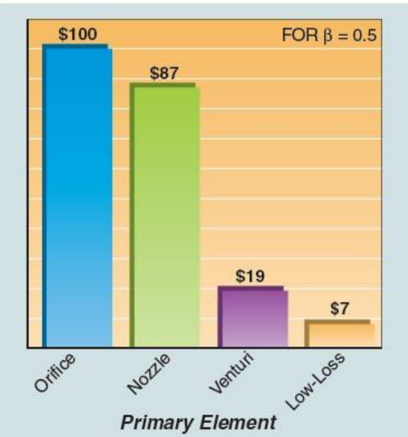
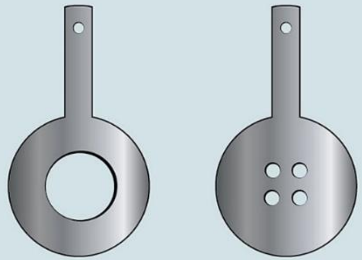
Flow elements have different internal designs to achieve different objectives.

- **Flow Nozzle**
- **Venturi Tube**
- **Low-Loss Flow Tube**
- **Orifice Plate**

Relative Power Consumption

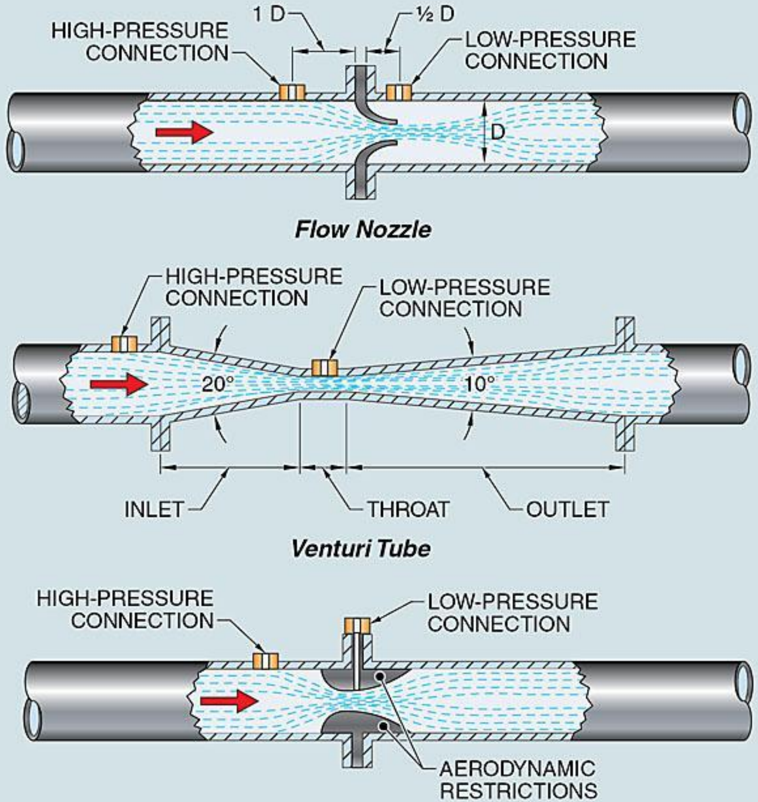


Compact Orifice Flowmeters



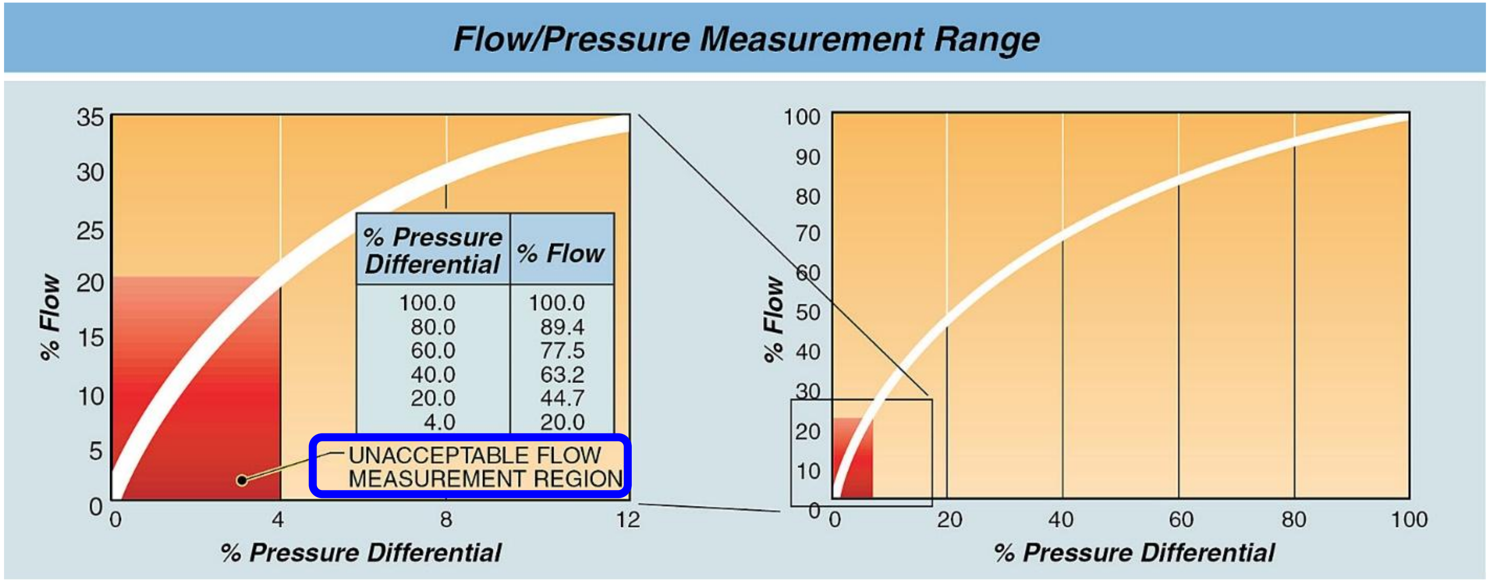
Standard *Conditioning*

Flow Elements



Measurement Limit and Rangeability

- The flow rate is proportional to the square root of the differential pressure. The square root relationship affects the rangeability of the flow metering system.
- **Rangeability, or turndown ratio,** is the ratio of the maximum flow to the minimum measurable flow at the desired measurement accuracy. This is a characteristic of the instrument and is not adjustable.
- For example, if the maximum measurable flow rate of a flowmeter is 100 gpm and the minimum measurable flow rate is 20 gpm, the rangeability is 5 to 1.



