

Flow Sensors

Introduction

Flow is defined as the rate (volume or area per unit time) at which a substance travels through a given cross section and is characterized at specific temperatures and pressures. The instruments used to measure flow are termed flow meters. The main components of a flow meter include the sensor, signal processor and transmitter. Flow sensors use acoustic waves and electromagnetic fields to measure the flow through a given area via physical quantities, such as acceleration, frequency, pressure and volume. As a result, many flow meters are named with respect to the physical property that helps to measure the flow.

Flow measurement proves crucial in various industries including petroleum and chemical industries. Consequently, flow measurement becomes a major component in the overall economic success or failure of any given process. Most importantly, accurate flow measurements ensure the safety of the process and for those involved in its success.

Before reading about the intricate details of various flow meters it's a good idea to think about aspects other than the design, governing equations, and the mechanism a flow meter uses in identifying a flow profile. To gain more from this section consider the following questions when learning about each flow meter because when choosing a flow meter the two main things to think about are cost and application:

- 1. What mechanism does this flow meter use to measure flow?**
- 2. How expensive is it?**
- 3. What impact does it have on the system?** (How much power does it withdraw from the system and does the disturbance of flow cause significant problems up or downstream?)
- 4. What are the accuracy limits of the tool?** (Increased accuracy and precision results in higher cost especially for those with automated noise filtering and signal amplifying capabilities.)

Sometimes you may be given an assignment to purchase a tool for your company's system and given with it a list of qualities to look for in order of importance, sometimes you're going to have to make this list yourself. The following table is a component of the TRIZ method for developing a list of qualities in descending order of importance on the left, perpendicular to the factor it has an impact on, to the right. For a given system you figured out that the cheapest solution for accurately measuring the flow rates of various pipe lines is by placing multiple flow meters in a series of positions. From a few calculations using propagation of error you find a moderate range of accuracy limits necessary for your system to be considered well monitored. You know the accuracy limits are less important than the total cost of all the flow meters because your boss told you not to waste any money. On the table you can see that **Cost** is at the top of the left column so **Cost** is the main concern. **Accuracy** is in the farthest left column on the top row so **Cost** most dramatically exacerbates the **Accuracy** of the flow meter when it's minimized. In the intersecting box you see that the lowest price flow meters are the ones with the least amount of accuracy, generally speaking. The next most important quality of your assignment is to get flow meters with the appropriate accuracy, thus **Accuracy** is below **Cost** in the left column. Looking to the top row you see that the **Accuracy** of the flow meter most greatly effects the **Impact on the system**. If you have a low quality flow meter it may be due to the side of the mechanism used to measure flow or the power the

meter draws from the system (through mixing, frictional losses, increase in the turbulence of the flow, or buoyant effects caused from heat transfer). Completing the rest of the table you can decide if there are contradictions to what you thought were the most important qualities based on the inputs in the intersecting cells.

	Accuracy	Impact on system	Cost	Maintenance
Cost	Low accuracy/precision meters costs the least	Lower costs will result in larger meters that increase it effects on flow		Lowest cost means the flow meter will need frequent Maint.
Accuracy		Higher accuracy low cost flow meters have more surface area	What is the right price? How much error can I afford?	How long will it be reliable before it needs to be cleaned and recalibrated?
Maintenance	Application dependent, more Maint. Increases reliability	Down time, accumulation of deposits, disturbing flow	Down time, buildup on meter increases drag	
Impact on system	Lower impact may mean lower accuracy		Are there other costs of impact from installing the flow meter	How intricate is the meter, can it be quickly cleaned and recalibrated



Triz model for Cost = dominant factor followed by accuracy, Impact and Maintenance

An example where this model is important is for a system containing suspended particles in a fluid. If you want to measure the flow rate it might be cheapest to use a pitot tube yet the increased cost of maintaining the flow meter extends into down time of the system, more work from the technicians for a relatively small aspect of the process and lower profits as a result. For this system, maintenance would be the most important factor followed by accuracy, impact on the system and cost. If cost were least important factor you could afford to install a couple doppler meters, gather accurate measurements and the impact of the measurements on the system would be relatively low.

Common Types of Flow Meters

The flow rate as determined by the flow sensor is derived from other physical properties. The relationship between the physical properties and the flow rate is derived from fundamental fluid flow principles, such as Bernoulli's equation.

DIFFERENTIAL PRESSURE

These sensors work according to Bernoulli's principle which states that the pressure drop across the meter is proportional to the square of the flow rate.

$$-\Delta p \propto V^2$$

Using the pressure drop across a pipe's cross section is one of the most common manners to determine a flow measurement. As a result, this property has heavy implications for industrial applications. Flow meters characterized by differential pressure come in several different varieties and can be divided into two categories, laminar and turbulent. Differential pressure sensors operate with respect to Bernoulli's principle. Bernoulli's principle states that the pressure drop across the meter is proportional to the square of the flow rate.

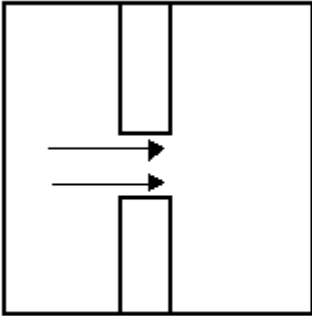
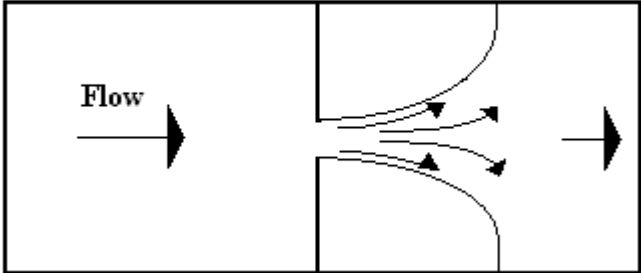
Orifice Meter

Orifice plates are installed in flow meters in order to calculate the material balances that will ultimately result in a fluid flow measurement on the sensor. An orifice plate is placed in a pipe containing a fluid flow, which constricts the smooth flow of the fluid inside the pipe. By restricting the flow, the orifice meter causes a pressure drop across the plate. By measuring the difference between the two pressures across the plate, the orifice meter determines the flow rate through the pipe. The larger the pressure drop, the faster the flow rate would be. There are two types of orifice meters that are usually used in industry, they are the orifice-square edge and the orifice-conic edge. The orifice-square edge has insignificant friction at the interface between the fluid and the orifice plate. These types of orifice plates are recommended for smooth fluid flows, particularly clean liquids and gases such as steam. Generally, drain holes are incorporated in the design so that liquids and gases do not accumulate inside the pipes. Multi-phase fluids are not recommended for the orifice-squared edge because clogging becomes a significant problem as time progresses. The orifice-conic edge is similar to the orifice-square edge, the primary difference being that the orifice-conic edge has a gradually expanding cross-sectional area, and this cross-sectional area is circular in shape. A conic-edge design is often a better choice for low velocity, high viscosity flows. Both types operates best under comparable temperature and pressure conditions, pipe sizes and provide similar accuracies.

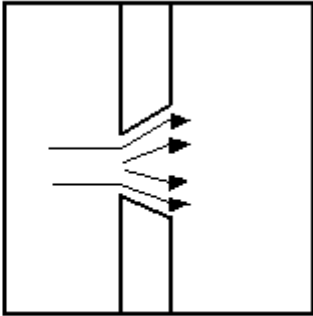
Orifice meters used in conjunction with DP (Differential Pressure) cells are one of the most common forms of flow measurement. In addition, an orifice meter can be used to measure flows when there is a significant difference in pressure in the pipe, like between the upstream and downstream sides of a partially obstructed pipe, which is exactly what the orifice meter does on its own. The plate offers a precisely measured obstruction that essentially shrinks the pipe and forces the flowing substance to constrict. A DP cell allows the comparison of pressure on the upstream (unobstructed) side and the downstream (constricted) side. A greater rate of fluid flow would usually result in a larger pressure drop, since the size of the orifice remains constant and the fluid is held longer building potential energy on the

upstream side of the orifice. Some of the other types of orifice plates include concentric, eccentric and segmental plates, each having different shapes and placements for measuring different processes. These plates are available in varied shapes so that the meter has the optimum structure for different applications. Moreover, the density and viscosity of the fluid, and the the shape and width of the pipe also influences the choice of plate shape to be used.

