

FLOW MEASUREMENT IN CLOSED CONDUITS

R. A. Chantler

Mechanical and Electrical Design, Department of Water Affairs and Forestry, Pretoria, South Africa

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Summary

The measurement of flow in a pipeline or other closed conduit by means of various types of flow meters is described from both an analytical and a practical point of view. The various principles of flow measurement, by both indirect and direct means, are treated. A number of flow meters are described, with their operating principles and applications or restrictions. Flow meter selection, installation and calibration are also addressed.

1. Introduction

Flow measurement is one of the most important variables that needs to be measured in industry, water distribution and sewage treatment. Due to the large variation in fluid properties and flow applications, many types of flow meters have been developed, each suited to a particular purpose.

Not one type of flow meter exists that can be used for all applications. Of the numerous flow metering techniques that have been proposed in the past, only a few have found widespread practical application. The design engineer will have to choose between a number of acceptable alternatives for each installation and will have to consider many different parameters, the more important of which are the following:

- initial capital outlay and operating cost;
- maintenance cost and maintainability;

- accuracy and reliability; and
- energy loss and range-ability.

In this article, the whole range of readily available industrial meters are covered and the principles upon which they operate are discussed together with advantages and disadvantages with reference to the above parameters.

2. Categories of Flow Meters and Important Definitions

Although a large number of physical principles have been used to measure flow, flow meters can be divided into two main categories: meters that measure quantity, and meters that measure rate of flow (from which quantity can be inferred). Quantity is measured volumetrically, or by mass; and rate of flow is either directly measured by velocity-area integration, or indirectly deduced from measurement of a pressure differential (see *Flow Measuring Techniques*).

2.1 Accuracy

Accuracy is defined as the percentage deviation of the indicated from the actual, but is often confused with terms such as linearity, repeatability or calibration factor. Accuracy is generally stated by the flow meter manufacturer as the percentage deviation of its indication from the value of the flow at the full-scale reading. If the accuracy of a meter whose full flow reading is one hundred liters per second is quoted as $\pm 1\%$, then at ten liters per second, the accuracy may only be $\pm 10\%$.

2.2 Repeatability

Repeatability is a more important criterion, since by *in-situ* calibration a meter with excellent repeatability can imply a high degree of confidence at the quoted accuracy.

2.3 Linearity

By linearity is meant the relationship between the input signal (as plotted on the X-axis) and the output signal (plotted on the Y-axis). If the graph is a straight line it is linear, if curved it is nonlinear. Some types of meters give a nonlinear output, e.g., pressure differential type meters such as rotameters, Venturi and orifice-plate meters; others have linear outputs such as positive displacement, turbine, electromagnetic and ultrasound flow meters, which is preferable for accurately measuring low flows.

2.4 Calibration Factor

Meters that are calibrated by the manufacturer under ideal conditions rarely can be expected to perform in an actual installation exactly as calibrated. A calibration factor has often to be applied to the output values to correct for this discrepancy. It may be of the order of $\pm 0.5\text{--}1\%$. The calibration factor may be determined by comparison with another calibrated meter installed in line with the meter in question, or by some other means, such as a volumetric test.

3. Types of Flow Meters

There are two types of flow meters for measuring quantity or rate of flow. Quantity may be measured by volumetric meters, also known as positive displacement meters, which give an output in terms of liters, kiloliters or cubic meters delivered. These are the type of meter found in domestic or industrial water supply applications. The other type of meter measuring rate of flow is used where the exact quantity delivered is not as important as the discharge or flow rate. This type of flow meter is generally used in bulk water supply applications, pumping stations and water treatment plant.

3.1 Volumetric Meters: Positive Displacement Meters

Positive displacement meters are the most common volumetric meters used in industry. They are available in many configurations but all operate on the same principle: the meter traps and tallies a known quantity of fluid passing through it from its input to its output. A typical positive displacement meter is shown in Figure 1. The meter intercepts the full flow in the pipeline. A sealed rotor traps a known volume of fluid as it is being rotated by the moving fluid. The rotation of the rotor then gives a direct indication of the quantity of fluid passing through.

A positive displacement meter hence subdivides the flow per revolution into a certain number of “packets” of known volume. By tallying the number of revolutions, the quantity of fluid is obtainable from the meter’s revolution counter.