% Pressure Differential	% Flow
100.0	100.0
80.0	89.4
60.0	77.5
40.0	63.2
20.0	44.7
4.0	20.0

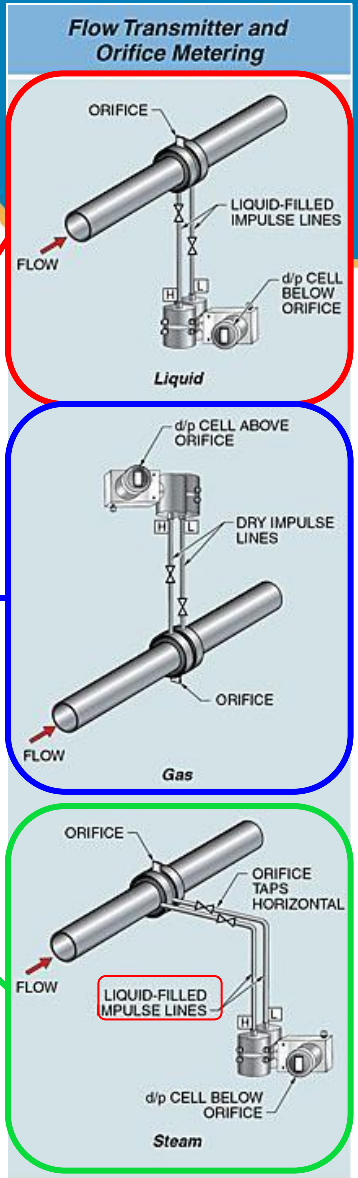
Orifice

The location of a flow transmitter varies with the type of flowing fluid.

When liquid flow is being measured, the measuring instrument must be mounted below the elevation of the flow element and the impulse lines must be filled with the liquid. Care must be exercised to ensure that no bubbles of air are trapped in the instrument or the impulse lines. The length of the impulse lines has no effect on the measurement accuracy as long as the two impulse lines start and end at equal elevations.

When gas flow is being measured, the measuring instrument must be mounted above the elevation of the flow element and the diameter of the impulse lines must be large enough and routed so that any liquids that may condense in the impulse lines drain freely into the main piping."

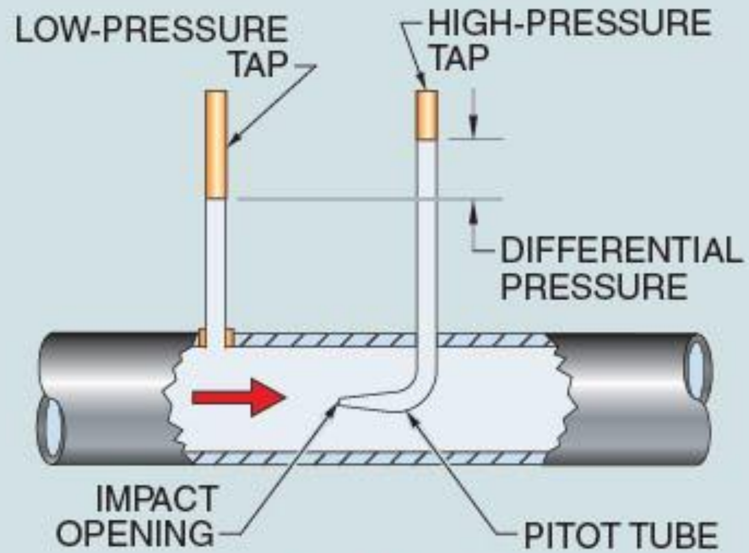
"When steam flow is being measured, the measuring instrument must be mounted below the elevation of the flow element even though the fluid is a vapor. Steam condenses to water very easily, and mounting the measuring instrument below the flow element allows the instrument and impulse lines to fill with condensate. The steam condensate protects the instrument from contact with the hot steam. Mounting the instrument above the flow element can create drainage problems and can subject the instrument to prohibitively high temperatures. When installing the instrument and impulse lines, trapped air can be removed by initially blowing steam through the lines. The steam condensing process takes some time, but can be speeded up by cooling the outsides of the impulse lines with water or by manually backfilling the impulse lines with water."



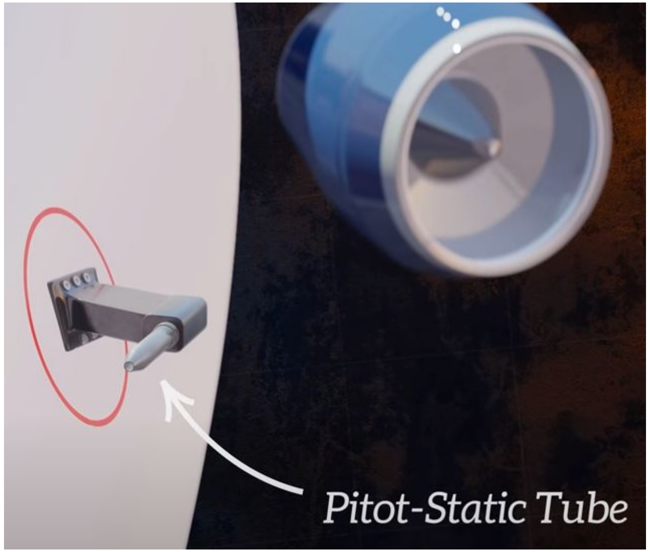
Pitot Tube

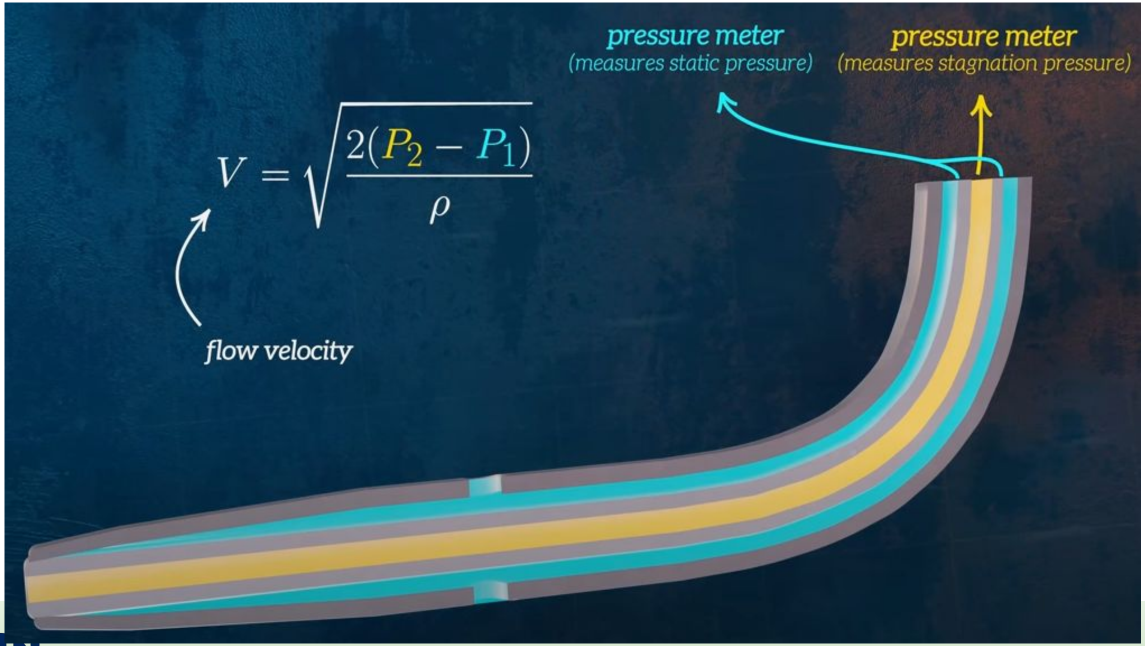
A pitot tube is a flow element consisting of a small bent tube with a nozzle opening facing into the flow. The nozzle is called the impact opening and senses the velocity pressure plus the static pressure. The static pressure is sensed at the pipe wall perpendicular to the fluid stream. Pitot tubes are commonly used to measure air velocity. **For example, pitot tubes are used for measuring air velocity in ducts and for measuring the airspeed of planes.**

