Cairo University
Faculty of Engineering
Mech. Power Department

ACC Virtual Labs
Automatic Control Circuits & Virtual Labs for Mechanical Power Systems
معمل التحكم الأتوماتيكى و المعامل الإفتراضية لأنظمة القوى الميكانيكية

دبلوم تطبيقات التحكم الأوتوماتيكى فى نظم القوى الميكانيكية

MEP 560 - Measurements

Types of Flow Meters

By

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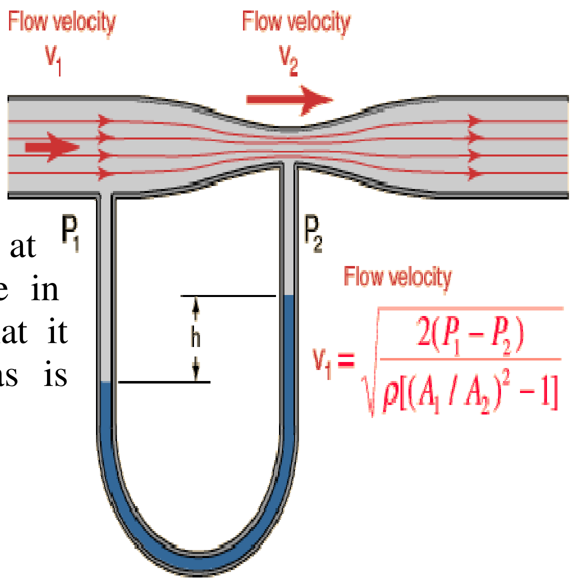
Contents:

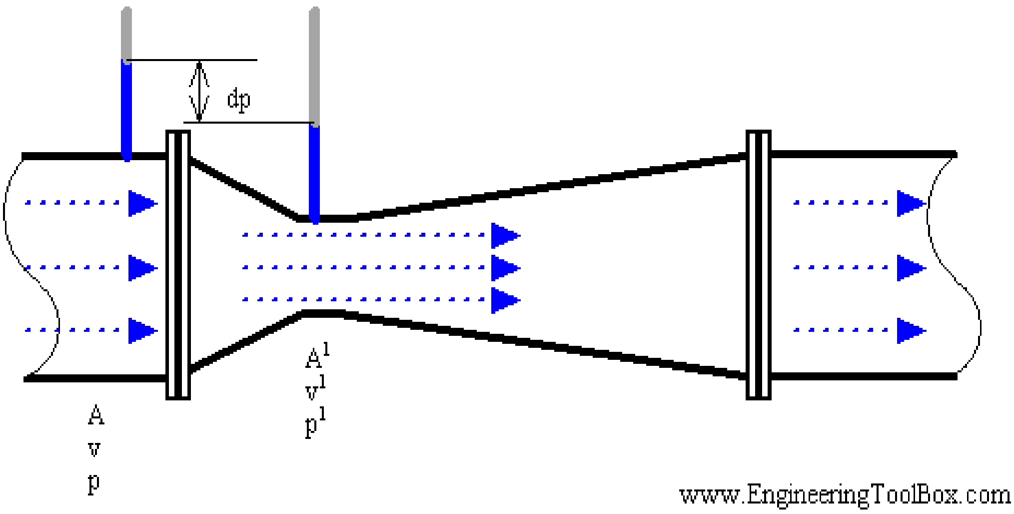
1-Venturi Flow-meter:

A practical instrument which makes use of the Bernoulli effect and a manometer pressure gauge is the venturi flowmeter. The illustration shows that you can express the fluid velocity v_1 at inlet of the device in terms of the difference in pressure measured by the manometer. Note that it presumes that the density of the flowing gas is constant, which will not necessarily be true.



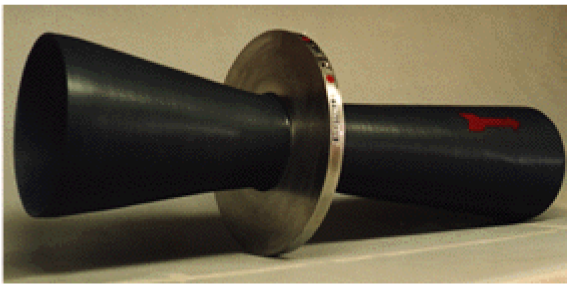
96" Vinyl ester fiberglass universal venturi tube manufactured by Westfall Manufacturing Company for BIF. Pipe Size 96" S.S.Throat 60.9" Overall Length 186"

Due to simplicity and dependability, the Venturi tube flowmeter is often used in applications where it's necessary with higher TurnDown Rates, or lower pressure drops, than the orifice plate can provide. In the Venturi Tube the fluid flowrate is measured by reducing the cross sectional flow area in the flow path, generating a pressure difference. After the constricted area, the fluid is passes through a pressure recovery exit section, where up to 80% of the differential pressure generated at the constricted area, is recovered.



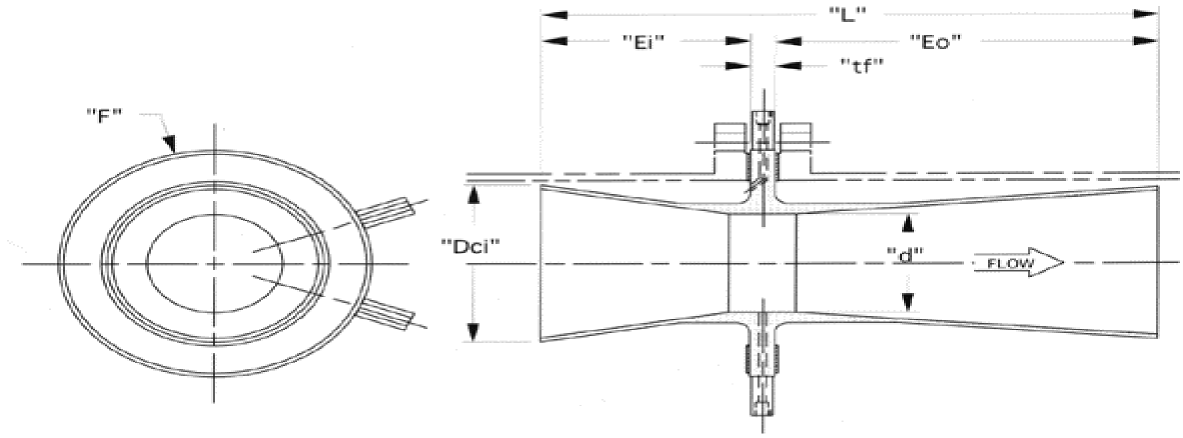
With proper instrumentation and flow calibrating, the Venturi Tube flowrate can be reduced to about 10% of its full scale range with proper accuracy. This provides a TurnDown Rate 10:1.