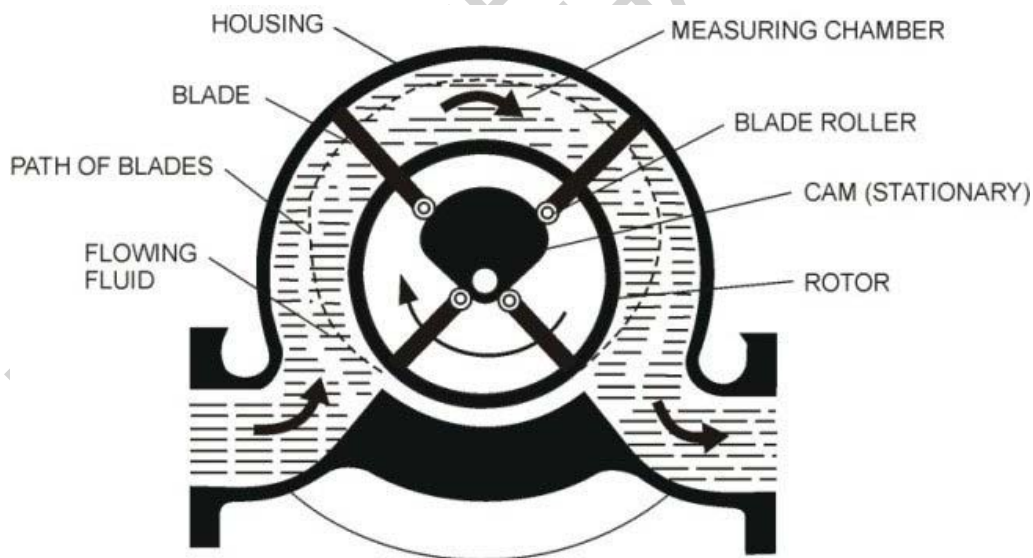


Figure 1. A typical positive-displacement flow meter

Positive displacement meters can be very accurate, typically $\pm 0.25\%$ of flow over a 10:1 range. They possess good repeatability ($\pm 0.05\%$) and range-ability if operated correctly. They are suitable for high viscosity fluids, but since they rely on close mechanical tolerances, they are limited to applications in which the fluid is clean. The presence of any particles would rapidly produce wear at the mechanical seals and degrade the meter’s performance. The cost of positive displacement meters is high since

they are precision instruments and require regular maintenance. A substantial pressure loss also is caused by the meter. As a result of these features, positive displacement meters are used mainly when high accuracy is required such as the custody transfer of oil and are not used in the water industry except for treated domestic water metering and for supporting functions such as chemical dosing and fuel flow measurements.

3.2 Rate-of-Flow Meters

Nearly all the water flow meters at in use at the beginning of the twenty-first century, measure the discharge i.e., rate at which a fluid (water) is flowing. The total quantity of fluid that has passed within any particular time interval can then be obtained by integrating the rate of flow over that time interval. Rate-of-flow meters are thus also being used as quantity meters. A description of the most common rate of flow meters follows.

4. Differential Pressure Meters: Principles of Operation

In order to understand the operation of differential pressure flow meters, use is made of Bernoulli's equation, named in honor of Daniel Bernoulli, a Swiss mathematician who published one of the first books on fluid flow in 1738. In its simplest form, the equation states that for a fluid of constant density (incompressible) and zero viscosity under steady flow, the total energy per unit mass is constant along any streamline (see *Fluid Mechanics*).

$$\frac{P}{\rho} + \frac{1}{2}v^2 + gz = \text{CONSTANT} \quad (1)$$

where

- P = the pressure at a point
- v = the velocity at that point
- ρ = the fluid density
- g = the acceleration due to gravity
- z = the elevation of the point above an arbitrary horizontal reference plane

The second term, $(\frac{1}{2}v^2)$, is readily recognized to be the kinetic energy per unit mass of fluid. Similarly the third term, (gz) , corresponds to the potential energy given to unit mass of fluid by raising it from the datum level to the height z . This can be considered to be the gravitational energy per unit mass of the fluid. The first term, (P/ρ) represents the ability of a unit mass of fluid to do work by virtue of its pressure energy.

Bernoulli's equation is thus interpreted to mean that the total energy per unit mass of fluid (pressure + kinetic + gravitational) remains constant along a streamline for any ideal fluid.

To illustrate how Bernoulli's equation can be applied to flow measurement, consider the pipe shown in Figure 2, which also indicates the principle of operation of a Venturi

meter. The pipe rapidly converges from its nominal size to a smaller size, followed by a short parallel-sided throat section, before slowly expanding to its full size again.