Pitot Tubes



Standard Pitot Tube





[Understanding Bernoulli's Equation]

Chapter 20

Mechanical Flowmeters

Variable-Area Flowmeters
Turbine Meters • Paddle Wheel Meters • Open-Channel Flow Measurements

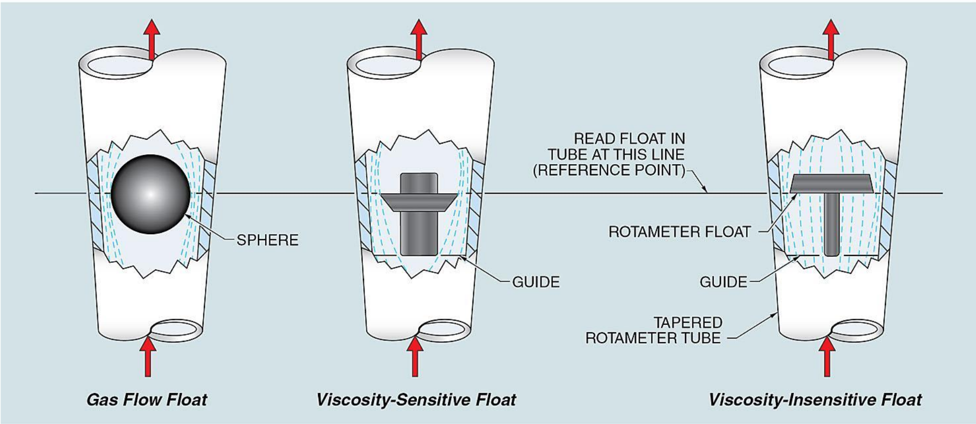
Rotameter

Rotameter floats have different configurations for different fluids and applications.

A rotameter is a variable-area flowmeter consisting of a tapered tube and a float with a fixed diameter. The float of the rotameter changes its position in the tube to keep the forces acting on the float in equilibrium. One of the forces is gravity acting on the float. The other force is produced by the velocity of the process fluid. When the float changes position, the open area between the float diameter and the tube varies. Under most circumstances, the rotameter tube must be vertical.

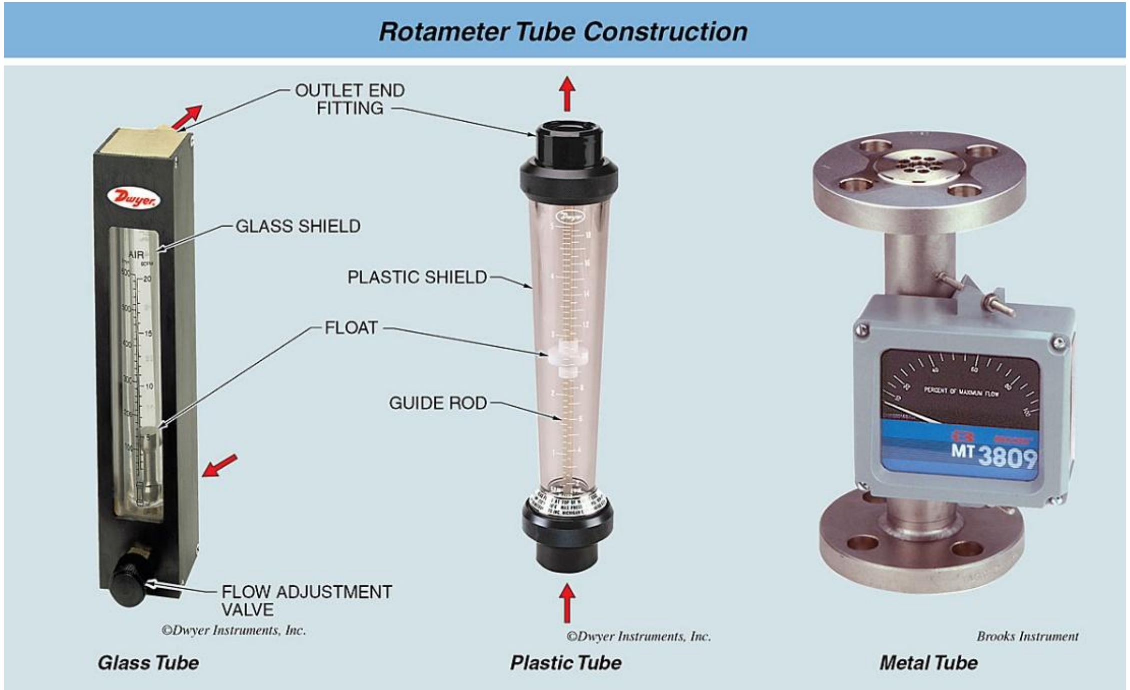
Floats are available in different configurations and thus have different reference points. Floats have a sharp edge at the point where the reading should be made on the scale. The scale can be calibrated for direct reading of flow rate, or for percent of full scale. The spool-shaped floats have a lower guide disk serving as a stabilizer and a top disk edge providing the point of measurement.

Rotameter Float Configurations



Rotameter

Rotameters can have clear tubes for direct reading or opaque tubes with a magnetic linkage to a meter.

