1 Flow measurement

Flow, defined as volume per unit of time at specified temperature and pressure conditions. The principal classes of flow-measuring instruments used in the process industries are variable-head, variable-area, positive-displacement, and turbine instruments; mass flowmeters; vortex-shedding and ultrasonic flowmeters; magnetic flowmeters; and Coriolis mass flowmeters [1].

Velocity is a measure of speed and direction of an object. When related to fluids it is the rate of flow of fluid particles in a pipe

Laminar flow of a liquid occurs when its average velocity is comparatively low and the fluid particles tend to move smoothly in layers. The velocity of the particles across the liquid takes a parabolic shape.

Turbulent flow occurs when the flow velocity is high and the particles no longer flow smoothly in layers and turbulence or a rolling effect occurs.

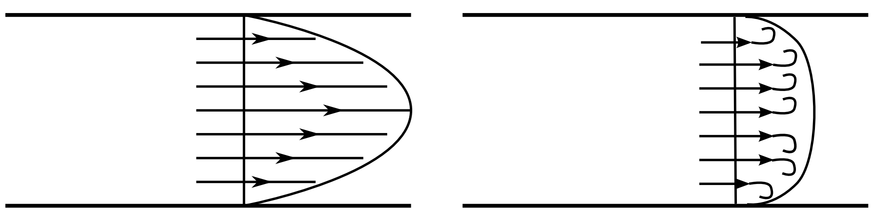

Figure 1: Flow velocity variations across a pipe: Laminar and turbulent flows

Viscosity is a property of a gas or liquid that is a measure of its resistance to motion or flow. A viscous liquid such as syrup has a much higher viscosity than water and water has a higher viscosity than air. Dynamic or absolute viscosity is used in the Reynolds and flow equations. Typically the viscosity of a liquid decreases as temperature increases [2].

Volumetric flow rate represents that volume of fluid which passes through a pipe per unit of time. This form of measurement is most frequently achieved by measuring the velocity of a fluid with a difference pressure sensor as it travels through a pipe of known cross sectional area.

Mass flow is a measure of the actual amount of mass of the fluid that passes some point per unit of time.

Total flow is the volume of liquid flowing over a period of time and is measured in gallons, cubic feet, liters and so forth.

Flow measurements are normally indirect measurements using differential pressures to measure the flow rate. Flow measurements can be divided into the following groups: volumetric flow rate, total flow, and mass flow. The choice of the measuring device will depend on the required accuracy and fluid characteristics.

Volumetric flow is often deduced by knowing the cross sectional area of the fluid.

$$Q = V \cdot A, \tag{1}$$

where Q - flow rate, V - average velocity, and A - cross-sectional area of the pipe.

Mass flow rate can only be calculated from the velocity or the volumetric flow rates if the density is constant.

$$W = Q \cdot \rho, \tag{2}$$

where W - the mass flow rate, Q - volumetric flow rate, ρ - density of the fluid. The flow of gases is normally measured in terms of mass per unit time. While most liquids are nearly in-compressible, densities of gases vary with operating temperature and pressure [2].

1.1 Differential Pressure Flowmeters

One of the most common methods of measuring flow is with a Differential Flowmeter. This technique requires the pressure to be measured on both sides of an imposed restriction in the path of normal flow. The flow rate of the material can be calculated from the change in pressure: the restriction produces an increase in pressure which can be directly related to flow rate.

The relationship between the flow rate and the change in pressure can be shown as:

$$V = k\sqrt{h/\rho}; \tag{3}$$

$$Q = k \cdot A\sqrt{h/\rho}; \tag{4}$$

$$W = k \cdot A\sqrt{h\rho}, \tag{5}$$

where k is the constant and h - height caused by differential pressure.

Orifice Plate

The orifice plate is the most popular primary device found in most process plants. Orifice plates are applicable to all clean fluids, but are not generally applicable to fluids containing solids in suspension(dirty fluids) [3].

Orifice plates that are to handle liquids containing small amounts of dissolved air should contain a small vent hole bored at the top to permit the air to pass through the plate. Specifications have been established for the size of this vent hole in relation to the size of the orifice. Plates for use with steam should have a similar hole drilled at the bottom to drain any condensed steam. In certain flow measurements, the orifice plate should also have a bottom drain hole to permit the condensation to drain.

There are two main types of orifices for various applications:

- Concentric (square edged, quadrant edged);
- Eccentric or segmental square edged;

The sharp edge of the orifice plate must be maintained. If the edge is permitted to become rounded, even slightly, it will cause the meter to become inaccurate [4].