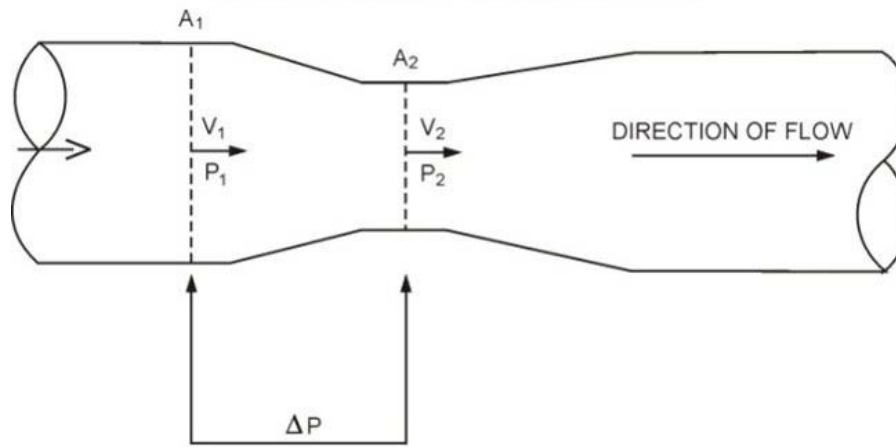


Figure 2. Venturi meter

Assuming that the flow velocity and pressure are uniformly distributed over the conduit cross-sections at points 1 and 2, for a reference plane passing through the center of the pipe, i.e., $z = 0$, the following equation is obtained:

$$(P/\rho)_1 + (1/2v^2)_1 = (P/\rho)_2 + (1/2v^2)_2 \quad (2)$$

From the equation of continuity for an incompressible fluid the discharge, i.e., volumetric flow rate, Q , must be constant. Hence:

$$Q = V_1 A_1 = V_2 A_2 \quad (3)$$

where A_1 and A_2 are the cross-sectional areas of the pipe at points 1 and 2, respectively. Combining the above two equations yields the following expression for the velocity at point 1:

$$V_1 = \sqrt{\left\{ \frac{(2\Delta p / \rho)}{(Ar^2 - 1)} \right\}} \quad (4)$$

where $\Delta p = P_1 - P_2$ and $Ar. = A_1/A_2$

i.e., by simplification, if the area ratio A_1/A_2 is large, the following is obtained:

$$V_1 \propto \sqrt{P_1 - P_2} \quad (5)$$

where \propto denotes “is proportional to.”

By measuring the difference in pressure Δp at points 1 and 2, and assuming the fluid density is constant, the flow velocity can be obtained, knowing the area ratios between the conduit and the throat of the flow meter. This forms the basis of all differential pressure flow meters. The discharge or flow rate is then simply the conduit flow velocity times the conduit area.

A simplified explanation for the operation of these flow meters is that as the fluid enters a constriction, it accelerates, thereby, increasing its kinetic energy. Since the total energy is constant, a reduction in pressure occurs. This results in a differential pressure being established across the constriction and the velocity is proportional to the square root of this pressure differential.

4.1 Fixed Area Meters: Venturi and Orifice Meters

The type of meter shown in Figure 2, known as a Venturi meter, was developed by Giovanni Venturi as early as 1797. Venturi meters, in general, are large, and therefore, expensive and this has led to the development of the more compact orifice plate flow meter, which is still the flow meter most widely in use. It consists of an orifice plate inserted between flanges as shown in Figure 3. The difference in pressure across the plate again is proportional to the square of the flow velocity, and can be used to measure flow rate. Although the cost of an orifice plate meter is far lower than that of a Venturi meter, the energy loss it produces is far greater. For a Venturi meter the pressure loss is 5–20% of the differential pressure, and for an orifice plate meter about five times greater.