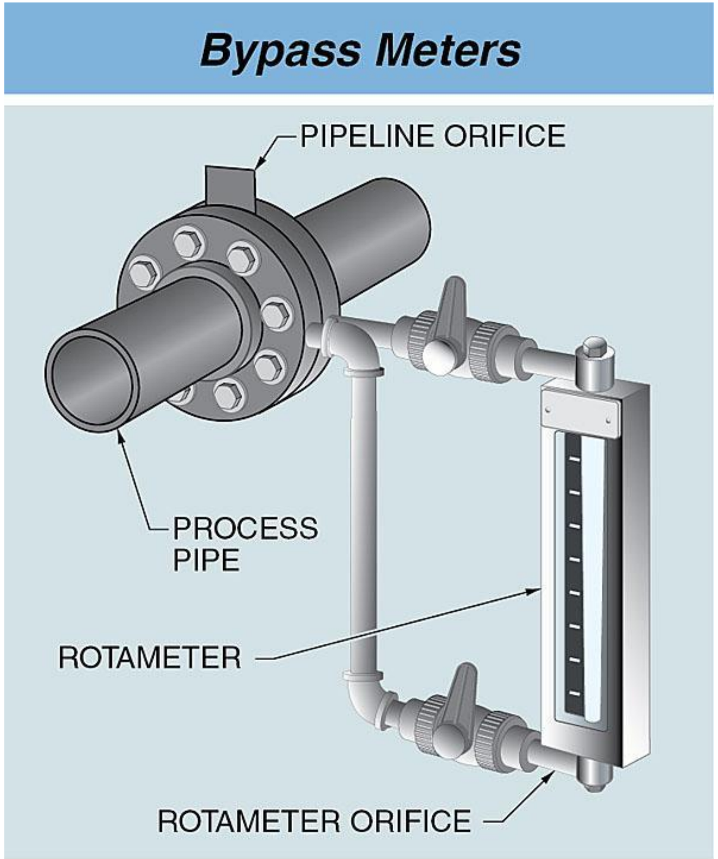


Bypass Meters

A bypass meter combines an orifice plate with a rotameter to obtain better rangeability from the linear scale of the rotameter.

A bypass meter is a combination of a rotameter with an orifice plate used to measure flow rates through large pipes. The advantage of a bypass meter is the linear scale of the rotameter and accompanying better rangeability. The differential pressure across the mainline orifice plate must be matched to the differential pressure across the rotameter at the maximum flow rate.

Can be mounted on horizontal pipes



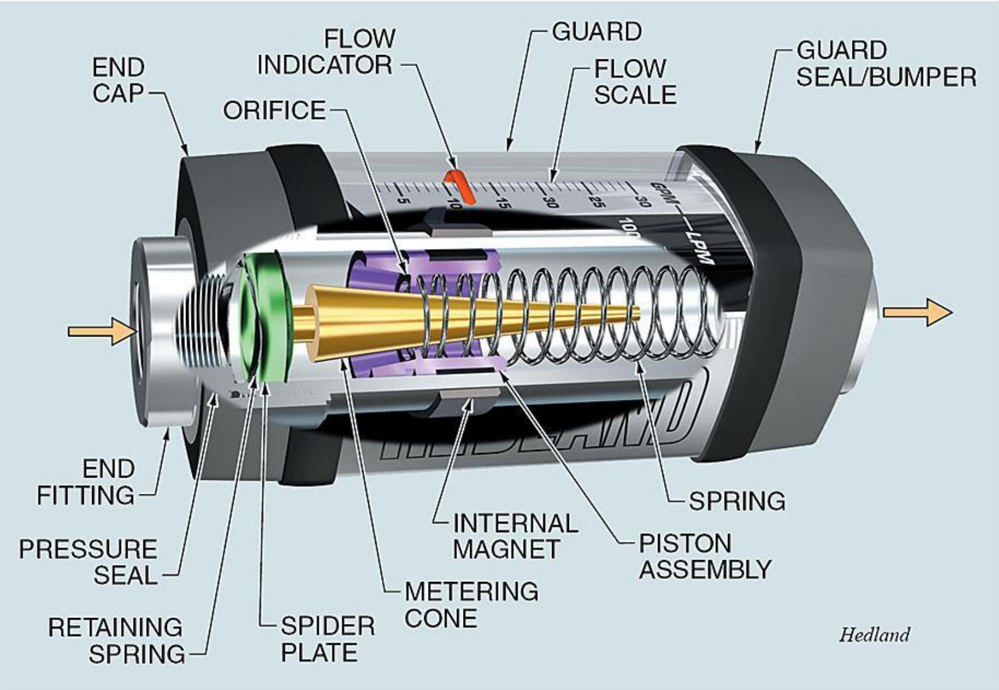
INSTRUCTIONS

Metering-Cone Meter

A metering-cone meter uses a straight tube and a tapered cone instead of the tapered tube of a standard rotameter.

A metering-cone meter is a flowmeter consisting of a straight tube and a tapered cone, instead of a tapered tube, with an indicator that moves up and down the cone with changes in flow. The variable area is the annular space between the float and the tapered cone. The indicator is often spring-loaded to allow the meter to be mounted at any angle.

Metering-Cone Meters

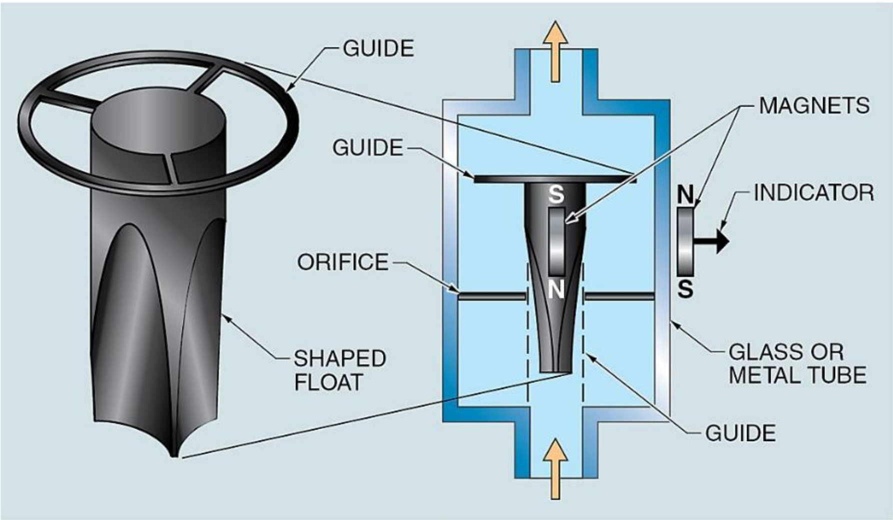


shaped-float and orifice meter

A shaped-float and orifice meter uses an orifice as part of the float assembly to act as a guide. The float has a shaped profile that provides more open flowing area as the float rises.

