Measurement of Flow Rate

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This review covers common instrumentation and techniques that are used to measure bulk flow rates, namely the amounts of fluids that pass through a certain cross section of a pipe, duct, channel or other flow conduit per unit time. Bulk flow measurement is not concerned with local velocity variations across the cross section, neither short-time (e.g. turbulent) fluctuations. Measured flow rates can be either mass flow rates \( m \), or, when dealing with liquids or low-speed gases, volume flow rates \( Q \). Flow rate measurement is an essential activity in a variety of industries and utility services, but it is also employed regularly in the fluid mechanics laboratory, notably in the important role of monitoring and controlling the experimental conditions. The operation of flow rate measurement systems is based on diverse physical principles; with some exceptions, such systems require calibration or empirical corrections. The following presentation is mainly concerned with bulk flow measurement in “simple” flows, which are single-phase and either steady or very slowly varying. Some of these methods can be extended to flows of multi-phase fluids, slurries and granular materials, but the reader is advised to consult specialized manufacturers and references when dealing with such media. More details on general methods for the measurement of flow rate and specific instruments can be found in several monographs and books [2, 4, 9, 10, 11], handbooks [15, 12, 6, 13] and manufacturer’s catalogs (e.g. [7]).

1 Direct methods

The simplest flow rate measurement methods are direct, which means that they measure a typical flow velocity or the amount of discharged fluid over a period of time. Such methods are more suitable for liquid than gas flows. For example, one may obtain a rough measurement of the bulk velocity of flows in water tunnels and open channels by timing the motion of suspended or floating objects. For flows of non-volatile liquids in an open-loop configuration, the volume flow rate can be measured by timing the filling of a container by the discharge of the apparatus; similarly, the mass flow rate can be measured by weighing the discharged fluid. In such cases, one must take care that discharging of fluid has no appreciable effect on the operation of the system, as for example would be the case if removal of liquid from the loop resulted in lowering the head of a feeding tank or shifting the operating point of a pump. Direct flow rate
measurement methods, applicable to liquid and gas flows in both open- and closed-loop configurations, include the use of positive displacement flow meters, to be discussed in the next section.

2 Positive displacement flow meters

*Positive displacement* (PD) flow meters are devices which isolate fixed volumes of the fluid flowing into their inlet in sealed compartments and then discharge them to the outlet. Neglecting leakage and other possible deficiencies, one can easily compute the volume flow rate from the size and number of compartments in the device and the measured rate of repetition of the cycle of their operation. In many cases, the same instruments can be configured to measure the total volume of fluid that passes through them over a time interval, and, for this reason, PD meters are commonly used to monitor the consumption of water, natural gas and hydrocarbon fuels. PD meters may be operating passively, receiving power from the flowing fluid, or driven by an external source to create the fluid motion, in which case they are called *metering pumps*. There is a great variety of designs of PD meters, most of which can be classified as rotary, reciprocating or nutating. The important parameters for their operation are the leakage and the pressure loss across them. Sealing relies on capillary action in narrow gaps between meshing parts, thus leakage depends on the speed of operation, the viscosity of the fluid and the wear of the moving components and the housing. To minimize leakage, the components are manufactured under small tolerances and the clearances between meshing parts are kept low; this necessitates the use of clean fluids, and in most cases the meter is accompanied by a filter. PD meters are suitable for fluids with relatively wide ranges of viscosity. Increasing viscosity improves the sealing action but also increases pressure losses, which have to be maintained as low as possible in order to avoid significant loading of the fluid system. Temperature variation affects the operation of PD meters in two ways: by affecting the viscosity of the fluid, with implications on leakage and pressure loss, and by affecting the density of the fluid, which is of concern when converting volume flow rate to mass flow rate. Manufacturers would normally provide charts describing the operation characteristics of each model, such as the pressure loss for different flow rates and fluid viscosities as well as correction factors and uncertainties at different speeds. A few representative designs of PD meters are discussed below [2, 13, 9, 15, 1, 3].

2.0.1 PD flow meters for liquids:

**Nutting disk meters:** The main element of these meters is a disk which is rotating in a nutating (precessing, wobbling) fashion, while both its sides are partially in contact with a dual conical housing (Fig. 1a). Fluid enters through the inlet port facing one side of the disk during half of the cycle, in isolation from the outlet port; it is then swept by the precessing motion of the disk to the outlet during the following half of the cycle, while being in isolation from
Reciprocating piston flow meters: These meters contain a number of plungers or pistons, driven by a wobble plate and sweeping the volumes of corresponding cylinders, while at the same time opening and closing input and output ports or valves (Fig. 1b).