The flow rate Q for a liquid is given by

$$Q = \frac{k \cdot A_2}{\sqrt{1 - (A_2/A_1)^2}} \cdot \sqrt{\frac{2(p_1 - p_2)}{\rho}}, \tag{6}$$

whereA_1 is the pipe cross-sectional area, A_2 - the orifice cross-sectional area.

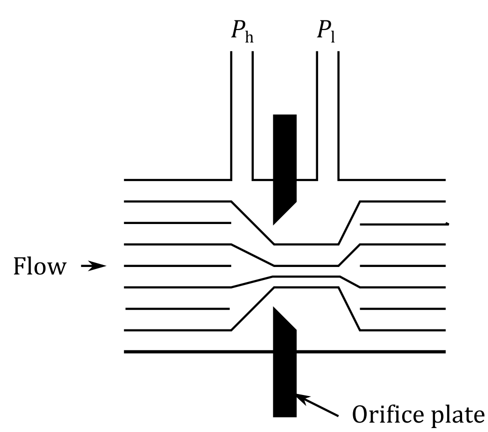

Figure 2: Orifice Plate

Advantages
✓ Easily fitted between flanges.
✓ Suitable for most gases and liquids.
✓ Large range of sizes and opening ratios.
✓ Simple construction, no moving parts.
✓ Inexpensive, does not increase dramatically with size.
✓ Well-known and proven technology, well understood.

Disadvantages
✓ Inaccuracy, typically 1%.
✓ Viscosity limits measuring range.
✓ Cause some unrecoverable pressure loss.
✓ Pipeline must be full (typically for liquids).
✓ Require straight pipe runs to ensure accuracy is maintained.
✓ Erosion and physical damage to the restriction affects measurement accuracy.
✓ Accuracy is affected by density, pressure and viscosity fluctuations.

Venturi Tube

In a venturi tube, the fluid is accelerated through a nozzle shaped inflow piece (converging cone) which induces a local pressure drop. After passing through the cylindrical restriction, it is released through an expanding section (diffuser) where it returns the flow to near its original pressure.

The Venturi Tube is often selected because pressure drop is not as significant as with the orifice plate and accuracy is better maintained.

Due to the relatively high cost of the Venturi Tube, applications are generally limited to high flow rate fluids, such as main steam lines .

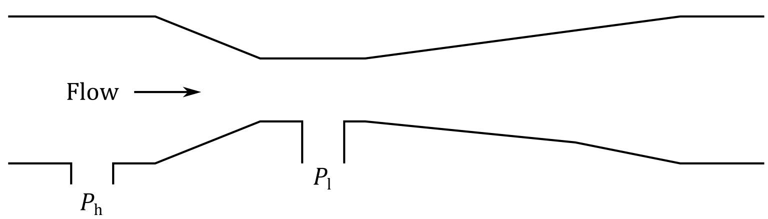

Figure 3: Venturi tube

Advantages
✓ Less significant pressure drop across restriction.
✓ Less significant pressure drop across restriction.
✓ Less significant pressure drop across restriction.

Disadvantages
✓ More expensive.
✓ Requires large section for installation.

Flow Nozzle

The flow nozzle is a good compromise on the cost and accuracy between the orifice plate and the Venturi tube for clean liquids [2]. The flow nozzle is even shorter. Nozzles produce pressure losses of the order of 40 to 60%. Nozzles are cheaper than venturi tubes, give similar pressure differences, and have an accuracy of about ±0.5%. They have the same non-linear relationship between the pressure and the volume rate of flow [4].

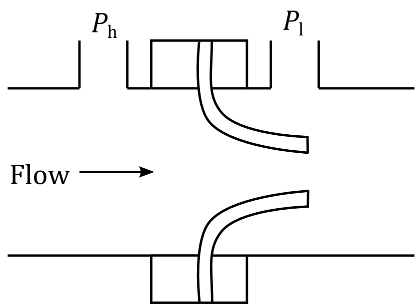

Figure 4: Flow Nozzle

Advantages
✓ High velocity applications.
✓ Operate in higher turbulence.
✓ Physically smaller than the venturi.
✓ Used with fluids containing suspended solids.

Disadvantages
✓ More expensive than orifice plates.
✓ Higher unrecoverable pressure loss.

Elbow can be used as a differential flow meter. When a fluid is flowing, there is a differential pressure between the inside and outside of the elbow due to the change in direction of the fluid.