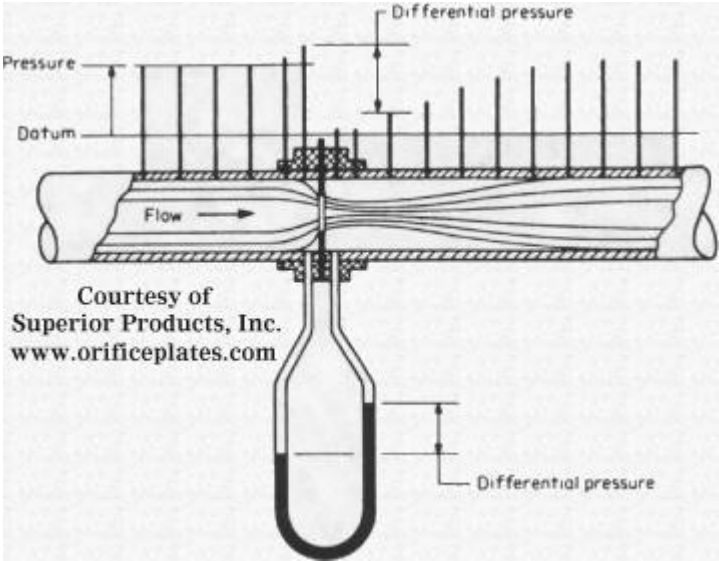
Pipe Wall

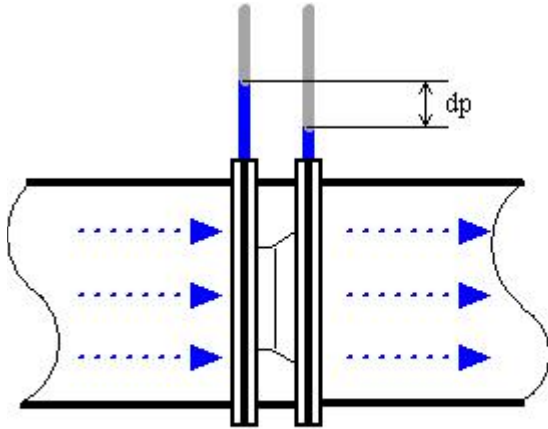


Orifice-Square Edge



Orifice-Conic Edge





www.EngineeringToolBox.com

Such a pressure drop across the plate is then related to the flow rate using basic fluid mechanics principles that incorporate parameters such as density of the fluid and size of the pipe. The flow rate Q , given by the orifice meter, is usually modeled with the following equation:

$$Q = \frac{C_d A_2}{\sqrt{1 - (A_2/A_1)^2}} \sqrt{\frac{2(p_1 - p_2)}{\rho}}$$

Where $p_1 - p_2$ is the pressure drop across the plate, ρ is the fluid density, A_1 is the pipe cross-sectional area, A_2 is the orifice cross-sectional area, and C_d is the discharge coefficient (usually about 0.6). C_d is used to account for energy losses within the system.

The orifice meter is one of the most commonly used flow meters, since it is inexpensive to install and operate, it is uncomplicated and easy to construct, and it is highly robust and long lasting. Orifice meters are not only simple and cheap, they can also be delivered for almost any application and be made of any material. This simplicity of its design and function is one of its paramount advantages, with the meter essentially consisting of just a modified plate. This not only reduces its initial price but also shrinks its operating costs, maintenance expenses, and spare parts expenditure and availability. Lower flow rates reduces their accuracy, whereas higher flow rates combined with high quality, unworn orifice plates increases it. The orifice plate is best when a sharp edge is present towards the upstream side of the meter. Wear reduces the accuracy of orifice plates. The turndown rate of orifice plates are generally less than 5:1. More information about turndown rates is mentioned in a later section.

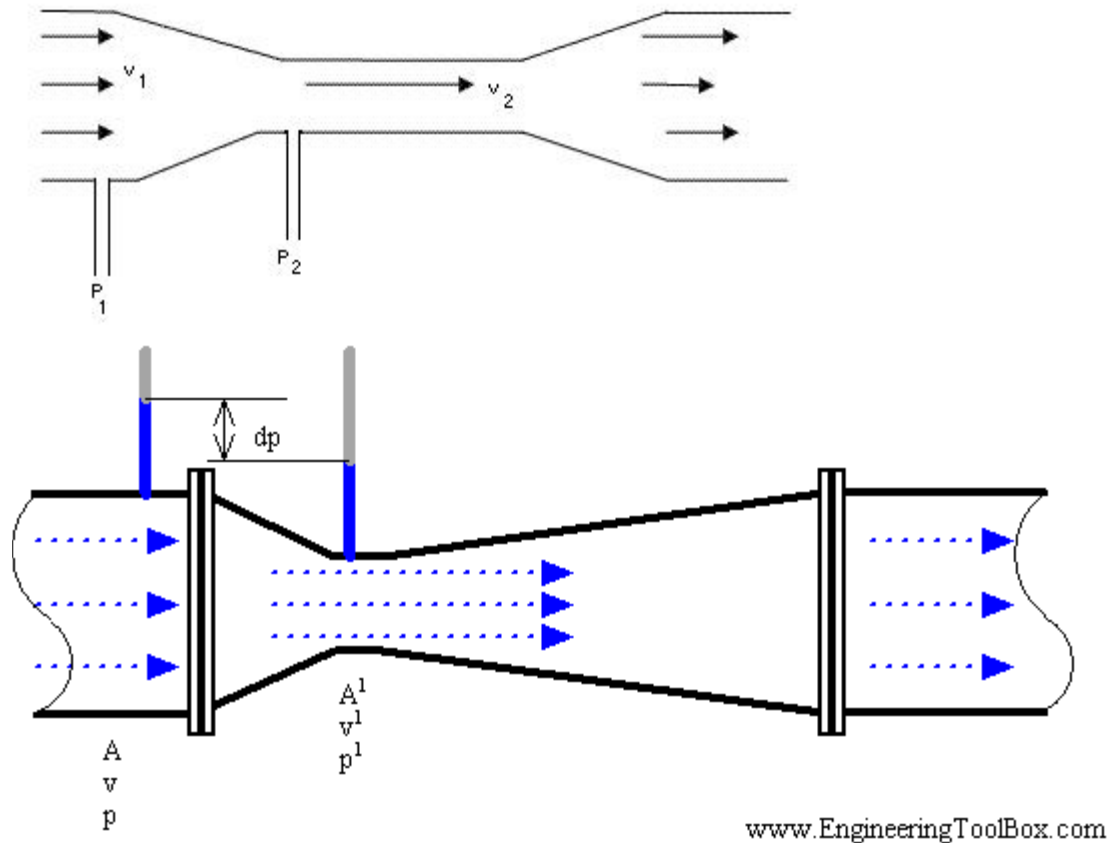
Venturi Meter

Venturi meters can pass 25 – 50% more flow than an orifice meter. In a Venturi meter setup, a short, smaller diameter pipe is substituted into an existing flow line. Because the Venturi meter is insensitive to changes in the velocity profile of the fluid flow, the pipe design does not need to be straight like the orifice meter. Though initially expensive, the Venturi meter has relatively low maintenance and operation costs.

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.

There are two main types of Venturi meters. The first one, known as the classical Herschel Venturi meter, is a very long meter characterized below. Pressure readings at different points in the meter are combined to provide an average pressure reading. Cleaning the classical Venturi meter is limited. The second type of Venturi meter is known as the short form Venturi meter. This differs from its longer counterpart by reduced size and weight.

By Bernoulli's principle the smaller cross-sectional area results in faster flow and therefore lower pressure. The Venturi meter measures the pressure drop between this constricted section of pipe and the non-constricted section.