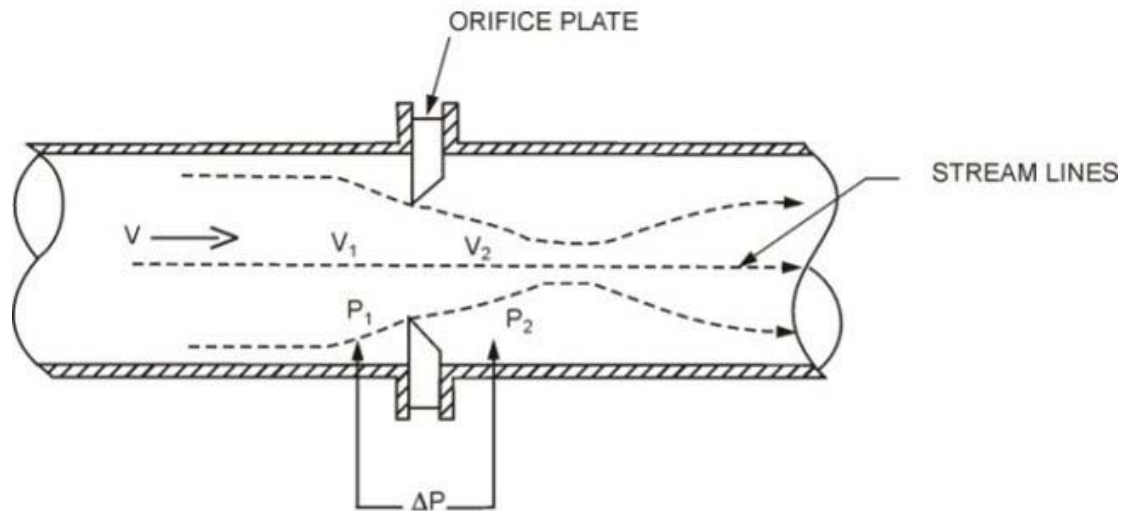


Figure 3. Orifice plate flow meter

The nonlinear, square-root relationship between flow and pressure difference is a severe limitation and results in limited range-ability of Venturi and orifice plate meters. Accuracy in the latter depends on how precisely the orifice plate has been mounted within the pipe as well as on the sharpness of the edge of the orifice. If erosion takes place due to solid particles in suspension, accuracy deteriorates rapidly. Under correct

conditions of operation, an accuracy of $\pm 1.5\%$ of the full scale flow can be obtained. Advantages of the orifice plate meter are that it has no moving parts, is suitable for clean liquids and has a price which is independent of pipe size.

The orifice plate does not constitute a flow meter by itself since a device capable of measuring the differential pressure created by it is required. Great advances have recently been made to improve the performance of these devices. The older instruments used a mercury-filled U-tube with some mechanical linkage to an indicator, chart or integrator. The modern method employs diaphragm-operated differential pressure cells, utilizing strain gauges for sensing the diaphragm deflection, and electrical or electronic circuits for the indication, recording and integrating functions.

In attempts to reduce the energy losses of orifice plates, as well as to avoid the need for accurately machined edges, and without going to the cost of a Venturi tube, various proprietary nozzles have been developed such as a short-form and an insert-type Venturi tube, and the Dall flow tube. The theory for these is identical to that for orifice plate flow meters.

4.2 Variable Area Meters: Rotameters

Variable area flow meters—also called rotameters—utilize the same principle as differential pressure meters, i.e., the relationship between kinetic energy and pressure energy. In differential pressure devices, the size of restriction is fixed and the differential pressure changes with flow rate, while in the variable area meter, the area of restriction changes as the flow rate changes, but the pressure differential remains constant (being equal to the weight of the floater divided by its area).