The pressure difference is proportional to the flow rate of the fluid. The elbow meter is good for handling particulates in solution, with good wear and erosion resistance characteristics but has low sensitivity. The disadvantages are that accuracy will be lacking (typically 5%) and dirty flows can plug the taps.

Primary element

When obstructing the flow using the differential pressure method of sensing, note that they do cause some unrecoverable pressure loss in the line. Differential type instruments that cause a restriction are easily affected by disturbances to inflow and outflow.

Secondary element

The secondary element is a differential pressure transmitter. This device provides the electrical output signal for interfacing to other instrumentation or control equipment. The output from this device is proportional to either the differential pressure or the flow rate.

One of the most common inaccuracies induced in differential pressure flowmeters is not allowing enough straight pipe.

1.2 Variable Area Flowmeters

Variable Area flowmeters work with low viscous liquids at high velocities. The principle of operation is that the flow stream displaces a float placed in the stream. The rate of flow is related to the area produced by forcing the float up or down, and varying the area.

Rotameter

A constant pressure difference is maintained between the main flow and that at the constriction by changing the area of the constriction. The rotameter has a float in a tapered vertical tube with the fluid flow pushing the float upwards. The fluid has to flow through the constriction which is the gap between the float and the walls of the tube and so there is a pressure drop at that point. Since the gap between the float and the tube walls increases as the float moves upwards, the pressure drop decreases. The float moves up the tube until the fluid pressure is just sufficient to balance the weight of the float. The greater the flow rate the greater the pressure difference for a particular gap and so the higher up the tube the float moves. A scale alongside the tube can thus be calibrated to read directly the flow rate corresponding to a particular height of the float [5].

The inside of the measuring tube is conical and has guide strips for the float. For physical indication, there is a scale on the outside to indicate the flowrate. Metal versions are available that have a means of transmitting the float position.

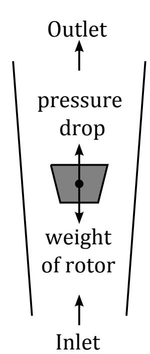

Figure 5: Rotameter

Advantages
✓ Inexpensive.
✓ Very basic operation.
✓ Wide range of applications.
✓ Easy installation and simple to replace.

Disadvantages
✓ Limited accuracy.
✓ Erosion of device (wear and tear).
✓ Operates in vertical position only.
✓ Depends on density, viscosity and temperature.
✓ Can be expensive for large diameters.
✓ Fluid must be clean, no solids content, high viscosity.

1.3 Oscillatory Flow Measurement

Oscillatory flow equipment generally measures the velocity of flow (hence they are often referred to as velocity flowmeters) and the volumetric flow rate is calculated.

The primary device generates a signal that is proportional to fluid velocity. This eliminates the errors that are amplified in square root calculations.

Vortex Flowmeter

As the liquid passes around the obstruction, the stream cannot follow the sharp contours and becomes separated from the body. These vortices are rotational flow zones that form alternately on each side of the element with a frequency proportional to the liquid flow rate. Differential pressure changes occur as the vortices are formed and shed. This pressure variation is used to actuate the sealed sensor at a frequency proportional to vortex shedding.

Thus, a train of vortices generates an alternating voltage output with a frequency identical to the frequency of vortex shedding. This frequency is proportional to the flow velocity.

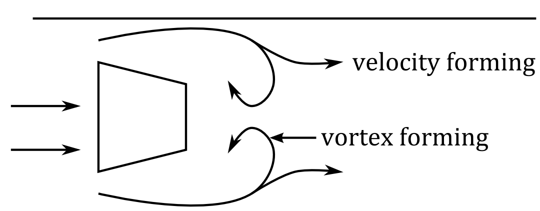

Figure 6: Vortex

The output of a vortex flowmeter depends on the K-factor. The K-factor relates to the frequency of generated vortices to the fluid velocity.

$$V = \frac{f_{\text{vortex}}}{K_{\text{factor}}}$$

Advantages
✓ Suitable for liquid, gas or steam.
✓ Used with non-conductive fluids.
✓ No moving parts, low maintenance.
✓ Low installation cost.
✓ Good accuracy, linear response.
✓ Not affected by viscosity, density, pressure or temperature.

Disadvantages
✓ Uni-directional measurement only.
✓ Clean fluids only.
✓ Not suitable for viscous liquids.
✓ Large unrecoverable pressure drop.
✓ Straight pipe runs required for installation.