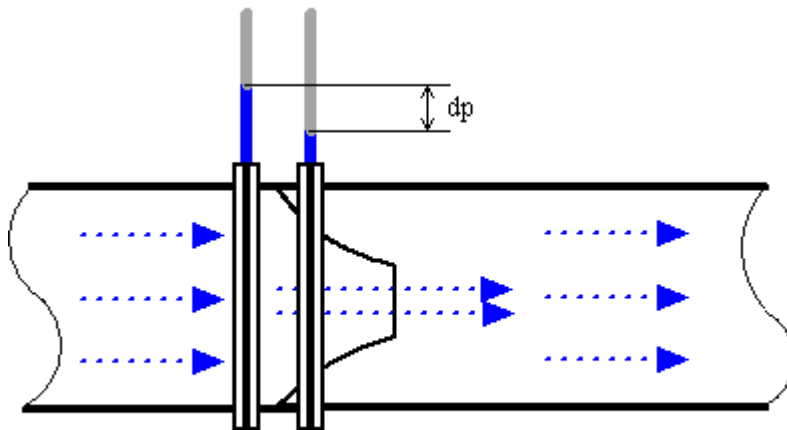
The discharge coefficient for the Venturi meter is generally higher than that used for the orifice, usually ranging from .94 to .99.

The Venturi meter is most commonly used for measuring very large flow rates where power losses could become significant. The Venturi flow meter has a higher start up cost than an orifice, but is balanced by the reduced operating costs.

Due to simplicity and dependability, the Venturi tube flowmeter is often used in applications where higher turndown ratios or lower pressure drops than orifice plates can provide are necessary. With proper instrumentation and flow calibrating the venturi meter flowrate can be reduced to about 10% of its full scale range with proper accuracy. This provides a turndown ratio of around 10:1.

Flow Nozzle

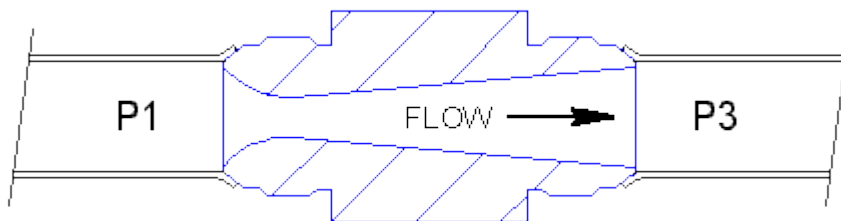
Another type of differential pressure flowmeter is the flow nozzle. Flow nozzles are often used as measuring elements for air and gas flow in industrial applications. At high velocities, Flow Nozzles can handle approximately 60 percent greater liquid flow than orifice plates having the same pressure drop. For measurements where high temperatures and velocities are present, the flow nozzle may provide a better solution than an orifice plate. Its construction makes it substantially more rigid in adverse conditions and the flow coefficient data at high Reynolds numbers is better documented than for orifice plates. Liquids with suspended solids can also be metered with flow nozzles. However, the use of the flow nozzles is not recommended for highly viscous liquids or those containing large amounts of sticky solids. The turndown rate of flow nozzles is similar to that of the orifice plate. The flow nozzle is relatively simple and cheap, and available for many applications in many materials.



www.EngineeringToolBox.com

The Sonic Nozzle- Critical(Choked)Flow Nozzle

One type of flow nozzle is the sonic nozzle. The Sonic Nozzle is a converging-diverging flowmeter. It consists of a smooth rounded inlet section converging to a minimum throat area and diverging along a pressure recovery section or exit cone.

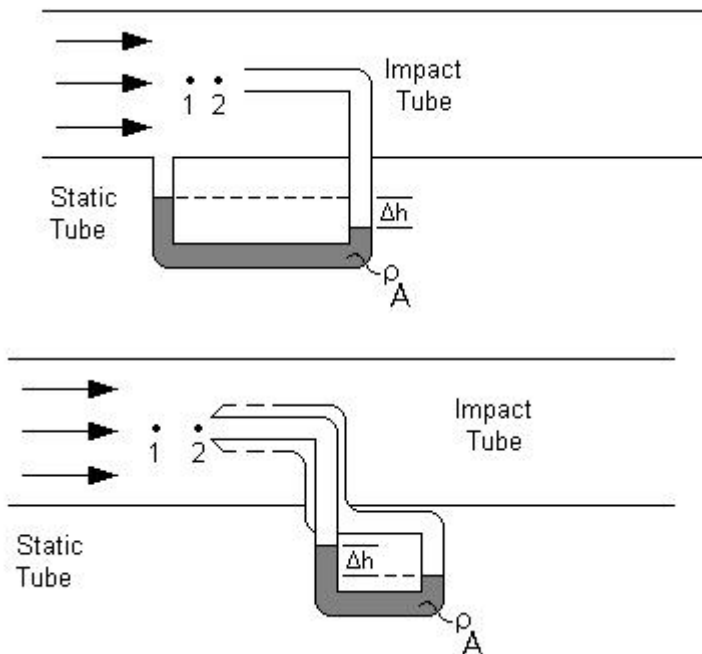


The Sonic Nozzle is operated by either pressurizing the inlet (P1) or evacuating the exit (P3), to achieve a pressure ratio of 1.2 to 1 or greater, inlet to outlet. When a gas accelerates through a nozzle, the velocity increase and the pressure and gas density decrease. The maximum velocity is achieved at the throat, the minimum area, where it breaks Mach 1 or sonic. At this point it's not possible to increase the flow by lowering the downstream pressure. The flow is choked. Pressure differences within a piping system travel at the speed of sound and generate flow. Downstream differences or disturbances in pressure, traveling at the speed of sound, cannot move upstream past the throat of the Nozzle because the throat velocity is higher and in the opposite direction.

Sonic Nozzles are used in many control systems to maintain fixed, accurate, repeatable gas flow rates unaffected by the downstream pressure. If you have a system with changing or varying gas consumption downstream and you want to feed it a constant or locked flowrate, a Sonic Nozzle is an excellent way to achieve this.

Pitot Tubes

Pitot tubes measure the local velocity due to the pressure difference between points 1 and 2 in the diagrams below. Unlike the other differential flow meters, the pitot tubes only detect fluid flow at one point rather than an overall calculation. The first diagram shows a simple pitot tube configuration while the second shows a compact pitot tube configuration.



Both tubes work in a similar manner. Each pitot tube has two openings, one perpendicular to the flow and one parallel to the flow. The impact tube has its opening perpendicular to the fluid flow, allowing the fluid to enter the tube at point 2, and build up pressure until the pressure remains constant. This point is known as the stagnation point. The static tube, with openings parallel to the fluid flow gives the static pressure and causes a sealed fluid of known density to shift in the base of the tube. Pressure drop can be calculated using the height change along with the fluid densities and the equation below.

$$\Delta p = \Delta h(\rho_A - \rho)g$$

with Δp as the pressure drop, ρ_A as the known fluid density, ρ as flowing fluid's density, and g as the acceleration due to gravity.

This pressure drop can be related to the velocity after accounting for the losses throughout the piping in the system, given by C_p . This dimensionless coefficient is found through accurate calibration of the pitot tube. The equation below describes this relationship.