30" MODEL 2300 Westfall Venturi
30"x12.960 w/150 C.S. FLNG



12"x4.35" Westfall MODEL 2300
FRP Venturi w/316 STN. STL. FLNG.

Venturi Flow Meter- Model #2300



Bernoulli's equation

$$\frac{P_1}{\rho g}+\frac{1}{2g}v_1^2=\frac{P_3}{\rho g}+\frac{1}{2g}v_3^2+\Sigma f \qquad \textbf{(2)}$$

where Σf represents the total friction loss that is usually assumed negligible. This equation can be simplified and rearranged to give (Foust et. al, 1981; Janna, 1993)

general head meter equation

$$F_1 = A_1V_1 = C_{meter}YA_3\sqrt{\frac{2(P_1-P_3)}{\rho(1-A_3^2/A_1^2)}} \qquad \textbf{(3)}$$

The meter coefficient, C_{meter}, accounts for all non-idealities, including friction losses, and depends on the type of meter, the ratio of cross sectional areas and the Reynolds number. The compressibility factor, Y, accounts for the expansion of compressible gases; it is 1.0 for incompressible fluids. These two factors can be estimated from correlations (ASME, 1959; Janna, 1993) or can be determined through calibration. Equation (3) is used for designing head flow meters for specific plant operating conditions. When the process is operating, the meter parameters are fixed, and the pressure difference is measured. Then, the flow can be calculated from the meter equation, using the appropriate values for C_{meter} and Y. All constants are combined, leading to the following relationship.

relationship for installed head meter

$$F = C_0\sqrt{\frac{(P_1-P_3)}{\rho_0}} \qquad \textbf{(4)}$$

In the usual situation in which only reproducibility is required, the fluid density is not measured and is assumed constant; the simplified calculation is where the density is assumed to be its design value of ρ_o. This is a good assumption for liquid and can provide acceptable accuracy for gases in some situations. Again, all constants can be combined (including C_o) into C_1 to give the following relationship.

relationship for installed head meter with constant density

$$F = C_0 \sqrt{P_1 - P_3} \qquad (5)$$

If the density of a gas varies significantly because of variation in temperature and pressure (but not average molecular weight), correction is usually based on the ideal gas law using low cost sensors to measure T and P according to

relationship for installed head meter, gas with constant MW, changing T and P

$$F = C_0 \sqrt{\frac{(P_1 - P_3)}{\rho_0}} \sqrt{\frac{P_0 T}{P T_0}} \qquad (6)$$

where the density (assumed constant at ρ_o), temperature (T_o) and pressure (P_o) were the base case values used in determining C_o. If the density varies significantly due to composition changes and high accuracy is required, the real-time value of fluid density (ρ) can be measured by an on-stream analyzer for use as ρ_o in equation (4) (Clevett, 1985).

The flow is determined from equation (5) by taking the square root of the measured pressure difference, which can be measured by many methods. A U-tube manometer provides an excellent visual display for laboratory experiments but is not typically used industrially. For industrial practice a diaphragm is used for measuring the pressure drop; a diaphragm with one pressure on each side will deform according to the pressure difference. Note that the pressure in the pipe increases after the vena contracta where the flow cross section returns to its original value, but because of the meter resistance, the pressure downstream of the meter (P_3) is **lower** than upstream pressure (P_1). This is the **"non-recoverable" pressure drop** of the meter that requires energy, e.g., compressor work, to overcome and increases the cost of plant operation. The non-recoverable pressure losses for three important head meters are given in Figure 5.

The low pressure at the point of highest velocity creates the possibility for the liquid to partially vaporize; it might remain partially vaporized after the sensor (called **flashing**) or it might return to a liquid as the pressure increases after the lowest pressure point (called **cavitation**). We want to avoid any vaporization to ensure proper sensor operation and to retain the relationship between pressure difference and flow. Vaporization can be prevented by maintaining the inlet pressure sufficiently high and the inlet temperature sufficiently low.

2- Orifice Plates:

An orifice plate is a very simple device installed in a straight run of pipe. The orifice plate contains a hole smaller than the pipe diameter. The flow constricts, experiences a pressure drop, and then the differential pressure can be related to a flow.

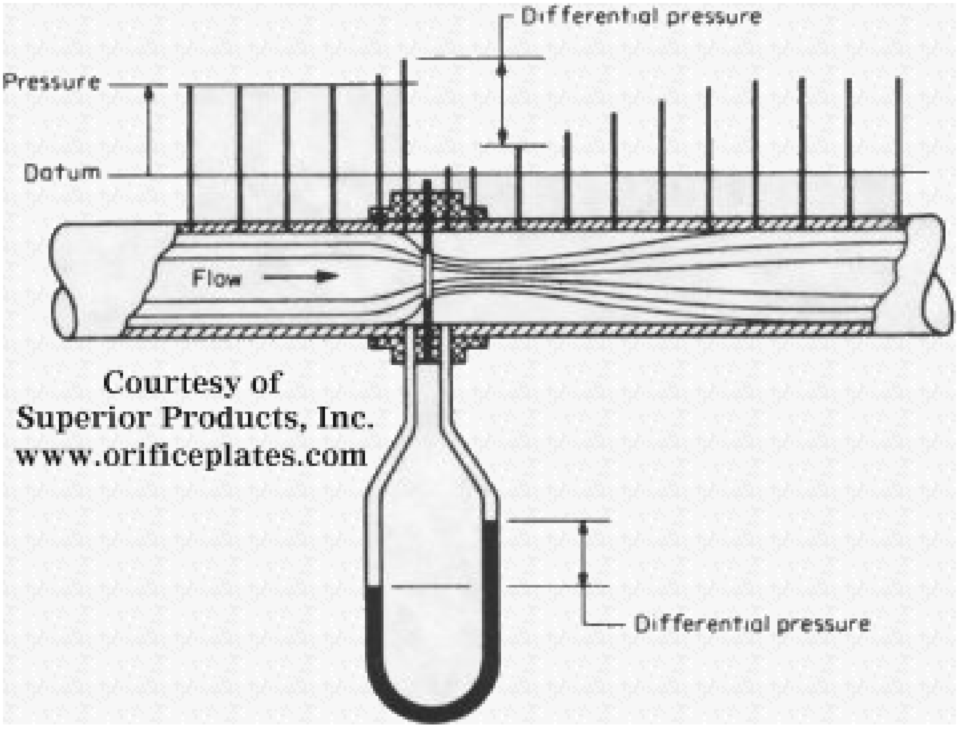


Figure 1: Orifice Plate Arrangement

For a discussion of how pressure drop is related to liquid flow for concentric orifices, visit

www.LMNOeng.com. They have a very good explanation on their website.