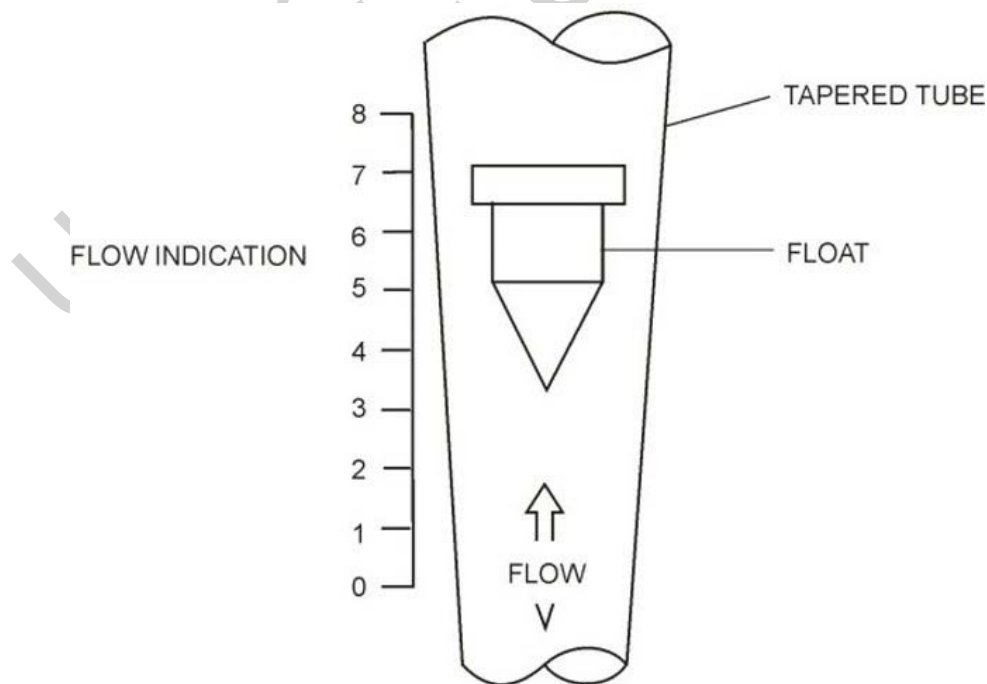


Figure 4. Variable-area flow meter (rotameter)

A variable-area flow meter consists of a vertical, tapered tube containing a suspended floater as shown in Figure 4. The floater has the same diameter as the tube interior at its base. The tube tapers outward upwards, so that it is larger in internal diameter at the top than at the base. Fluid flows through the tube from bottom to top, carrying the floater upwards. As the floater rises, the annular space between tube and floater increases until the lifting force produced by the differential pressure across the floater equals the submerged weight of the floater. The tube is calibrated to indicate the flow rate from the position at which the floater is in equilibrium.

Although usually not capable of high accuracy (typically $\pm 2\%$ full scale over a 10:1 range), variable-area meters are cheap, simple, require no external power supply and are suitable for registering very low flow rates.

5. Direct-Reading Types of Flow Meters

There are a number of types of flow meters that have the advantage of giving a direct reading of flow rate based on the measurement of velocity rather than pressure differential. As these meters, therefore, have a linear calibration, the implication is that the accuracy of measuring low flows is as good as that of high flows.

The following types of direct reading flow meters will be discussed, firstly a purely mechanical type: the turbine meter, and then the electromagnetic, the vortex shedding and the various acoustic types. The latter are the ultrasonic and the Doppler types of flow meters.

5.1 Turbine Meters

A turbine meter consists of a bladed rotor suspended in a fluid stream with its axis of rotation perpendicular to the flow direction as shown in Figure 5. The rotor is driven by the fluid impinging on the blades and its angular velocity is directly proportional to the flow rate.

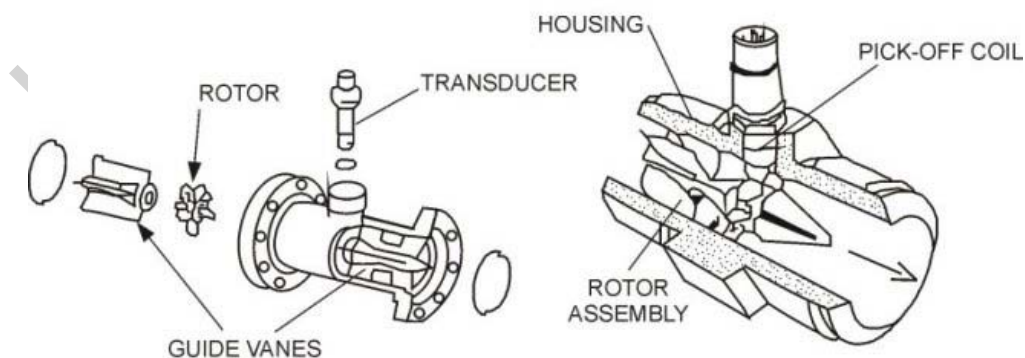


Figure 5. Turbine flow meter

Various methods are possible for measuring the speed of rotation of the rotor. One method consists of a pick-up coil mounted on the outside of the meter body. The coil has a magnet and magnetic field and the rotor blades have tips made of ferrous material.

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Biographical Sketch

Ron Chantler holds the degrees B.Sc. (Hons.) Mechanical Engineering (Manchester) and Electrical Engineering (University of the Witwatersrand, Johannesburg), and is a Chartered Engineer (UK) and Professional Engineer (RSA). His professional experience includes five years as Design Engineer on Nuclear Power Plants in the UK, and thirty five years as Professional Engineer (Mechanical and Electrical) with the Department of Water Affairs, South Africa. Publications include the proceedings of a Conference on Early Flood Warning Measures, Reports on Flow Metering, and Guidelines for Equipping Dams with Flood Gates.