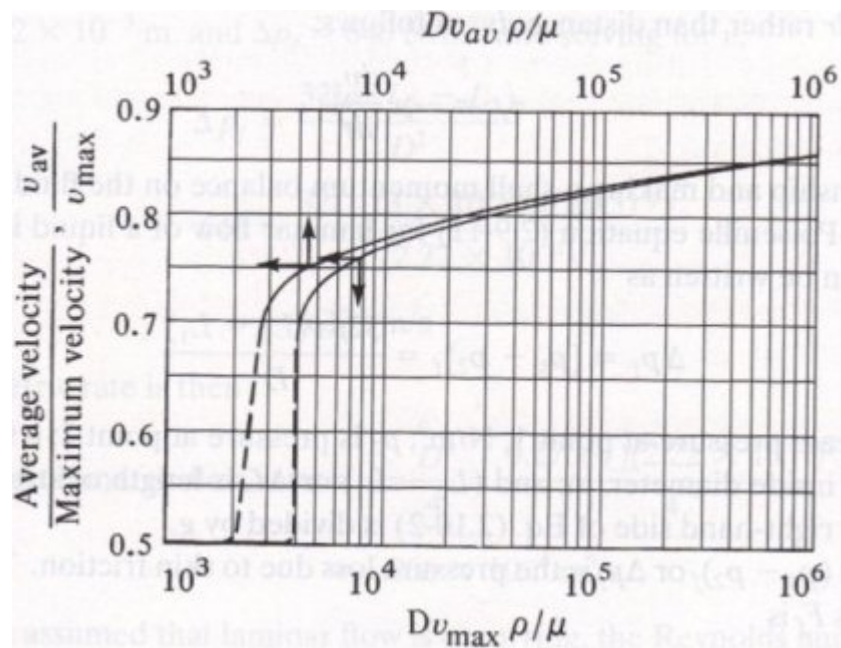
$$v = C_p \sqrt{\frac{2(p_1 - p_2)}{\rho}}$$

with v as the fluid velocity, C_p as the loss coefficient, p_1 as the pressure at point 1, p_2 as the pressure at point 2, and ρ as the flowing fluid's density.

By placing the tube at the exact center of the pipe, the maximum velocity can be measured and the average velocity can be calculated via the Reynolds number. The governing equation and chart are below.

$$Re = \frac{Dv_{max}\rho}{\mu}$$

with Re as the Reynolds number, D as the pipe diameter, v_{max} as the maximum velocity, ρ as the flowing fluid's density, and μ as the flowing fluid's viscosity.



Adapted from Geankoplis.

Finally, the flow rate can be found by accounting for the area of the pipe.

$$Q = v_{avg} \frac{\pi}{2} r^2$$

with Q as the volumetric flow rate, v_{avg} as the average velocity, and r as the pipe's radius.

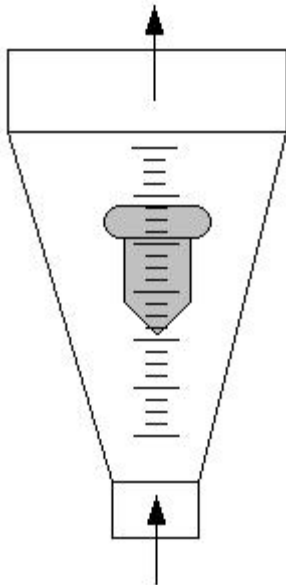
It should be noted that all the equations apply to incompressible fluids only, but these can be used to approximate gas flows at moderate velocities. This flow meter must also be placed at least 100 pipe diameters in distance, downstream of the nearest flow obstruction. This ensures no unwanted pressure fluctuations and accurate pitot tube readings. Furthermore, fluids containing large particles can clog the pitot tube and should be avoided.

DIRECT FORCE

These flow meters are governed by balancing forces within the system.

Rotameter

A rotameter is a vertically installed tube that increases in diameter with increasing height. The meter must be installed vertically so that gravity effects are easily incorporated into the governing equations. Fluid flows in through the bottom of the tube and out through the top. Inside the glass tube there is a float that changes position with the flow rate. When there is no liquid flow, the float rests in the bottom of the meter.



The applied concept for the rotameter is differential area. As the flow rate of the fluid changes, the position of the float changes and annular area change directly, keeping a constant pressure drop across the meter. Changes in float position and annular area are approximately linear with changes in flow rate. Upon achieving a stable flow rate, the vertical forces are balanced and hence the position of the float remains constant. The volumetric flow is given by the following equation:

$$Q = C A_b \sqrt{\frac{2g \left(\frac{V_f (\rho_f - \rho)}{A_f} - \rho h_f \right)}{\rho \left[1 - \left(\frac{A_b}{A_a} \right)^2 \right]}}$$

with C being the discharge coefficient, A_b being the cross sectional area of the top of the float, V_f volume of the float, ρ_f the density of the float, ρ the density of the fluid h_f the height of the float, A_a the cross sectional area of the bottom of the float.

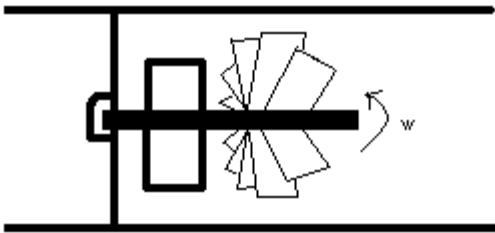
Generally, rotameters are inexpensive and simple to use. This allows them to be used in many plant applications.

For the full derivation of the above equation, refer to the attachment.

[1]

Turbine Meter

A turbine wheel is placed in a pipe that holds the flowing fluid. As the fluid flows through the turbine, the turbine is forced to rotate at a speed proportional to the fluid flow rate. A magnetic pick-up is mounted to the turbine wheel, and a sensor records the produced voltage pulses. Voltage information can then be translated into the actual flow meter reading.



The following is the equation used to model the turbine meter:

$$Q = VA = \frac{\omega (\bar{r})^2 A^2}{\bar{r} A \tan \beta - 0.037 Re^{-0.2} n (R_o + R_i) D \sin \beta}$$

with A the pipe area, \bar{r} the root mean squared radius, ω rotational speed, β the angle between the flow direction and the turbine blades, R_o the outer blade radius, R_i the inner radius, and D the distance between blades.

There are two main advantages of the turbine meter over conventional differential head devices

- 1) The extended are more accurate registration of flow in the low flow range of process operation. This results from the registration being proportional to the velocity rather than the velocity square
- 2) The comparatively low head loss across the meter

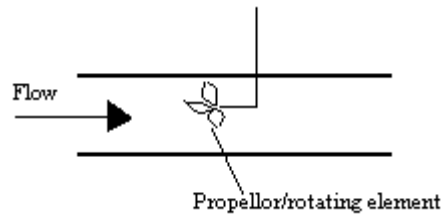
Another advantage to using this type of flow meter is reliability. Extensive testing has proven these results. Additionally, the turbine flow meter does not have a high installation cost. However, due to the turbine wheel motion, a low to medium pressure drop can result. Turbine wheel replacement may also be required due to abrasion caused by particles within the fluid.

For a more detailed derivation of the above equation, please look at the following:

[2]

Propeller Flow Meter

Propeller flow meters have a rotating element similar to the wheel in turbine meters. Again, rotation is caused by fluid flow through the propeller, and voltage pulses are created as the propeller passes a magnetic or optical sensor. Similarly, the frequency of the pulses is proportional to flow rate of the fluid and the voltages can be directly correlated with the fluid flow rate.



Propeller flow meters are often used specifically with water, though other fluids may also be used. Low cost coupled with high accuracy make propeller flow meters a common choice in many applications.

Paddle Wheel Sensors

A kind of propeller sensor is the paddle wheel sensor. Paddle wheel sensors are similar to turbine sensors, except for one thing. The shaft of the paddle wheel sensor is perpendicular to the flow of the fluid while the turbine sensor's shaft is parallel to the flow of the fluid. This adds several advantages for the paddle wheel flow sensor. Due to the shaft being perpendicular to the flow, it sustains less axial force from the fluid, and thus less friction. Paddle wheel sensors also have a smaller number of blades, so there is less force needed to turn the paddle wheel. This means that a paddle wheel can be accurate at lower flows, have a high efficiency, as well as a longer lifetime.

There are two kinds of paddle wheel sensors, insertion and inline sensors. There is more than one design for an insertion sensor, but one popular design has the bearing built into the rotor and the shaft sliding through it as the center axis of spin. The blade sticks out and is inserted into the pipe with the flowing fluid.

An inline paddle wheel sensor is used for smaller pipes. It contains a rotor assembly with the magnet sealed inside and a main body.