It is also important to note that relating differential pressure to flow across an orifice depends on the location of the pressure taps in relation to the orifice. In Figure 2 below, the pressure taps are designated as P1 and P2. "D" is the diameter of the pipe and "d" is the diameter of the orifice.

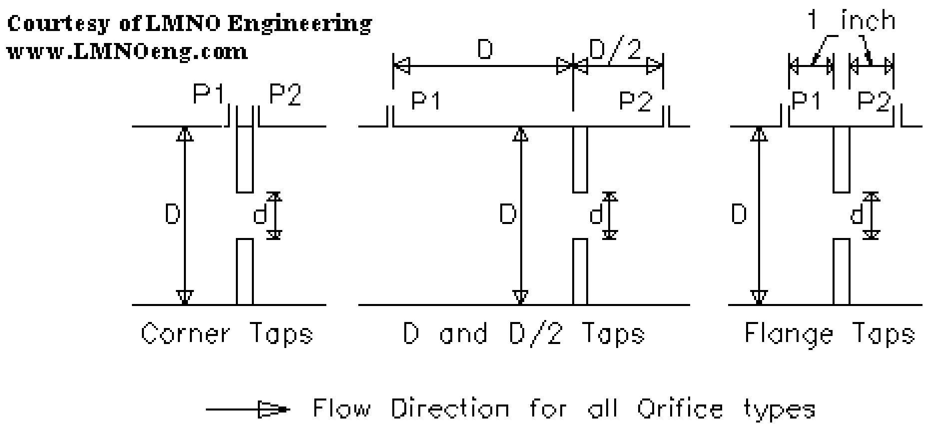
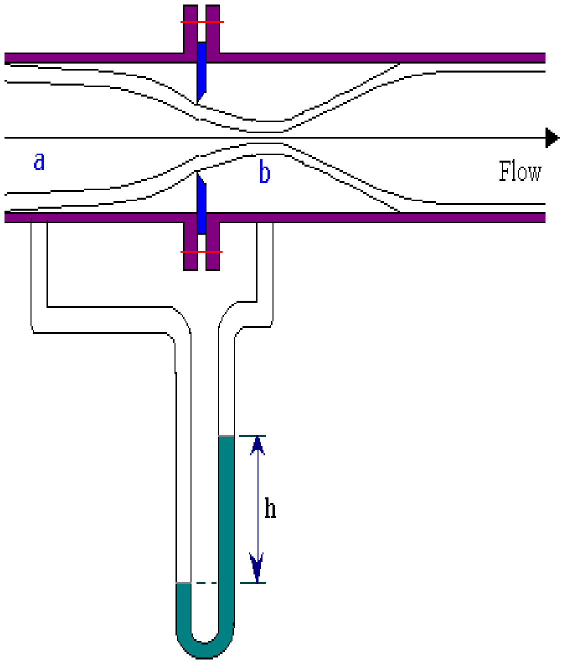


Figure 2: Various Tap Positions for Orifice Plates



The venturi meter described earlier is a reliable flow measuring device. Furthermore, it causes little pressure loss. For these reasons it is widely used, particularly for large-volume liquid and gas flows. However this meter is relatively complex to construct and hence expensive. Especially for small pipelines, its cost seems prohibitive, so simpler devices such as orifice meters are used. The orifice meter consists of a flat orifice plate with a circular hole drilled in it. There is a pressure tap upstream from the orifice plate and another just downstream. There are three recognized methods of placing the taps. And the coefficient of the meter will depend upon the position of taps.

The principle of the orifice meter is identical with that of the venturi meter. The reduction of the cross section of the flowing stream in passing through the orifice increases the velocity head at the expense of the pressure head, and the reduction in pressure between the taps is measured by a manometer. Bernoulli's equation provides a basis for correlating the increase in velocity head with the decrease in pressure head.

$$v_b = \frac{1}{\sqrt{1-\beta^4}}\sqrt{\frac{2(p_a - p_b)}{\rho}}$$

where $\beta = D_b/D_a = (A_b/A_a)^{0.5}$

One important complication appears in the orifice meter that is not found in the venturi. The area of flow decreases from A_a at section 'a' to cross section of orifice opening (A_o) at the orifice and then to A_b at the *vena contracta*. The area at the vena contracta can be conveniently related to the area of the orifice by the *coefficient of contraction* C_c defined by the relation:

$C_c = A_b/A_o$ Therefore, $v_bA_b = v_oA_o$, i.e., $v_o = v_bC_c$, Inserting the value of $A_b = C_cA_o$