Turbine Flowmeter

Turbine meters have rotor-mounted blades that rotate when a fluid pushes against them. They work on the reverse concept to a propeller system. The rotational speed of the turbine is proportional to the velocity of the fluid.

Different methods are used to convey rotational speed information. The usual method is by electrical means where a magnetic pick-up or inductive proximity switch detects the rotor blades as they turn. As each blade tip on the rotor passes the coil it changes the flux and produces a pulse. Pulse rate is directly proportional to the flowrate.

Turbine meters require a good laminar flow. They are not accurate with swirling flows. They are not recommended for use with high viscosity fluids due to the high friction of the fluid which causes excessive losses as the turbine becomes too much of an obstruction. The viscosity of the liquid must be known for use of this type of meter [2].

Advantages
✓ High accuracy, repeatability.
✓ Very high-pressure capability.
✓ Suitable for non-conductive liquids.
✓ Suitable for very low flow rates.
✓ Temperature range of fluid measurement: -220^oC to $+350^oC$.

Disadvantages
✓ Viscosity must be known.
✓ Not effective with swirling fluids.
✓ Not suitable for viscous liquids.
✓ Only suitable for clean liquids and gases.
✓ Specifications critical for measuring range and viscosity.
✓ Pipe system must not vibrate.

1.4 Magnetic Flowmeters

The principle behind these flowmeters is Faraday's law of electromagnetic inductance. The magnitude of the voltage induced in a conductive medium moving at right angles through a magnetic field is directly proportional to the product of the magnetic flux density, the velocity of the medium, and the path length between the probes.

Typical applications include metering viscous fluids, slurries, or highly corrosive chemicals.

Because magmeters should be filled with fluid, the preferred installation is in vertical lines with flow going upward. However, magmeters can be used in tight piping schemes where it is impractical to have long pipe runs, typically requiring lengths equivalent to five or more pipe diameters.

Advantages

✓ No restrictions to flow.
✓ No pressure loss.
✓ No moving parts.
✓ Good accuracy.
✓ Bi-directional.
✓ Independent of viscosity, density, pressure and turbulence.

Disadvantages

✓ Expensive.
✓ Limited to conductive liquids.

1.5 Positive Displacement

Positive displacement meters measure flow rate by repeatedly passing a known quantity of fluid from the high to low pressure side of the device in a pipe. The number of times the known quantity is passed gives information about the totalized flow.

Rotary vane, lobed impeller, oval gear meters (see Fig.7).

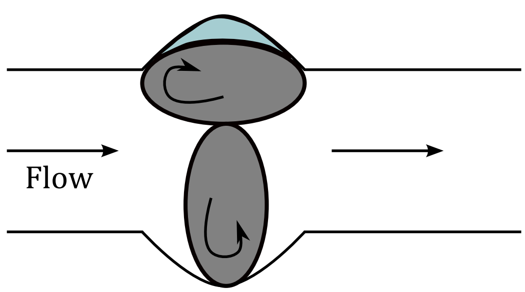

Figure 7: Oval Gear

Advantages
✓ Very high accuracy.
✓ Unaffected by viscosity.
✓ High rates and temperatures.
✓ Can measure non-conductive fluids.

Disadvantages
✓ Expensive.
✓ Some unrecoverable pressure loss.
✓ Limited operating range.
✓ Clean fluids only, limited life due to wear.
✓ Requires viscous fluid, not suitable for gas.
✓ Mechanical failure likely to cause blockage in pipe.

1.6 Ultrasonic

An ultrasonic flowmeter is based upon the variable time delays of received sound waves which arise when a flowing liquid's rate of flow is varied [1].

Two techniques:

- In the first technique two opposing transducers are inserted in a pipe so that one transducer is downstream from the other. These transducers are then used to measure the difference between the velocity at which the sound travels with the direction of flow and the velocity at which it travels against the direction of flow. The differential velocity is measured either by (1) direct time delays using sound wave burst or (2) frequency shifts derived from beat-together, continuous signals. The frequency measurement technique is usually preferred because of its simplicity and independence of the liquid static velocity. A relatively clean liquid is required to preserve the uniqueness of the measurement path.

- Flowing liquid must contain scatters in the form of particles or bubbles which will reflect the sound waves. These scatters should be traveling at the velocity of the liquid. A Doppler method is applied by transmitting sound waves along the flow path and measuring the frequency shift in the returned signal from the scatters in the process fluid. This frequency shift is proportional to liquid velocity.