For detailed mathematics of paddlewheels, see [Paddlewheel Flow Sensors: The Overlooked Choice](#)

Coriolis Mass Flow Meter

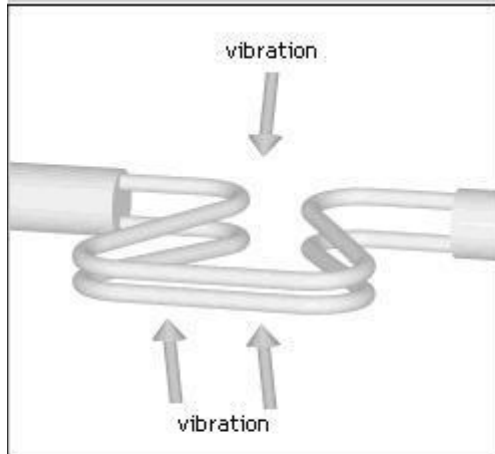
A Coriolis flow meter harnesses the natural phenomenon wherein an object will begin to "drift" as it travels from or toward the center of a rotation occurring in the surrounding environment. A merry-go-round serves as a simple analogy; a person travelling from the outer edge of the circle to its center will find himself deviating from his straight-line path in the direction of the ride's rotation.

Coriolis flow meters generate this effect by diverting the fluid flow through a pair of parallel U-tubes undergoing vibration perpendicular to the flow. This vibration simulates a rotation of the pipe, and the resulting Coriolis "drift" in the fluid will cause the U-tubes to twist and deviate from their parallel alignment.

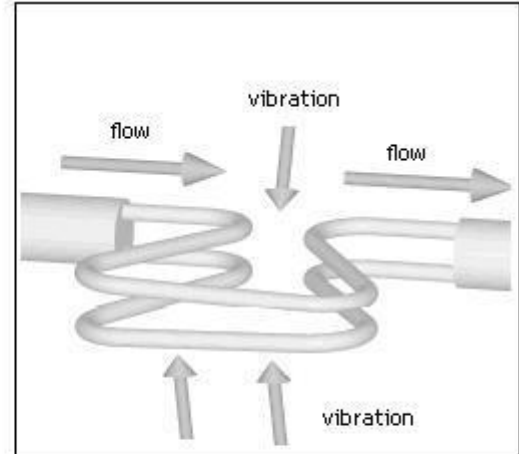
This Coriolis force producing this deviation is ultimately proportional to the mass flow rate through the U-tubes.

$$MassFlow = \frac{F_c}{2wx}$$

where F_c is the Coriolis force observed, w is the angular velocity resulting from rotation, and x is the length of tubing in the flow meter.



Coriolis flow meter undergoing no flow.



Coriolis flow meter exhibiting deflection as a result of mass flow

Adapted from Wikipedia's entry on Coriolis Mass Flow Meters.
http://en.wikipedia.org/wiki/Mass_flow_meter

Because the Coriolis flow meter measures the mass flow rate of the fluid, the reading will not be affected by fluctuations in the fluid density. Furthermore, the absence of direct obstructions to flow makes the Coriolis flow meter a suitable choice for measuring the flow of corrosive fluids. Its limitations include a significant pressure drop and diminished accuracy in the presence of low-flow gases.

To understand how the mass flow rate is measured with this device, refer to the following attachment.

[3]

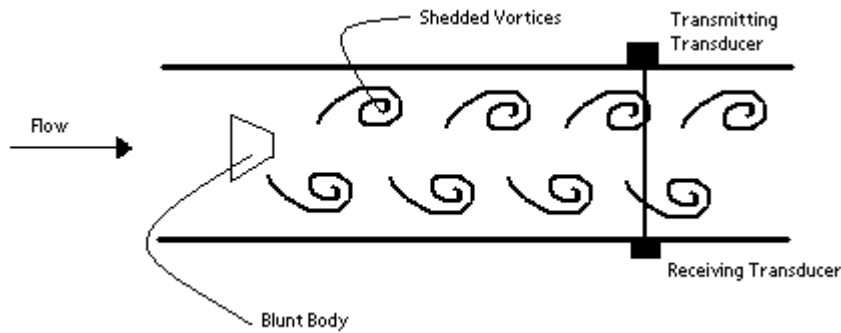
FREQUENCY

These flow meters use frequency and electronic signals to calculate the flow rate.

Vortex Shedding Flow Meter

A blunt, non-streamline body is placed in the stream of the flow through a pipe. When the flow stream hits the body, a series of alternating vortices are produced, which causes the fluid to swirl as it flows downstream. The number of vortices formed is directly proportional to the flow velocity and hence the flow rate. The vortices are detected downstream from the blunt body using an ultrasonic beam that is transmitted perpendicular to the direction of flow. As the vortices cross the beam, they alter the carrier

wave as the signal is processed electronically, using a frequency-to-voltage circuit. The following diagram shows the basic principle of the vortex-shedding flow meter:



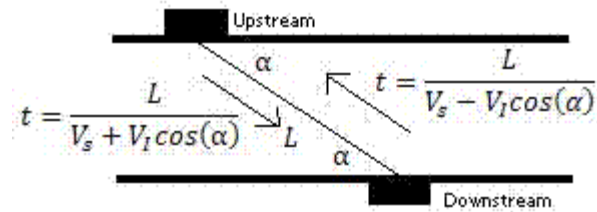
Vortex-shedding flow meters are best used in turbulent flow with a Reynolds number greater than 10,000. One advantage of using this type of flow meter is its insensitivity from temperature, pressure, and viscosity. The major disadvantage to using this method is the pressure drop caused by the flow obstruction.

Ultrasonic Flow Meters

There are two types of Ultrasonic meters, the transit time/time of flight and Doppler models, both of which have unique equations representing the principles behind them. The basis for these meters is monitoring ultrasonic waves in fluid passing through a pre-configured acoustic field. These meters are based on the technique of sound waves that change.

Transit Time/Time of Flight Flow Meters

Transit time meters have two opposing transducers outside of the pipe to measure the time of a signal sent from a transducer upstream to a transducer downstream and vice versa.

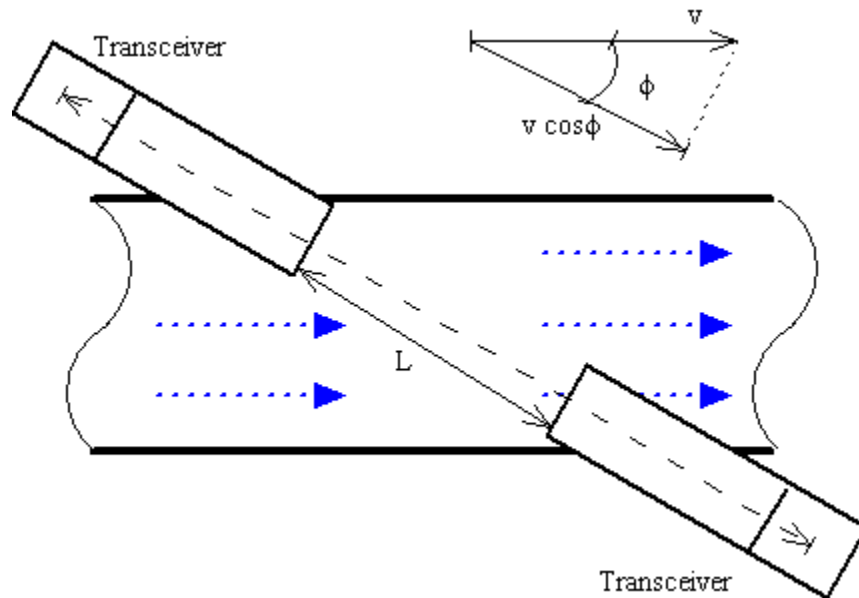


This allows the average velocity and hence the flow rate, Q, to be determined.

$$Q = K \left(\frac{\pi d^3 \tan \alpha}{8} \right) \left(\frac{1}{t_{UD}} - \frac{1}{t_{DU}} \right)$$

where d is the diameter of the pipe, α is the angle between direction of the flow and the pipe, t_{UD} is the time for the signal to reach downstream transducer from the upstream transducer, and t_{DU} is the time for signal to reach upstream transducer from the downstream transducer.