$$v_o = \frac{C_c}{\sqrt{1-(C_cA_o/A_a)^2}}\sqrt{\frac{2(p_a - p_b)}{\rho}}$$

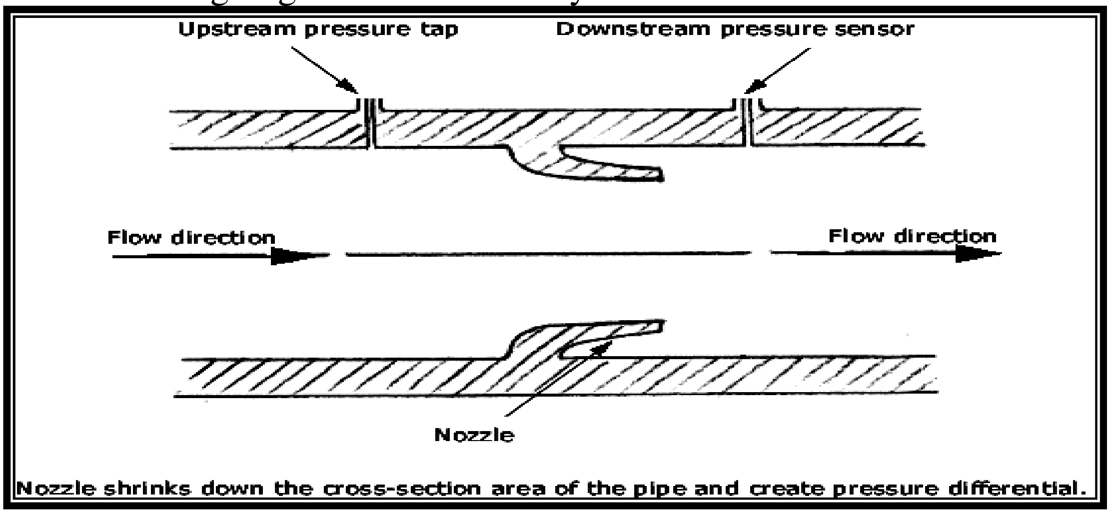
using the coefficient of discharge C_o (orifice coefficient) to take the account of frictional losses in the meter and the parameter C_c, the flow rate (Q) through the pipe is obtained as,

$$Q = \frac{C_oA_o}{\sqrt{1-(A_o/A_a)^2}}\sqrt{\frac{2(p_a - p_b)}{\rho}}$$

C_o varies considerably with changes in A_o/A_a ratio and Reynolds number. A orifice coefficient (C_o) of 0.61 may be taken for the standard meter for Reynolds numbers in excess of 10^4, though the value changes noticeably at lower values of Reynolds number.

<u>3- Nozzle Flow-meter:</u>

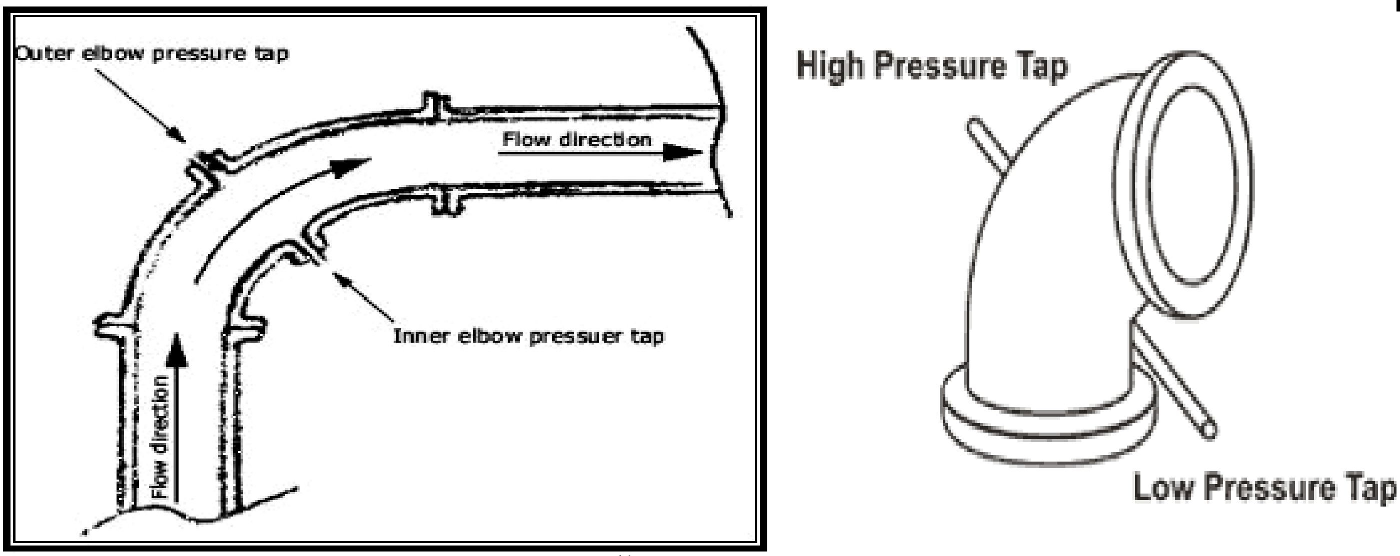
at high velocities, can handle approximately 60 percent greater liquid flow than orifice plates having the same pressure drop. Liquids with suspended solids can also be metered. However, use of the units is not recommended for highly viscous liquids or those containing large amounts of sticky solids.



Nozzle Flow-meter

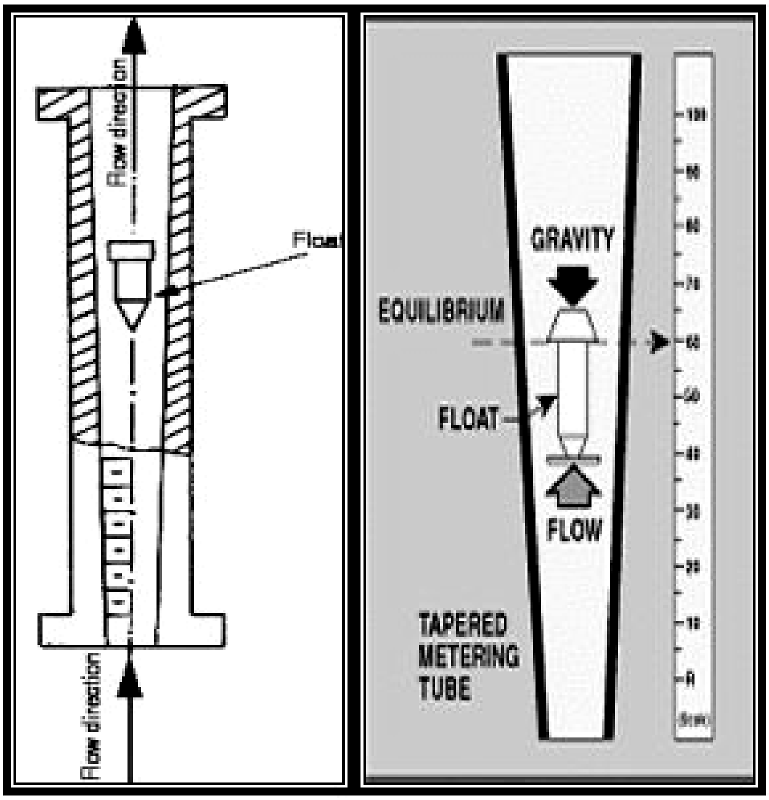
<u>4- Elbow meters:</u>

operate on the principle that when liquid travels in a circular path, centrifugal force is exerted along the outer edges. Thus, when liquid flows through a pipe elbow, the force on the elbow's interior surface is proportional to the density of the liquid times the square of its velocity. In addition, the force is inversely proportional to the elbow's radius.