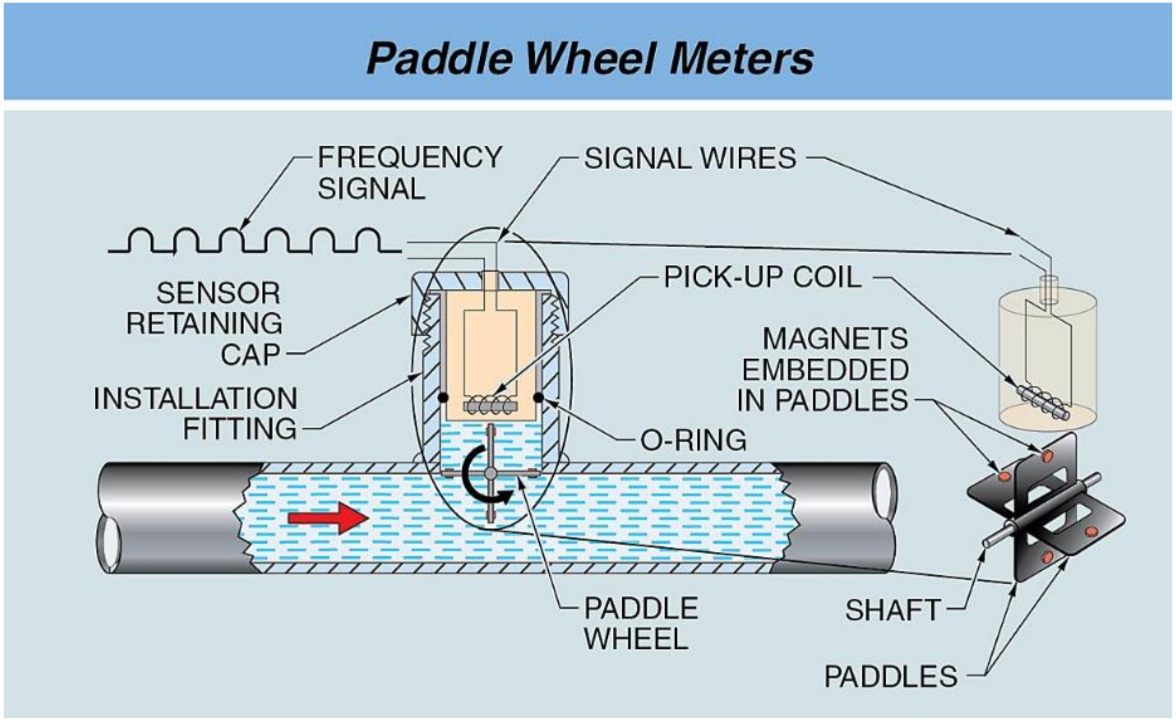
A shaped-float and orifice meter is a flowmeter consisting of an orifice as part of the float assembly that acts as a guide. Instead of a tapered tube, the float has a shaped profile that provides more open flowing area as the float rises. The variable area is the annular space between the float and the disk. The external readouts are available as indicators or transmitters with or without alarms

Shaped-Float and Orifice Meters



Paddle Wheel Meter

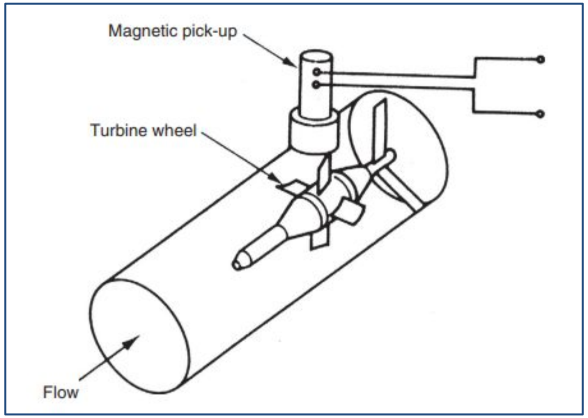
A paddle wheel uses a number of paddles mounted on a shaft fastened in a housing.



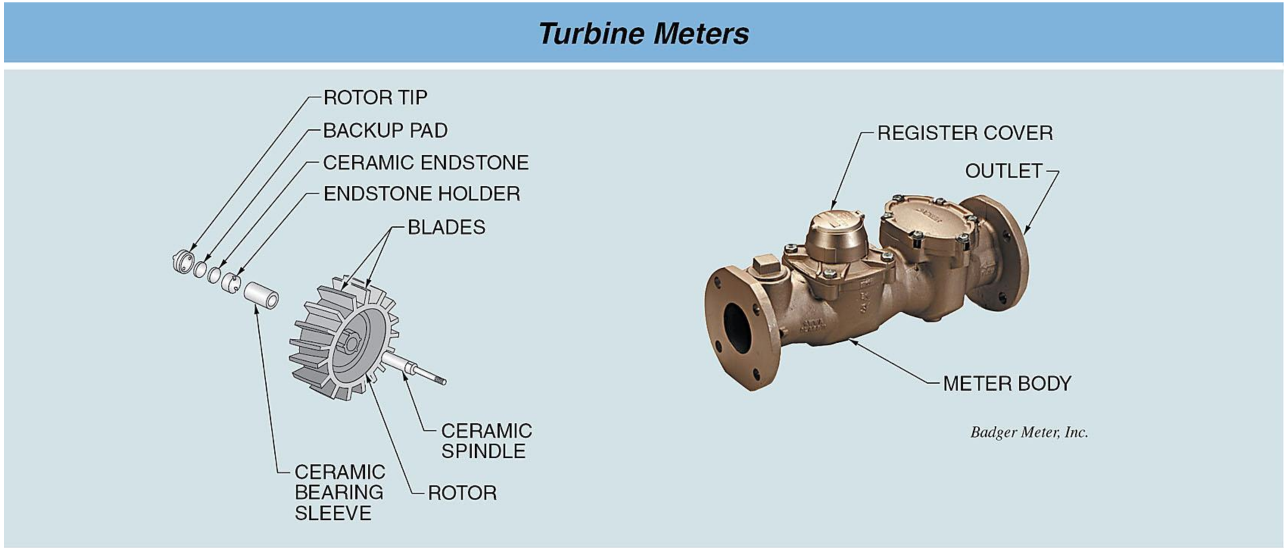
The housing is inserted so that only half of the paddles are exposed to the liquid velocity. The paddles rotate in proportion to the liquid velocity like an old-fashioned water wheel.

Turbine meter

A turbine meter uses turbine blades and counts the pulses produced by the blades as they pass an electromagnetic pickup.