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.



www.EngineeringToolBox.com

Two transmitters / receivers (transceivers) are located on each side of the pipe. The transmitters sends pulsating ultrasonic waves in a predefined frequency from one side to the other. The difference in frequency is proportional to the average fluid velocity.

Downstream pulse transmit time can be expressed as

$$t_d = L / (c + v \cos\Phi)$$

where t_d = downstream pulse transmission time L = distance between transceivers

Downstream pulse transmit time can be expressed as

$$t_u = L / (c - v \cos\Phi)$$

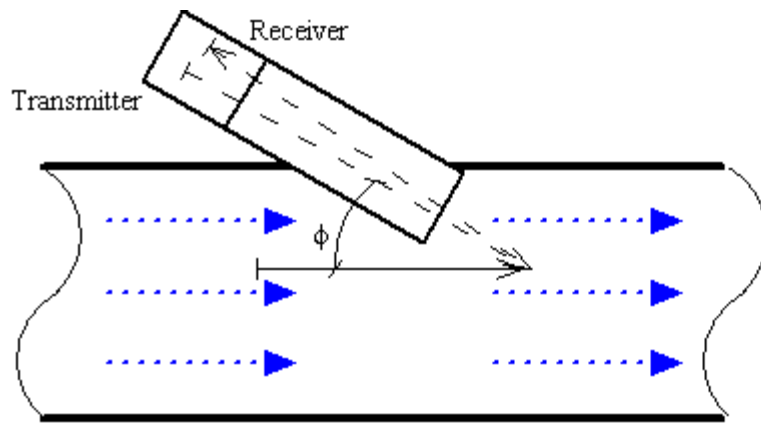
where t_u = upstream pulse transmission time

Since the sound travels faster downstream than upstream, the difference can be expressed as

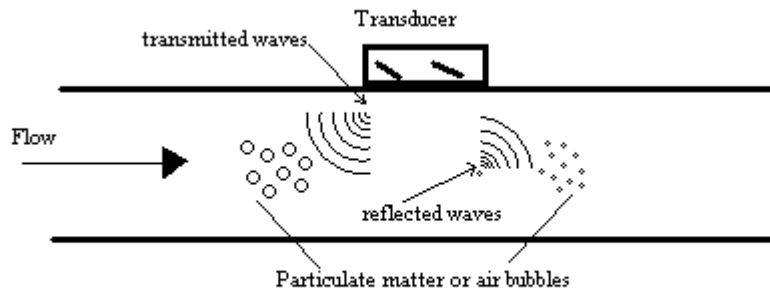
$$t = t_d - t_u = 2 v L \cos\Phi / (c^2 - v^2 \cos^2\Phi) \approx 2 v L \cos\Phi / c^2 \quad (4) \quad (\text{since } v \text{ is very small compared to } c)$$

Doppler Meters

Doppler meters use the frequency shift of an ultrasonic signal when it is reflected by suspended particles or gas bubbles (discontinuities) in motion. 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, the relative motion are measured. The resulting frequency shift is named the *Doppler Effect*.



www.EngineeringToolBox.com



These reflected signals travel at the velocity of light.

$$V_f = \frac{V_s \Delta f}{2 f_{actual} \cos \alpha}$$

where f is the actual frequency and Δf is the change in frequency or frequency shift.

The fluid velocity can be expressed as

$$v = c (f_r - f_t) / 2 f_t \cos \Phi$$

where

f_r = received frequency

f_t = transmission frequency

v = fluid flow velocity

Φ = the relative angle between the transmitted ultrasonic beam and the fluid flow

c = the velocity of sound in the fluid

This method requires that there are some reflecting particles in the fluid. The method is not suitable for clear liquids.

Advantages with the Doppler Effect Ultrasonic Flowmeter

Doppler meters may be used where other meters don't work. This could be in liquid slurries, aerated liquids or liquids with some small or large amount of suspended solids. The advantages can be summarized to:

- ☐ Obstruct less flow
- ☐ Can be installed outside the pipes
- ☐ The pressure drop is equal to the equivalent length of a straight pipe
- ☐ Low flow cut off
- ☐ Corrosion resistant
- ☐ Relative low power consumption

Limitations with Doppler Effect Ultrasonic Flowmeters

- ☐ Doppler flowmeters performance are highly dependent on physical properties of the fluid, such as the sonic conductivity, particle density, and flow profile.
- ☐ Non uniformity of particle distribution in the pipe cross section may result in an incorrectly computed mean velocity. The flowmeter accuracy is sensitive to velocity profile variations and to the distribution of acoustic reflectors in the measurement section.
- ☐ Unlike other acoustic flowmeters, Doppler meters are affected by changes in the liquid's sonic velocity. As a result, the meter is also sensitive to changes in density and temperature. These problems make Doppler flowmeters unsuitable for highly accurate measurement applications.

Benefits with Ultrasonic Flowmeters As A Whole

- ☐ Obstruction less flow
- ☐ Pressure drop equal to an equivalent length of straight pipe
- ☐ Unaffected by changes in temperature, density or viscosity
- ☐ Bi-directional flow capability
- ☐ Low flow cutoff
- ☐ Corrosion-resistant

- ☐ Accuracy about 1% of flow rate
- ☐ Relative low power consumption

Both meters are effective in measuring open channels and partially filled pipes but are very sensitive to flow conditions and hence should be calibrated with care. Also, there is no pressure drop since there are no obstructions in the flow path.

Limitations with Ultrasonic Flowmeters as A Whole

- ☐ The operating principle for the ultrasonic flowmeter requires reliability high frequency sound transmitted across the pipe. Liquid slurries with excess solids or with entrained gases may block the ultrasonic pulses.
- ☐ Ultrasonic flowmeters are not recommended for primary sludge, mixed liquor, aerobically digested sludge, dissolved air flotation thickened sludge and its liquid phase, septic sludge and activated carbon sludge.
- ☐ Liquids with entrained gases cannot be measured reliably.

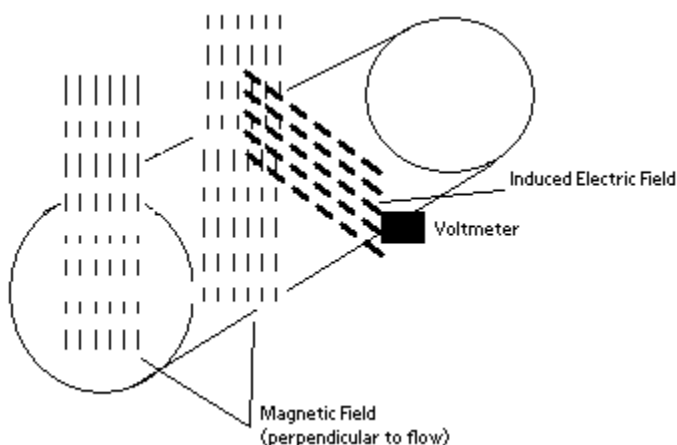
The following link will help to show how both types of the Ultrasonic meter works and how the above equations are derived.

[4]

OTHER TYPES

Magnetic Flow Meter

One magnetic model flow meter positions electric coils around the pipe of the flow to be measured. A pair of electrodes is set up across the pipe wall. The fluid flowing has a minimum value of electrical conductivity, the movement of the fluid through the pipe acts as a conductor moving across the magnetic field. There is an induced change in voltage between the electrodes, which is proportional to the flow velocity.



The flow velocity is found by measuring the changes of induced voltage of the conductive fluid passing through a controlled magnetic field at right angles. According to Faraday's Law, the magnitude of the

voltage induced is directly proportional to the product of the magnetic flux, distance between probes and the velocity of the medium (fluid).

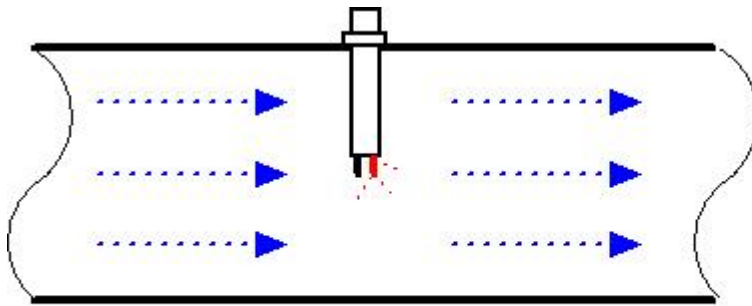
$$E = -N \frac{d\phi}{dt} = -NB \frac{dA}{dt} = -NBD \frac{dz}{dt} = -NBDv$$

where E is the voltage of induced current, N is the number of turns, B is the external magnetic field, ϕ is the magnetic flux, D is the distance between electrodes and v is the velocity of the fluid.