Rotary piston flow meters: These meters contain a cylindrical drum, which is mounted eccentrically inside a cylindrical housing and rotates with its outer surface in contact with the housing, while its inner surface maintains contact with an inner cylinder, coaxial with the housing (Fig. 1c).

Rotary vane flow meters: Flat vanes are inserted into matching slots around the perimeter of a rotating cylindrical drum, located eccentrically within
the housing. Centrifugal action or springs cause the vanes to slide out of the slots until they come into contact with the housing, thus isolating a volume of the flowing fluid and transporting it from the inlet towards the outlet (Fig. 1d).

**Rotor meters:** These meters contain rotating meshing elements of different shapes, including oval gears (Fig. 1e), circular gears, helical gears and lobes. The *rotary abutment meters* contain both specially shaped rotors and rotating vanes. In these devices, fluid is trapped in the space between the rotating elements or between an element and the housing and is pushed towards the outlet in isolation from the input.

**PD flow meters for gases:**

**Roots-type flow meters:** This is a trademark name that describes a particular design of a lobe meter (Fig. 1f), developed for use with gases.

**Diaphragm-type flow meters:** These meters are commonly used in domestic gas lines. They contain bellows that fill-up with gas during part of the cycle and discharge it to the outlet during a subsequent part; the gas flow from the inlet to the outlet is controlled by sliding valves and the motion of the bellows is linked to a mechanism that counts the cycles.

**Liquid-sealed drum-type flow meters:** Also known as *wet gas meters*, these devices consist of a hollow drum rotating within a cylinder partly filled with a liquid, which provides the sealing action.

### 3 Venturi, nozzle and orifice-plate flow meters

Also known as *restriction* or *obstruction flow meters*, these are devices that force the flow through a restriction, thus increasing its velocity and decreasing its pressure. The flow rate is estimated from a measured pressure difference and an empirical correction coefficient. In order to describe the idealized response of these devices, consider steady, uniform, inviscid, incompressible flow, in the absence of body forces, flowing within a circular tube with a diameter $D$ and guided to a restriction with a diameter $d$. Then, one may use continuity and Bernoulli’s equation to relate the ideal volume flow rate $Q_{id}$ to the pressure drop $\Delta p$ between the two cross-sections as

$$Q_{id} = \frac{\pi D^2/4}{\sqrt{1 - (d/D)^4}} \sqrt[4]{\frac{2\Delta p}{\rho}}$$  \hspace{1cm} (1)
To account for deviations from the idealized behaviour, one may introduce an empirical discharge coefficient $C_d$ to compute the actual volume flow rate as

$$Q = \frac{\pi D^2/4}{\sqrt{1 - (d/D)^4}} \sqrt{\frac{2\Delta p}{\rho}}$$

(2)

The value of $C_d$ depends mainly on the geometry of the apparatus and the Reynolds number, with $0 < C_d < 1$. For Reynolds numbers sufficiently large for the flow to be in the fully turbulent regime, $C_d$ becomes insensitive to Reynolds number and depends only on the shape of the device. It is desirable to keep its value as large as possible, in order to reduce the permanent pressure loss in the flow meter. On the other hand, large values of the discharge coefficient may only be achieved with carefully shaped and relatively long devices, which tend to be bulkier and more expensive than devices with lower $C_d$. Common low-loss restriction flow meters are the Venturi tubes (Fig. 2a,b) and the Dall tubes (Fig. 2c), while relatively high-loss meters include flow nozzles (Fig. 2d) and orifice plates (Fig. 2e). The designs of such devices are regulated by various standards (e.g. ISO and ASME standards), so that they may be used interchangeably and without the need for individual calibration. A limitation of obstruction flow meters is their relatively narrow dynamic range, which is a result of the non-linearity in the $Q - \Delta p$ relationship. Thus, the sensitivity of these flow meters decreases rapidly as the flow rate drops below about 25% of the full-scale value.
4 Open channel flow measurement

The volume or mass flow rate of liquids in open channels or partially filled pipes and ducts is often measured with the use of direct methods (see section 1). Another common approach is the use of flow restrictions, including weirs and Venturi flumes [9, 16, 8, 5, 12].