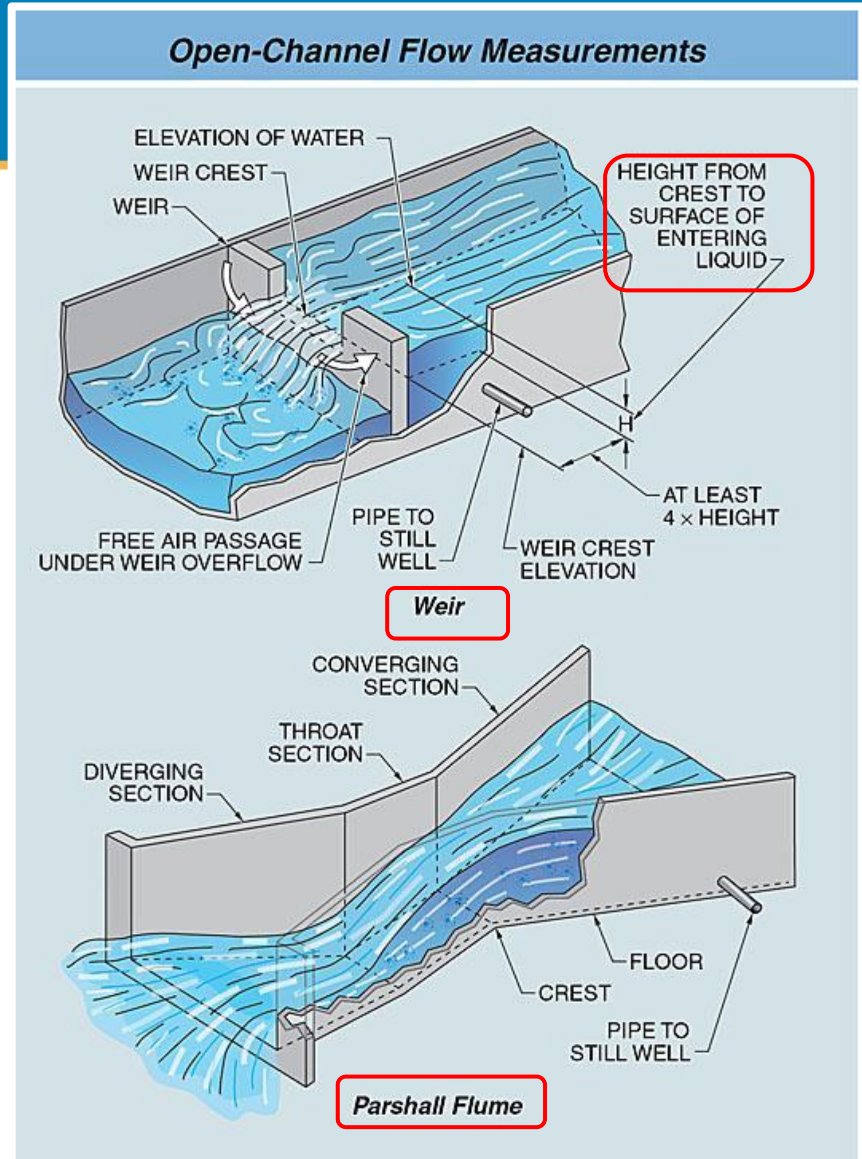
Measurement and Instrumentation: Theory and Application, Third edition (Oct 2020). By: Alan S. Morris, Reza Langari



The bearings are offered in a choice of materials to satisfy the friction and corrosion-resistance requirements of the application. Flow straighteners before and after the turbine wheel are sometimes included to ensure that the velocity of the fluid stream is the sole cause of its rotation. Turbine meters are very accurate and widely used in blending applications.

Open channel flow measurement

Measurement of flow in open channels uses a restriction to create a head of liquid. The height of the head that is created is measured by pressure or ultrasonic sensor and used to determine the flow rate. *The flow has a very restricted rangeability, just like differential measurements in piping.* Detailed information on how to design open-channel flow systems can be found in special reference books or in information from vendors. Common open-channel flow measurement devices are weirs and Parshall flumes