Some of the advantages are minimum pressure drop because of minimum obstructions in flow path; low maintenance cost because of no moving parts. One of the disadvantages is that it usually requires a fluid with an electrical conductivity of higher than 3 $\mu\text{S}/\text{cm}$.

Calorimetric Flow Meter

This type of flow meter is suitable for monitoring the flow rates of liquid and gaseous mediums. The calorimetric principle is based on two temperature sensors in close quarters of one another but thermally insulated from one another.



www.EngineeringToolBox.com

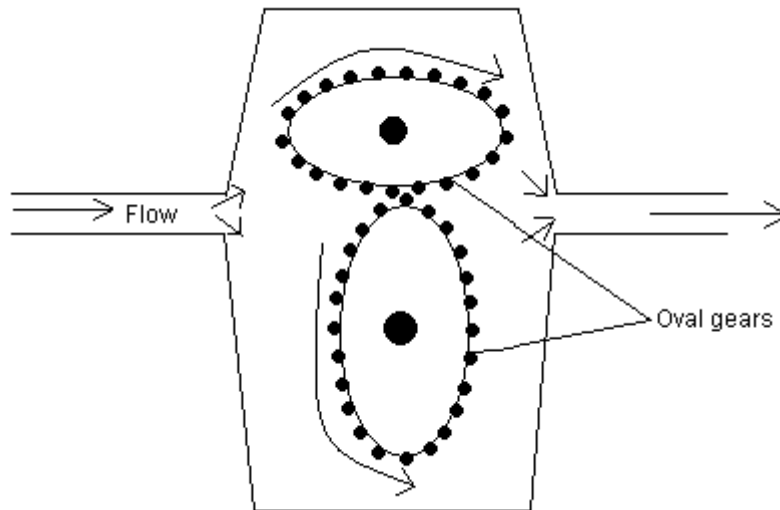
One of the two temperature sensors is constantly heated and the cooling effect of the flowing fluid is used to monitor the flow rate. In a stationary phase fluid condition there is a constant temperature difference between the two temperature sensors. When the fluid flow increases, heat energy is extracted from the heated sensor and the temperature difference between the sensors are reduced. The reduction is proportional to the flow rate of the fluid. The calorimetric flow meter can achieve relatively high accuracy at low flow rates.



Common applications: air compression, argon compression, nitrogen compression, carbon dioxide compression and flow detection of all fluids (liquids and gases)

Gear Flow Meter

This type of flow meter has oval shaped gears with fitting teeth which control the amount of fluid passing through. The flow rate is calculated by number of times the gears are filled and emptied. These meters have high accuracy and are used for measuring low flow and for high viscosity fluids. It is very easy to install these types of meters because it requires no pipe.



Thermal Flow meters

These flow meters take advantage of the thermal properties of the fluid to measure the flow of the fluid in a pipe. In most thermal flow meters, a measured amount of heat is applied to the heater of the sensor. Portions of this heat is lost to the fluid as it flows. Accordingly, as the fluid flow increases more heat is lost. The amount of heat lost is tracked using a temperature measurement instrument in the sensor. Then an electronic transmitter uses the heat input and temperature measurements to calculate the fluid flow, taking into account the thermal properties of the fluid.

Common applications of thermal flow meters are measuring the flow rate of clean gases like air, nitrogen, hydrogen, helium, ammonia, and argon. Most thermal flow meters are used to measure pure gases that would be used in laboratory experiments or semiconductor production. Mixtures like flue stack flow can also be measured but the mixture compositions must be known to use the appropriate thermal properties of each component in the mixture. The key advantage of this technology is its dependence on the thermal properties which are mostly independent of the gas density.

However caution should be taken if this type of flow meter is used to measure a fluid of unknown or varying composition. Additionally, thermal flow meters should not be used to measure abrasive fluids because they may damage the sensor. Some fluids can coat the sensor causing it to be inoperable and must be regularly cleaned to be useful.

Table of Flow Meters

The following table outlines specifics for most of the flow meters. This may be helpful in answering example 1. Accuracy is given in terms of FSD (full scale deflection) which is the deflection of meter's pointer to the farthest point on the scale. This implies the highest measurement.

Type of Flowmeter	Operating Temperature of Sensor (K)	Pressure Change (Comparative)	Pipe Size (mm)	Accuracy	Measurables	Advantages	Disadvantages
Orifice-Square Edge	<800	High	>40	± 1-2% FSD	Clean gases, steam, clean liquids, most dirty liquids and most corrosive liquids	Negligible friction at the boundary between the fluid and the orifice plate	Not suited for multi-phase fluids because clogging becomes a significant problem as time progresses
Orifice-Conic Edge	<800	High	>40	±2% FSD	Clean liquids, viscous liquids, mostly dirty liquids, and most corrosive liquids	Has a gradually expanding cross-sectional area and is good for low velocity, high viscosity flows	Not recommended for high velocity, low viscous flows
Venturi	<800	80-90% of Energy Recovered	>50	± 1-2% FSD	Clean gases, most dirty gases, steam, clean liquids, most viscous liquids, most dirty liquids, most corrosive liquids, and most fibrous, abrasive slurries	Pipe design does not need to be straight, relatively low maintenance and operation costs	Insensitive to changes in the velocity profile of the fluid flow, relatively expensive to orifice flow meters
Pitot Tube	<800	Low	>10	± 1-2% FSD	Clean gases, most dirty gases, steam, clean liquids, most viscous liquids, most dirty liquids, most corrosive liquids, and most fibrous, abrasive slurries	Detects fluid flow at one point from pressure drop	Clogs occur from fluids containing large particles
Electromagnetic	230-450	Low	6-100	±0.2 flow rate to 1.0% FSD	Clean liquids, viscous liquids, dirty liquids, corrosive liquids, fibrous slurries and abrasive slurries	Minimum P-drop because of few obstructions in flow path; low maintenance cost because of no moving parts	Requires a fluid with an electrical conductivity > 3 µS/cm
Turbine	10-530	Medium	6-600	± 0.5 flow rate	Clean gases, clean liquids, and most corrosive liquids	Relatively high-tested reliability and low installation cost	May cause low to medium P-drop from turbine wheel motion, may require turbine wheel replacement due to abrasion
Ultrasonic-Transit Time	100-530	Low	>12	±1 flow rate to ±2% FSD	Clean liquids, most viscous liquids, and corrosive liquids	Effective in measuring open channels and partially filled pipes	Very sensitive to flow conditions and thus need to be calibrated with care
Doppler	100-400	Low	>12	±1 flow rate to ±2% FSD	Most viscous liquids, dirty liquids, corrosive liquids, fibrous and abrasive slurries	Effective in measuring open channels and partially filled pipes	Very sensitive to flow conditions and thus need to be calibrated with care
Rotameter	Glass < 400 Metal < 800	Low	≤75	±0.5 flow rate to ±1% FSD	Clean gases, clean liquids, viscous liquids, and most corrosive liquids	Relatively inexpensive and simple to use	Typically fragile, must specifically be installed vertically with fluid flowing upwards
Vortex	80-680	Low	15-400	±0.5 flow rate to ±1 flow rate	Clean gases, most dirty gases, steam, clean liquids, and most corrosive liquids	Insensitive to temperature, pressure, and viscosity	Causes pressure drop due to flow obstruction
Coriolis	Insensitive to Temperature	Low	10-100	±1% FSD	All. Exception – Both clean and dirty gases can be measured only at high pressures	Effectively measures flow rates of high viscous liquids at a low pressure drop, insensitive to temperature, pressure, corrosive liquids, and fluctuating densities	Significant pressure drop and diminished accuracy in the presence of low-flow gases

Flow Profile Distortion

In the real world, the flow profile is not always symmetrical. Pipe fittings such as elbows, tee-pieces, and reducers can change the flow profile. One example of a fitting that alternates the flow profile is a sharp elbow which causes pure swirls throughout the fluid. Some flow meters are more sensitive to particular types of flow distortion. More complex flow conditions produce better velocity profile but there is a trade off since they are more expensive and give higher pressure drops.