Elbow meters

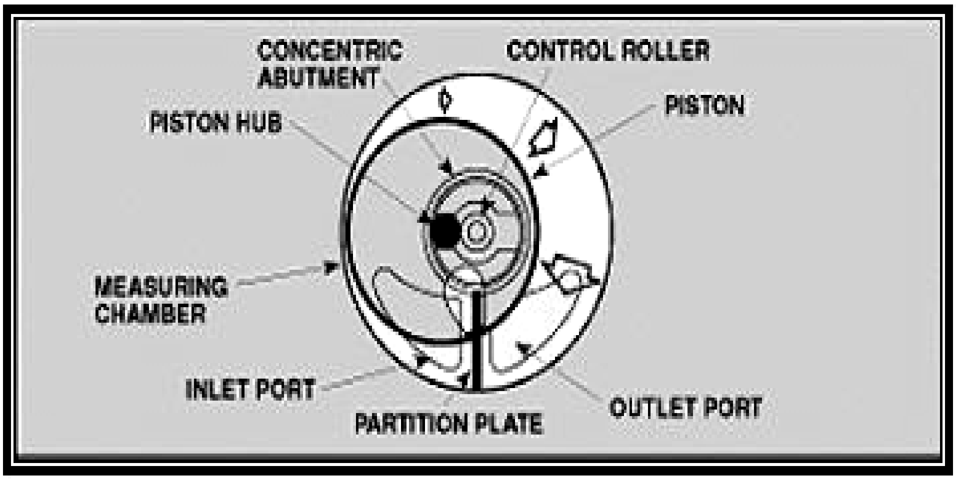
As fluid passes through a pipe elbow, the pressure at the outside radius of the elbow increases due to centrifugal force. Pressure taps located at the outside and inside of the elbow at 22.5 or 45 degrees will generate a reproducible measurement. Taps located at angles greater then 45 degrees are not recommended as flow separation may cause erratic readings.



5- Rota-meter:

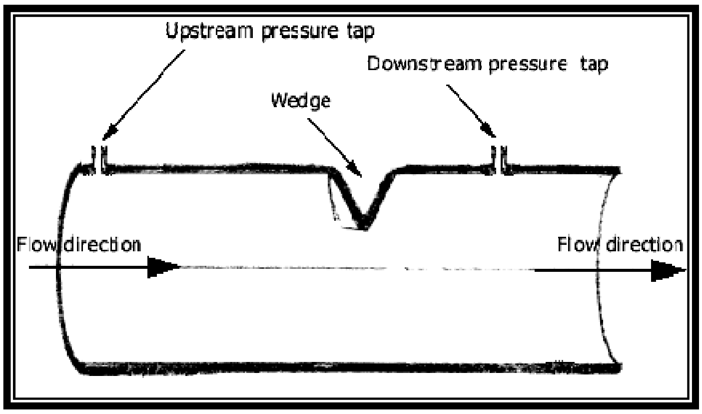
The most widely used variable area flowmeter. cross section area available to the flow varies with the flow rate. Under a (nearly) constant pressure drop, the higher the volume flow rate, the higher the flow path area. Variable-area meters, often called rotameters, consist essentially of a tapered tube and a float. Although classified as differential pressure units, they are, in reality, constant differential pressure devices. Flanged-end fittings provide an easy means for installing them in pipes. When there is no liquid flow, the float rests freely at the bottom of the tube. As liquid enters the bottom of the tube, the float begins to rise. The position of the float varies directly with the flow rate. Its exact position is at the point where the differential pressure between the upper and lower surfaces balance the weight of the float.

6- Positive-Displacement Meters



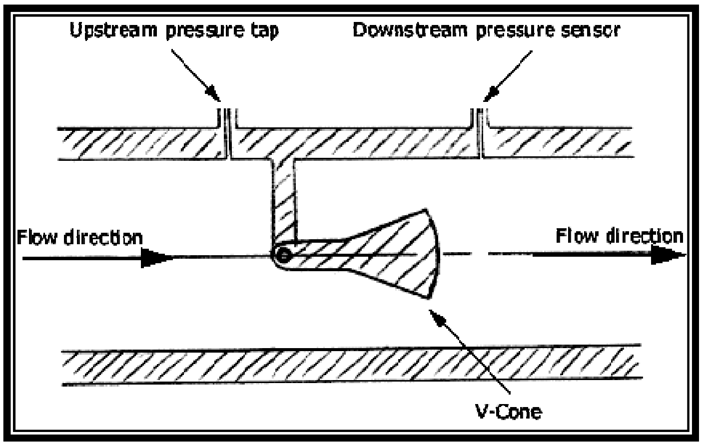
Operation of these units consists of separating liquids into accurately measured increments and moving them on. Each segment is counted by a connecting register. Because every increment represents a discrete volume, positive-displacement units are popular for automatic batching and accounting applications. Positive-displacement meters are good candidates for measuring the flows of viscous liquids or for use where a simple mechanical meter system is needed.