Chapter 21

Magnetic, Ultrasonic, and Mass Flowmeters

Magnetic Flowmeters • Ultrasonic Flowmeters • Mass Flowmeters

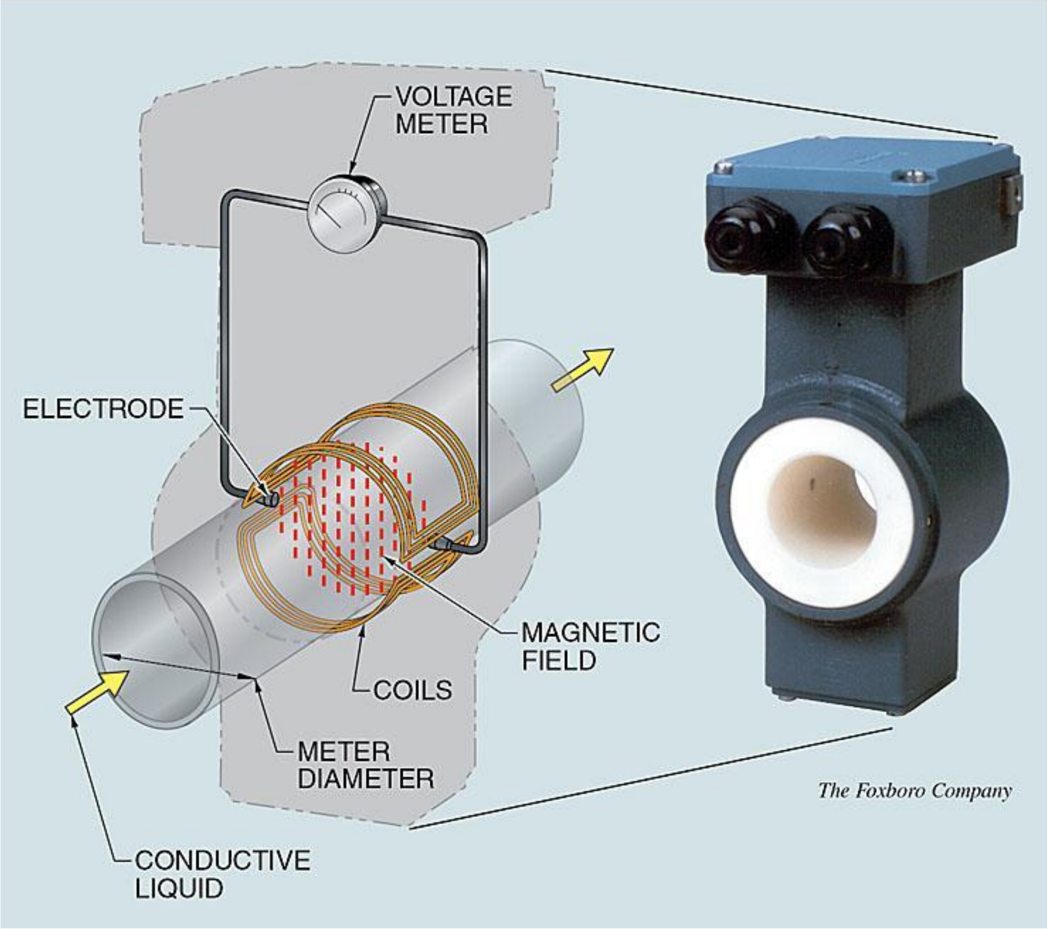
Magnetic Flowmeter

A magnetic meter, or magmeter, is a flowmeter consisting of a stainless steel tube lined with nonconductive material, with two electrical coils mounted on the tube like a saddle. Two electrodes are in contact with the electrically conductive fluid but insulated from the metal tubes. The electrodes are located opposite one another and at right angles to the flow and the magnetic field.

Property:

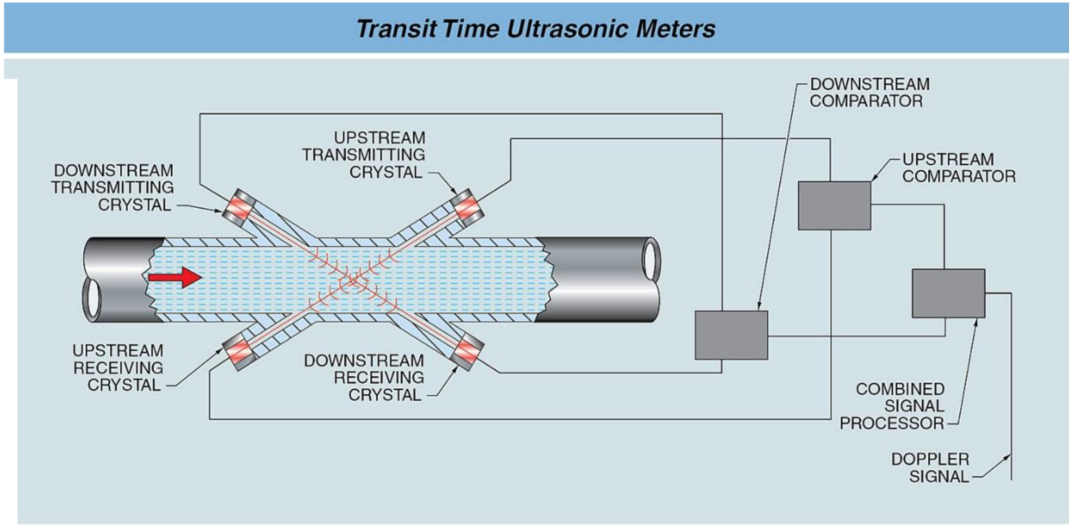
- Not in contact with fluids like mechanical sensors, useful for corrosive fluids
- Just for conductive fluid

Magnetic Flowmeters



Ultrasonic flowmeter

Transit time ultrasonic meters use two sets of transmitting and receiving crystals.



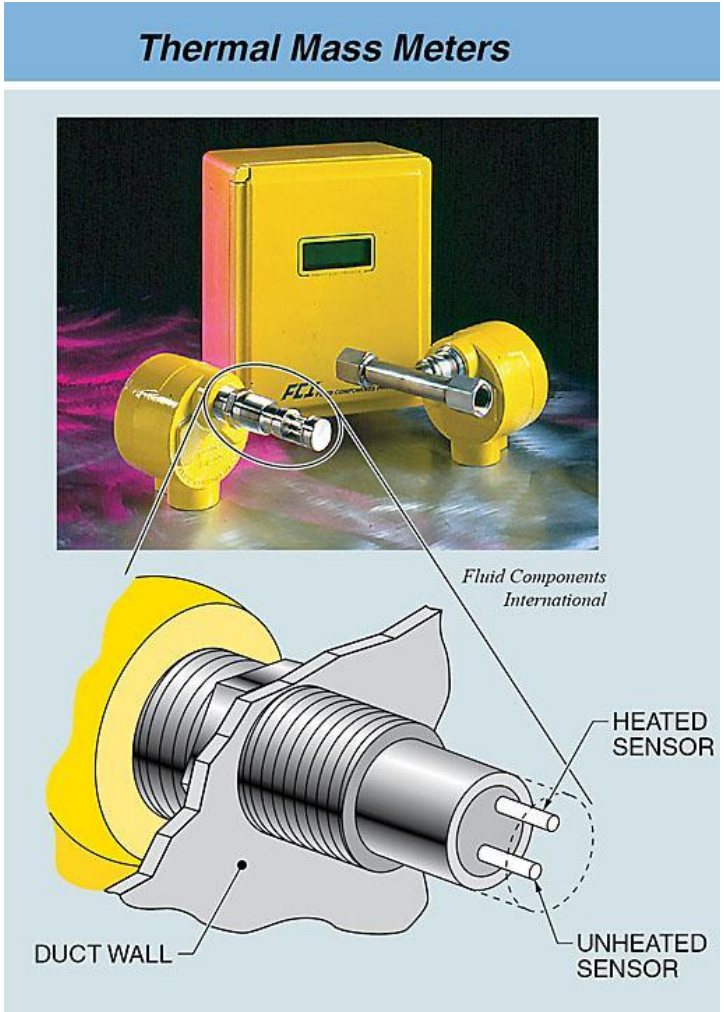
- It is not restricted to conductive fluids useful for measuring the flow of corrosive fluids and slurries
- high reliability and low maintenance requirements,
- Can be installed externally on the pipe, no need to be inserted therefore
  - it might have cost advantages
  - Avoid contact with hazardous material
  - Prevent contamination of the fluid (In food industry for example)

Thermal Mass meter

A thermal mass meter is a mass flowmeter consisting of two RTD temperature probes and a heating element that measure the heat loss to the fluid mass.

Thermal mass meters are predominantly used for measuring gas flows.