Turndown Ratio

The turndown ratio is a term used to describe the range of accurate operability of a specific flow meter. This rangeability is critical when selecting flow meters for specific applications. Typically, in a plant setting gas flow may not be constant, but accurate measurement of gas flow is needed ranging from no flow to full flow.

For example if nitrogen gas is being used in a plant conducting multiple batch reactions, sometimes the little nitrogen (100 m³/min) will be needed and other times full nitrogen flow (1000 m³/min) will be needed. For this system, the turndown ratio is 10:1. Accordingly, a flow meter must have a turndown ratio of at least 10:1.

For each type of flow meter, the turndown ratio is limited by the theoretical and physical constraints. For example, for an orifice meter the accuracy may be compromised near the limits of the rangeability. Orifice meters create a pressure drop in the measured fluid which is proportional to the velocity squared. If the

range of differential pressures becomes too large the overall accuracy of the flow meter at its range limits may be inconsistent.

Turndown ratio can be expressed as:

$$TR = q_{\max} / q_{\min} \quad (1)$$

where

TR = Turndown Ratio

q_{\max} = maximum flow

q_{\min} = minimum flow

The table below shows a list of typical turndown ratios for different flow meters.

Type	Turndown Ratio
Orifice Meter	3:1
Turbine Meter	10:1
Rotary Displacement Meter	10:1-80:1
Diaphragm Meter	80:1
Ultrasonic Meter	50:1
Thermal Meter	10:1-100:1

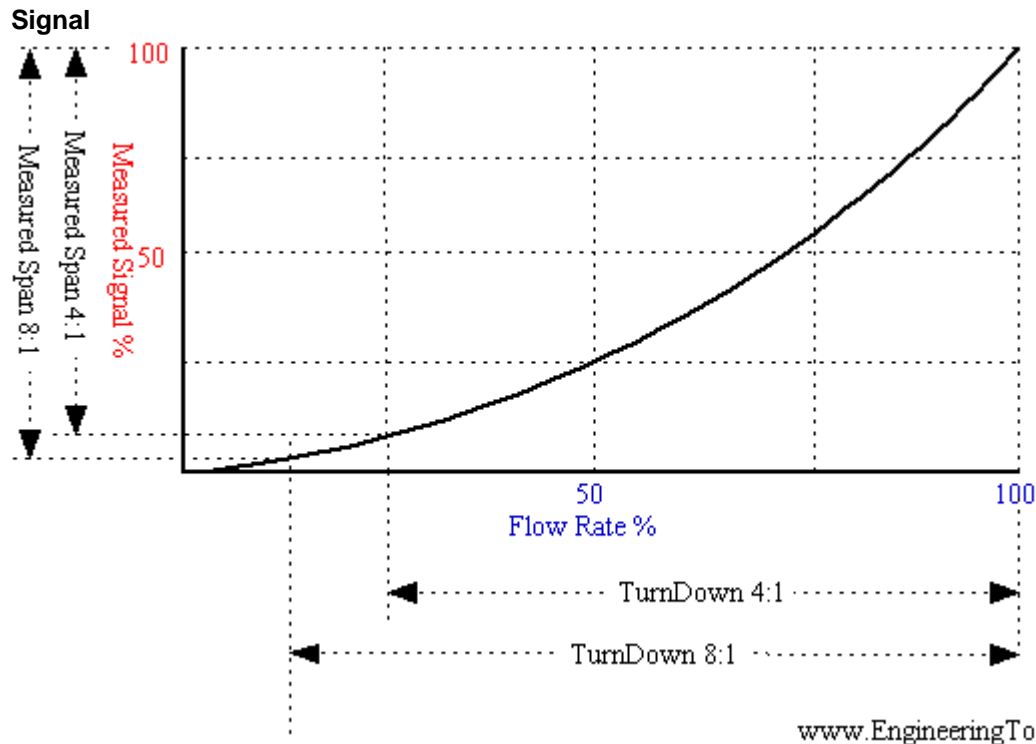
Example - Turndown Ratio for an Orifice Meter

The turndown ratio - TR - for an orifice meter with maximum flow of 12 kg/s and a minimum flow of 3 kg/s can be calculated as:

$$TR = (12 \text{ kg/s}) / (3 \text{ kg/s}) = 4 \text{ - normally expressed as turndown ratio of 4:1}$$

This is a typical turndown ratio for a orifice plate. In general a orifice plates has turndown ratio between 3:1 and 5:1.

Turndown Ratio and Measured



The graph above shows how the turndown ratio effects the measured signal % and flowmeter %. With an increased turndown ratio there is a larger range that the flowmeters can operate within. In a flow meter based on the orifice or venturi principle, the differential pressure upstream and downstream of an obstruction in the flow is used to indicate the flow. According the Bernoulli Equation the differential pressure increases with the square of flow velocity. A large turndown ratio will cramp the measurement signal at low flow rate and this is why venturi and orifice meters are not accurate at low flowrates.

Example 1

a) Oil is flowing in a medium sized pipe which is insensitive to temperature and pressure. Pressure drop measured is relatively low. Which type of flow meter is recommended?

Coriolis flow meter because it effectively measures flow rates of high viscous liquids at a low pressure drop. Coriolis flow meters are also insensitive to temperature and pressure.

(b) Why is Doppler only recommended for liquids containing suspended solids or gases?

The Doppler sensor transmits sound into the flow stream, which must be reflected back to the sensor to indicate flow velocity. Gas bubbles or suspended solids act as reflectors for the Doppler signal. Doppler flow meters are recommended for liquids containing solids or bubbles with a minimum size of 100 microns and a minimum concentration of 100 ppm.

(c) When would you use Vortex flow meters?

Vortex is mainly used to measure steam flow rates. They are also used to measure gases and liquids with low viscosity that contains hardly any solids.

(d) A conductive liquid is flowing in a pipe (1000 mm size) at the temperature of 430K. Which type of flow meter is recommended to measure the flow rate?

Electromagnetic flow meter is used in this case as it measures flow rates of conductive liquids.

Example 2

Kerosene at 20 deg C flows at 18 m³ / h in a 5 cm diameter pipe. If a 2 cm diameter thin plate orifice with corner taps is installed, what will the measured drop be in Pa? Why is orifice meter used in this case?

Data given: $C_d=0.6030$; $\mu = 192E-3 \text{ kg/ (m s)}$ for kerosene; $\rho = 804 \text{ kg/m}^3$

Solution: Orifice meter is used in this case because Kerosene is a clean and non viscous liquid.

Usually, pipe velocity is calculated using the velocity formula to calculate Re and C_d values. The pipe velocity is:

$$v = \frac{Q}{A} = \frac{\left(\frac{18}{3600}\right)}{\left(\frac{\pi}{4}(0.05)^2\right)} = 2.55 \text{ m/s} ;$$

In this case, we already have the C_d . So, using orifice pressure drop formula, calculate

$$Q = \frac{18}{3600} = 0.6030 \frac{(2\pi)(0.02)^2}{\sqrt{1 - \frac{(0.04)^2}{(0.02)^2}}} \sqrt{\frac{2\Delta p}{804}} = 0.005 \text{ m}^3/\text{h}$$

Final step is to solve for Δp to give 273 kPa.

$$\Delta p = \frac{(0.005)^2 * \left(1 - \frac{(0.04)^2}{(0.02)^2}\right) (804)}{(0.6030)^2 (2\pi)^2 (0.02)^4 (2)} = 273 \text{ kPa}$$

Source : <https://controls.engin.umich.edu/wiki/index.php/FlowSensors>