Advantages
✓ Suitable for large diameter pipes.
✓ No obstructions, no pressure loss.
✓ No moving parts, long operating life.
✓ Not affected by fluid properties.

Disadvantages
✓ Expensive.
✓ Pipeline must be full.
✓ Errors cause by build up in pipe.
✓Fluid must be acoustically transparent.
✓ Only possible in limited applications.

1.7 Coriolis Mass Flowmeters

The Coriolis flowmeter consists basically of a C-shaped pipe through which the fluid flows. The pipe, and fluid in the pipe, is given an angular acceleration by being set into vibration, this being done by means of a magnet mounted in a coil on the end of a tuning fork-like leaf spring. Oscillations of the spring then set the C-tube into oscillation. The result is an angular velocity that alternates in direction. At some instant the Coriolis force acting on a fluid in the upper limb is in one direction and in the lower limb in the opposite direction, this being because the velocity of the fluid is in opposite directions in the upper and lower limbs. The resulting Coriolis forces on the fluid in the two limbs are thus in opposite directions and cause the limbs of the C to become displaced. When the direction of the angular velocity is reversed then the forces reverse in direction and the limbs become displaced in the opposite direction. These displacements are proportional to the mass flow rate of fluid through the tube. The displacements are monitored by means of optical sensors, their outputs being a pulse with a width proportional to the mass flow rate. The flow meter can be used for liquids or gases and has an accuracy of $\pm0.5\%$. It is unaffected by changes in temperature or pressure [6].

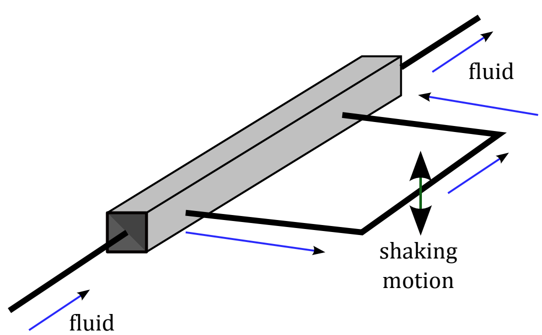

Figure 8: Coriolis

The meter should be installed so that it will remain full of fluid, with the best installation in a vertical pipe with flow going upward. There is no Reynolds number limitation with this meter, and it is quite insensitive to velocity profile distortions and swirl, hence there is no requirement for straight piping upstream.

Advantages
✓ Suitable for large diameter pipes.
✓ No obstructions, no pressure loss.
✓ No moving parts, long operating life.
✓ Not affected by fluid properties.

Disadvantages
✓ Expensive.
✓ Pipeline must be full.
✓ Errors cause by build up in pipe.
✓Fluid must be acoustically transparent.
✓ Only possible in limited applications.

Unfortunately, there is no best flowmeter. Factors such as accuracy, pressure loss, material to be measured, ease of changing capacity, and ease of installation along with cost must be carefully considered. Once the details of the problem have been gathered and the possible alternatives considered, the best selection will usually be clear. Some of the systems described read correctly to within a few percent. Some are considerably better. All should have good repeatability--important criterion for control [3].

Table 1: Flow meter selection criteria [2]

Meter type	Accuracy	Pipe size	Comments
Orifice plate	$\pm 1-5\%$ FSD	$> 12\ mm$	Low cost and accuracy
Venturi tube	$\pm 1\%$ FSD	$> 50\ mm$	High cost, good accuracy, low losses
Flow nozzle	$\pm 2\%$ FSD		Medium cost, accuracy
Elbow	$\pm 6-10\%$ FSD		Low cost, losses, sensitivity
Rotameter	$\pm 2\%$ of rate	$6 \ldots 50\ mm$	Low losses, line of sight
Turbine meter	$\pm 0.25\%$ FSD	$12 \ldots 750\ mm$	High accuracy, low losses
Electromagnetic	$\pm 0.5\%$ of rate	$4 \ldots 1500\ mm$	Conductive fluid, low losses, high cost
Vortex meter	$\pm 0.5\%$ of rate	$25 \ldots 200\ mm$	Poor at low flow rates
Strain gauge	$\pm 2\%$ FSD		Low cost, accuracy
Coriolis	$\pm 0.15\%$ FSD	$6 \ldots 75\ mm$	Not cheap, Accuracy
Oval gear	$\pm 0.35\%$ FSD	$4 \ldots 100\ mm$	Pulsations, Accuracy

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