7- Segmental Wedge:



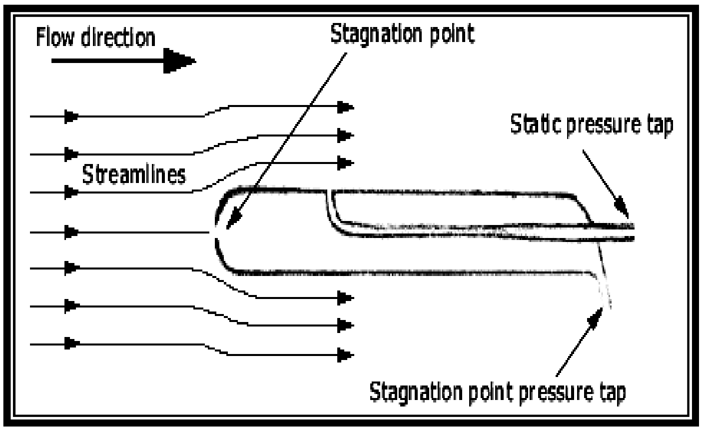
A wedge-shaped segment is inserted perpendicularly into one side of the pipe while the other side remains unrestricted. The change in cross section area of the flow path creates pressure drops used to calculate flow velocities.

8- V-Cone :-

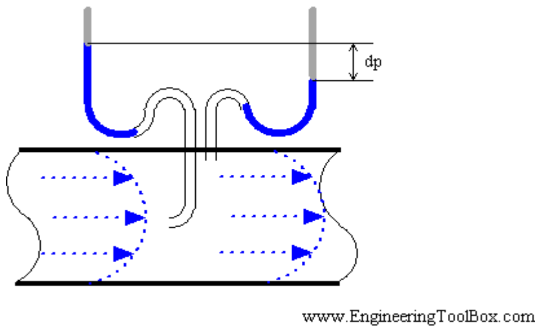


A cone shaped obstructing element that serves as the cross section modifier is placed at the center of the pipe for calculating flow velocities by measuring the pressure differential.

9- Pitot Tube:

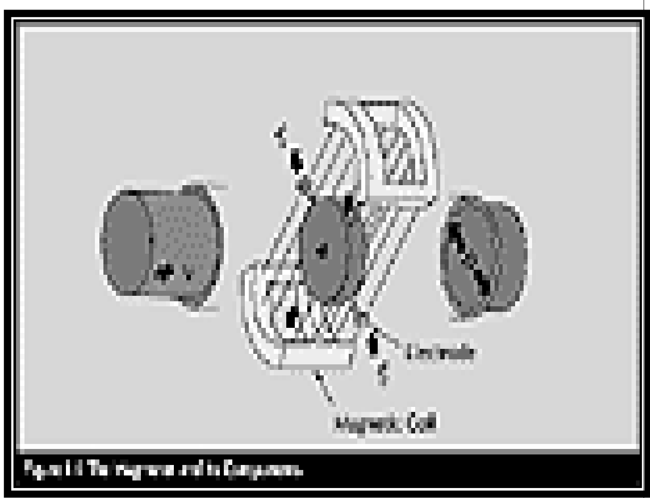


The pitot tubes are one the most used (and cheapest) ways to measure fluid flow, especially in air applications as ventilation and HVAC systems, even used in airplanes for the speed measurent.



The pitot tube measures the fluid flow velocity by converting the kinetic energy of the flow into potential energy. The use of the pitot tube is restricted to point measuring. With the "annubar", or multi-orifice pitot probe, the dynamic pressure can be measured across the velocity profile, and the annubar obtains an averaging effect. A probe with an open tip (Pitot tube) is inserted into the flow field. The tip is the stationary (zero velocity) point of the flow. Its pressure, compared to the static pressure, is used to calculate the flow velocity. Pitot tubes can measure flow velocity at the point of measurement. See Pitot Tube Flowmeters and Pitot Static Tubes for more details.

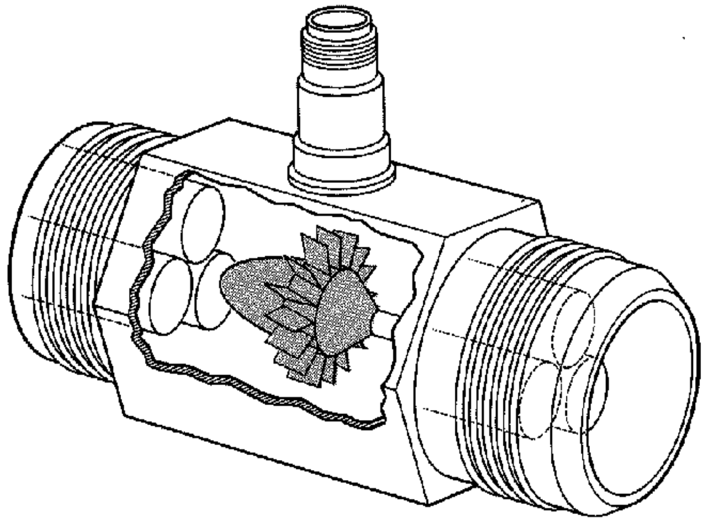
10-Magnetic Flowmeters:



The operation of magnetic flowmeters is based on Faraday's law of electromagnetic induction. Magmeters can detect the flow of conductive fluids only. Early magmeter designs required a minimum fluidic conductivity of 1-5 micro siemens per centimeter for their operation. The newer designs have reduced that requirement a hundredfold to between 0.05 and 0.1. The magnetic flowmeter consists of a non-magnetic pipe lined with an insulating material. A pair of magnetic coils is situated as shown in Figure 4-1, and a pair of electrodes penetrates the pipe and its lining. If a conductive fluid flows through a pipe of diameter (D) through a magnetic field density (B) generated by the coils, the amount of voltage (E) developed across the electrodes--as predicted by Faraday's law--will be proportional to the velocity (V) of the liquid. Because the magnetic field density and the pipe diameter are fixed values, they can be combined into a calibration factor (K) and the equation reduces to: $E = K\ V$