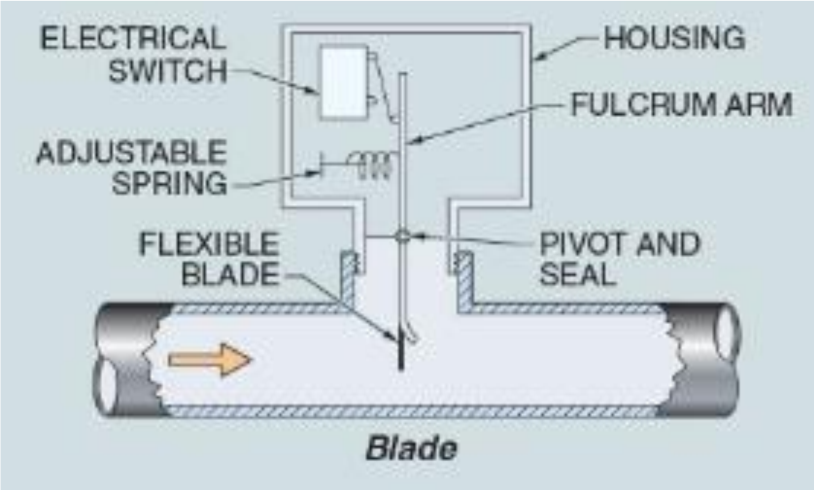
The two RTD probes are immersed in the flow stream. One probe is in an assembly that includes an adjacent heating element that is measured by the RTD probe. The other probe is separate and it measures the temperature of the flowing fluid.



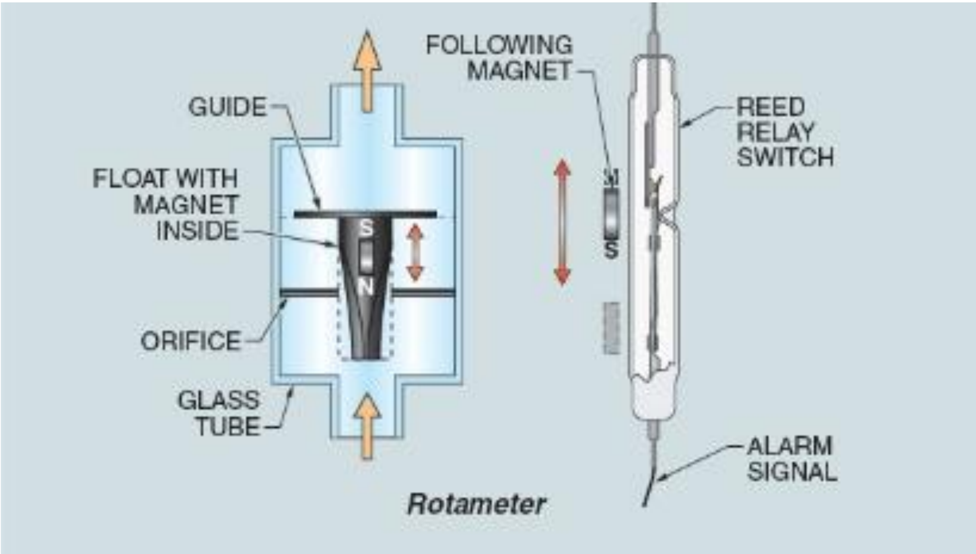
Flow Switches

Flow Switch

Flow switches are used to activate a signal or an alarm, or to actuate a control function, when flow reaches a predetermined level.

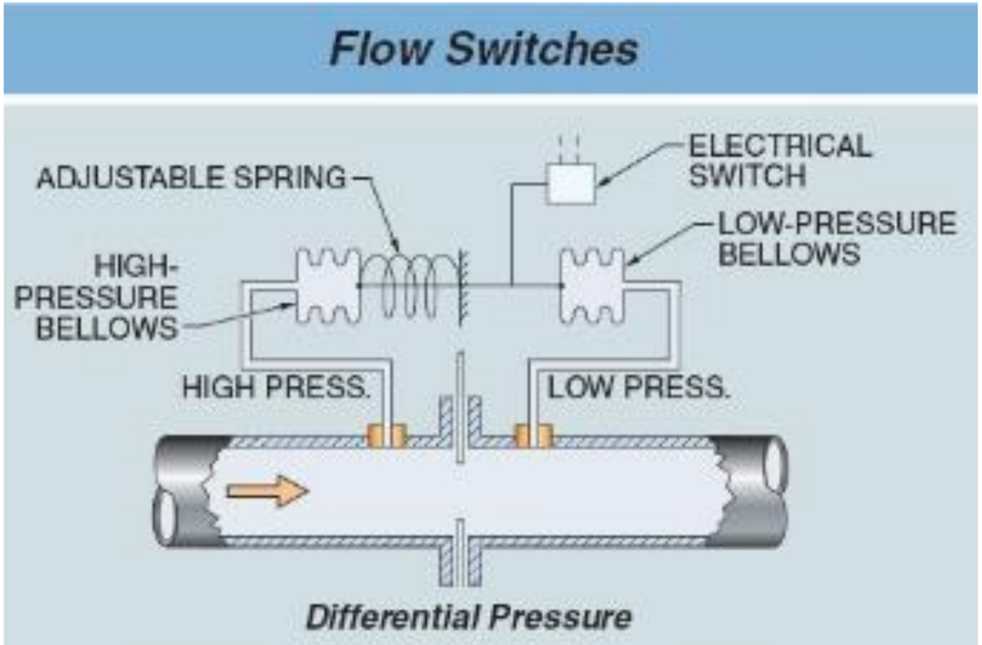


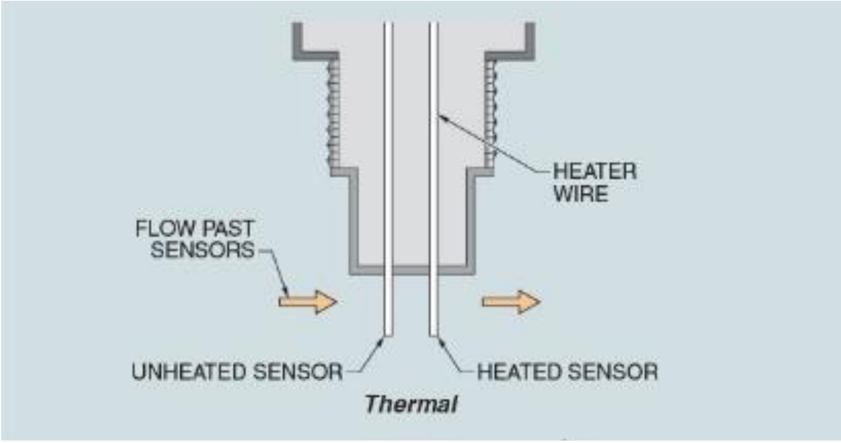
Blade



Rotameter

Flow Switch


Flow Switches
ADJUSTABLE SPRING
ELECTRICAL SWITCH
LOW-PRESSURE BELLOWS
HIGH-PRESSURE BELLOWS
HIGH PRESS.
LOW PRESS.
Differential Pressure


HEATER WIRE
FLOW PAST SENSORS
UNHEATED SENSOR
HEATED SENSOR
Thermal