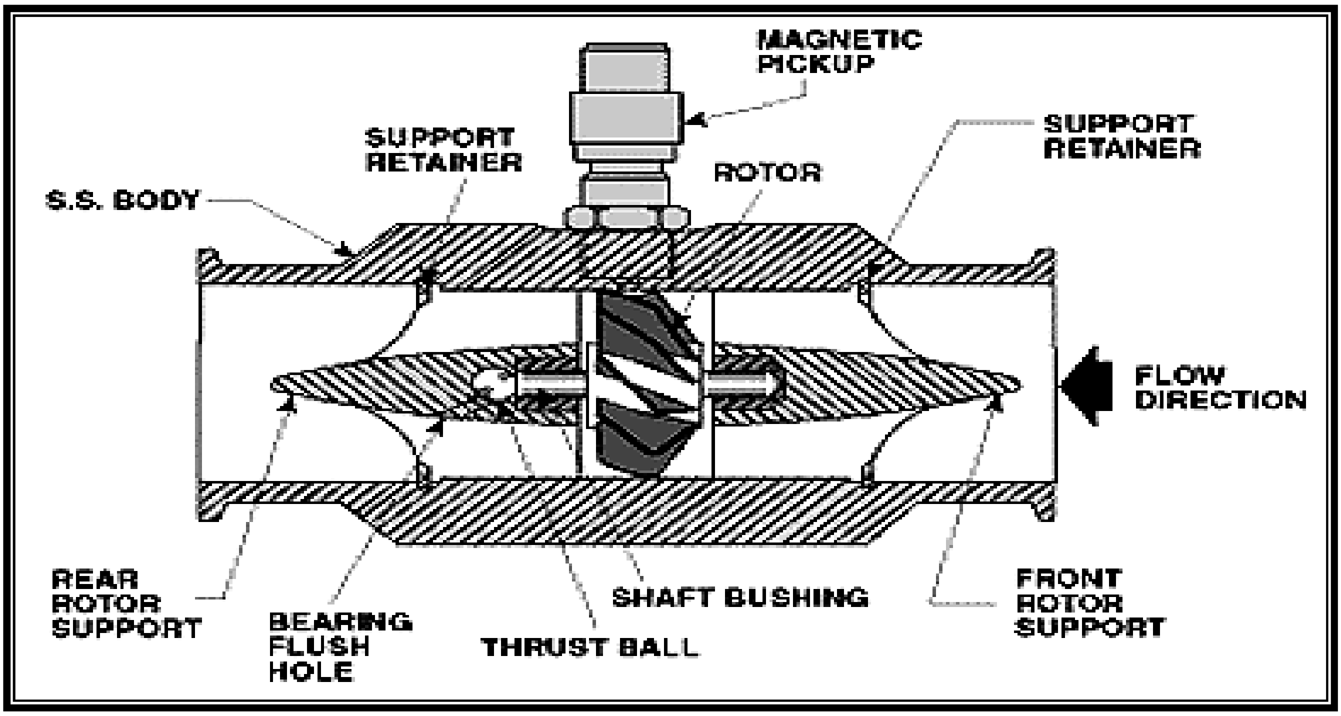
The velocity differences at different points of the flow profile are compensated for by a signal-weighing factor. Compensation is also provided by shaping the magnetic coils such that the magnetic flux will be greatest where the signal weighing factor is lowest, and vice versa. Manufacturers determine each magmeter's K factor by water calibration of each flowtube. The K value thus obtained is valid for any other conductive liquid and is linear over the entire flowmeter range. For this reason, flowtubes are usually calibrated at only one velocity. Magmeters can measure flow in both directions, as reversing direction will change the polarity but not the magnitude of the signal. The K value obtained by water testing might not be valid for non-Newtonian fluids (with velocity-dependent viscosity) or magnetic slurries (those containing magnetic particles). These types of fluids can affect the density of the field in the tube. In-line calibration and special compensating designs should be considered for both of these fluids.

11- Turbine meters:



have found widespread use for accurate liquid measurement applications. The unit consists of a multiple-bladed rotor mounted with a pipe, perpendicular to the liquid flow. The rotor spins as the liquid passes through the blades. The rotational speed is a direct function of flow rate and can be sensed by magnetic pick-up, photoelectric cell, or gears. Electrical pulses can be counted and totalized.

The number of electrical pulses counted for a given period of time is directly proportional to flow volume. A tachometer can be added to measure the turbine's rotational speed and to determine the liquid flow rate. Turbine meters, when properly specified and installed, have good accuracy, particularly with low-viscosity liquids. A major concern with turbine meters is bearing wear. A "bearingless" design has been developed to avoid this problem. Liquid entering the meter travels through the spiraling vanes of a stator that imparts rotation to the liquid stream. The stream acts on a sphere, causing it to orbit in the space between the first stator and a similarly spiraled second stator. The orbiting movement of the sphere is detected electronically. The frequency of the resulting pulse output is proportional to flow rate.

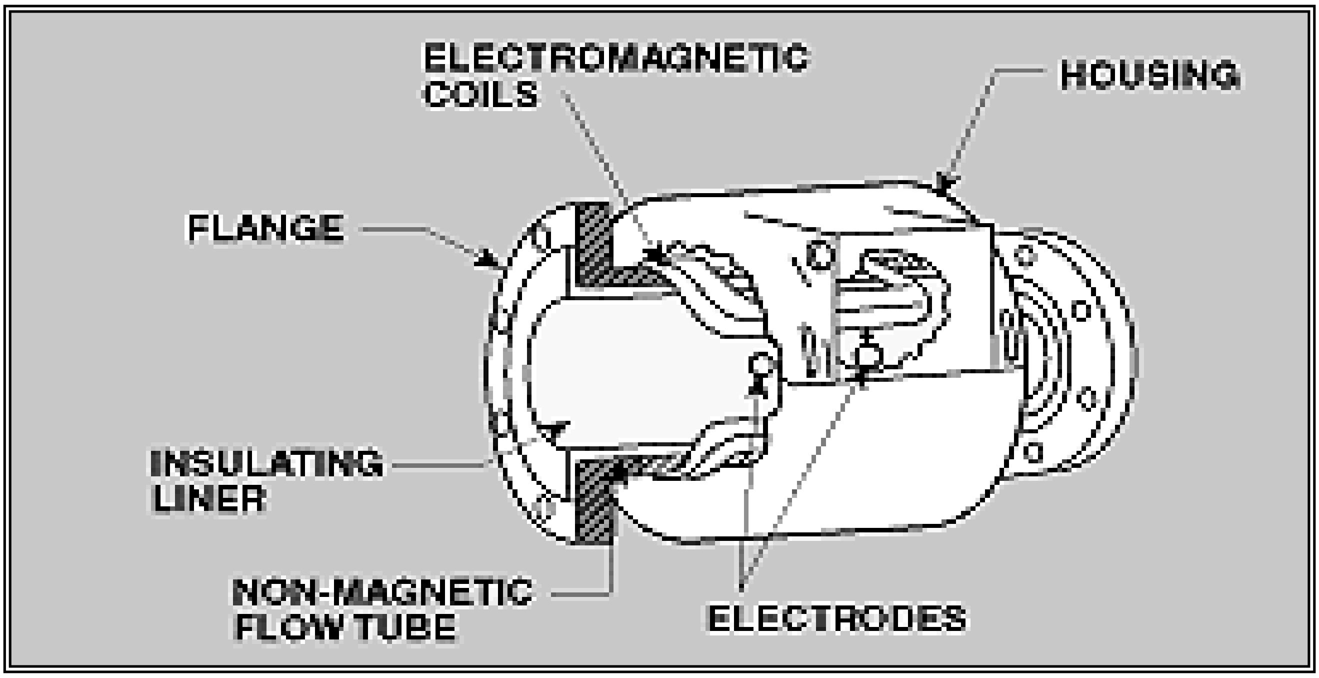


Turbine meters

12- Ultrasonic Flow-meters:

can be divided into Doppler meters and time-of-travel (or transit) meters. Doppler meters measure the frequency shifts caused by liquid flow. Two transducers are mounted in a case attached to one side of the pipe. A signal of known frequency is sent into the liquid to be measured. Solids, bubbles, or any discontinuity in the liquid, cause the pulse to be reflected to the receiver element, as in Fig. Because the liquid causing the reflection is moving, the frequency of the returned pulse is shifted. The frequency shift is proportional to the liquid's velocity. A portable Doppler meter capable of being operated on AC power or from a rechargeable power pack has recently been developed. The sensing heads are simply clamped to the outside of the pipe, and the instrument is ready to be used. Total weight, including the case, is 22 lb. A set of 4 to 20 millampere output terminals permits the unit to be connected to a strip chart recorder or other remote device.

Time-of-travel meters have transducers mounted on each side of the pipe. The configuration is such that the sound waves traveling between the devices are at a 45 deg. angle to the direction of liquid flow. The speed of the signal traveling between the transducers increases or decreases with the direction of transmission and the velocity of the liquid being measured. A time-differential relationship proportional to the flow can be obtained by transmitting the signal alternately in both directions. A limitation of time-of-travel meters is that the liquids being measured must be relatively free of entrained gas or solids to minimize signal scattering and absorption.



Ultrasonic flow-meters

13- Hot Wire:

Consider a wire that's immersed in a fluid flow. Assume that the wire, heated by an electrical current input, is in thermal equilibrium with its environment. The electrical power input is equal to the power lost to convective heat transfer,

$$I^2 R_w = h \cdot A_w \left(T_w - T_f\right)$$

where I is the input current, R_w is the resistance of the wire, T_w and T_f are the temperatures of the wire and fluid respectively, A_w is the projected wire surface area, and h is the heat transfer coefficient of the wire. The wire resistance R_w is also a function of temperature according to,

$$R_w = R_{\mathrm{Ref}} \left[1 + \alpha \left(T_w - T_{\mathrm{Ref}}\right)\right]$$

where α is the thermal coefficient of resistance and R_{Ref} is the resistance at the reference temperature T_{Ref}. The heat transfer coefficient h is a function of fluid velocity v_f according to King's law,

$$h = a + b \cdot v_f^c$$

where a, b, and c are coefficients obtained from calibration ($c \sim 0.5$). Combining the above three equations allows us to eliminate the heat transfer coefficient h,

$$\begin{aligned} a + b \cdot v_f^c &= \frac{I^2 R_w}{A_w \left(T_w - T_f\right)} \\ &= \frac{I^2 R_{\mathrm{Ref}} \left[1 + \alpha \left(T_w - T_{\mathrm{Ref}}\right)\right]}{A_w \left(T_w - T_f\right)} \end{aligned}$$

Continuing, we can solve for the fluid velocity,

$$v_f = \left\{ \left[\frac{I^2 R_{\mathrm{Ref}} \left[1 + \alpha \left(T_w - T_{\mathrm{Ref}}\right)\right]}{A_w \left(T_w - T_f\right)} - a \right] \Big/ b \right\}^{1/c}$$

Two types of thermal (hot-wire) anemometers are commonly used: constant-temperature and constant-current.

The constant-temperature anemometers are more widely used than constant-current anemometers due to their reduced sensitivity to flow variations. Noting that the wire must be heated up high enough (above the fluid temperature) to be effective, if the flow were to suddenly slow down, the wire might burn out in a constant-current anemometer. Conversely, if the flow were to suddenly speed up, the wire may be cooled completely resulting in a constant-current unit being unable to register quality data.

Constant-Temperature Hot-Wire Anemometers

For a hot-wire anemometer powered by an adjustable current to maintain a constant temperature, T_w and R_w are constants. The fluid velocity is a function of input current and flow temperature,

$$a + b \cdot v_f^c = \frac{I^2 R_w}{A_w \left(T_w - T_f\right)} = f\left(I, T_f\right)$$

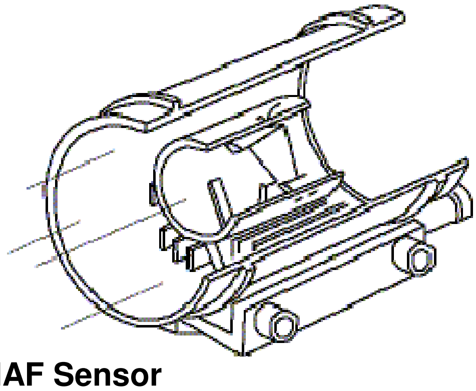
Furthermore, the temperature of the flow T_f can be measured. The fluid velocity is then reduced to a function of input current only.

Constant-Current Hot-Wire Anemometers:

For a hot-wire anemometer powered by a constant current I, the velocity of flow is a function of the temperatures of the wire and the fluid,

$$a + b \cdot v_f^c = \frac{I^2 R_{\mathrm{Ref}} \left[1 + \alpha \left(T_w - T_{\mathrm{Ref}}\right)\right]}{A_w \left(T_w - T_f\right)} = g\left(T_w, T_f\right)$$

If the flow temperature is measured independently, the fluid velocity can be reduced to a function of wire temperature T_w alone. In turn, the wire temperature is related to the measured wire resistance R_w. Therefore, the fluid velocity can be related to the wire resistance.



GM (Bosch) Hot Wire MAF Sensor