Weirs consist of obstructions positioned across the channel and over which the liquid is forced to flow. There are several types of weirs, both sharp-crested and broad-crested, with rectangular, V-shaped or trapezoidal openings (Fig. 2f). The most common type used in fluid mechanics and hydraulics laboratories is the sharp-crested, V-notch weir. An approximate expression for the flow rate over such weirs is [5]

\[ Q \approx 2.5 \tan \left( \frac{\theta}{2} \right) H^{5/2} \]  

where \( \theta \) is the full angle of the notch (usually equal to 90°) and \( H \) is the easily measurable head of the liquid above the weir, namely the vertical distance between the free surface and the lowest point in the weir opening.

Venturi flumes are converging-diverging channel constrictions, analogous to Venturi tubes used in pipes flows. They generally have low pressure losses and are available in several different designs, including flumes with rectangular, trapezoidal and U-shape cross sections; commonly used designs for sewage and irrigation flows are the Parshall and Palmer-Bowlus flumes. Their advantages over weirs is that they do not cause a water back-up and are less likely to be affected by deposited solids that may be transported by the water.

5 Averaging Pitot tubes

These instruments consist of a tube spanning the cross-section of the pipe and having multiple frontal openings such that it measures a total pressure roughly averaged over the cross section (Fig. 3a); they also have a second tube, facing backwards and monitoring the local static pressure. The volume flow rate is estimated from the pressure difference \( \Delta p \) as

\[ Q = C_d \frac{\pi D^2}{4} \sqrt{\frac{2\Delta p}{\rho}} \]  

where \( C_d \) is an empirical correction coefficient accounting for deviations from the ideal response. Simplicity of operation and low cost are the main advantages of averaging Pitot tube. Their limitations include the need for clean fluid and a narrow dynamic range, extending to only about 30% of full-scale.

6 Laminar flow elements

Laminar flow elements are pipe sections or devices of a larger diameter which contain tube bundles or relatively long honeycombs (Fig. 3b). The fluid is
Figure 3: Sketches of common flowmeters: a) averaging Pitot tube, b) laminar flow elements, c) rotameter, d) vortex shedding flow meter, e) drag flow meter f) turbine flow meter and g) paddlewheel flow meter.

subdivided to pass through these elements, which are sufficiently narrow for the Reynolds number in each element to be lower than the transitional value of about 2300. Thus, the flow in the elements is laminar and the pressure drop across the elements is related to the volume flow rate through the Hagen-Poiseuille expression, which is linear, in contrast with the quadratic expression for turbulent pipe flow. For fully-developed laminar flow in a circular tube of length $l$ and diameter $D$, this expression becomes

$$\Delta p = \frac{128 \mu l}{\pi D Q}$$

Due to their linear response, these flow meters are suitable for very low flow rates. Their disadvantages are large frictional pressure losses and bulkiness. They also tend to be clogged by impurities in the flow.

7 Rotameters

Rotameters, or, more generally, variable area flow meters, are simple and versatile devices that can be used with a wide variety of liquids and gases over wide ranges of flow rates. They consist of a vertical tube, tapered such that its cross section increases linearly upwards and a “float”, which is pushed upwards by the flowing fluid and stops at a position at which the drag, the buoyancy and the weight are in balance (Fig. 3c) [2, 12, 9]. The height of the float is proportional to the flow rate, which is displayed in appropriate units on a scale engraved on the tube. Variable area flow meters are not very sensitive to fluid viscosity and
can be corrected for density variations. They are popular because they require no external power, can be positioned near pipe bends and present relatively low pressure losses. They are fairly accurate, except in the lower end of their scale, typically below 10% of full-scale reading. Different tube and float materials, sizes and shapes are available for different applications. Tubes are commonly made of glass or transparent plastic, but stainless steel variations with magnetic sensing of the float position are also available for corrosive liquids or high temperatures and pressures.

8 Vortex shedding flow meters

The main component of the vortex shedding flow meters [2, 13, 9] is a bluff object immersed in the flowing fluid and spanning the pipe cross section (Fig. 3d). Their operation is based on the periodic shedding of vortices (Kármán vortex street) from the edges of the object; this occurs at a frequency \( f \) (in cycles per second), which is related to the frontal width \( h \) of the object and the flow velocity \( V \). In dimensionless form, the shedding frequency is called the Strouhal number

\[
S = \frac{hf}{V}
\]

(6)

For Reynolds numbers greater than a certain value (typically, about 5000), the Strouhal number maintains an essentially constant value in the range 0.14 to 0.21, depending on the shape of the object and independent of \( V \). The shedding frequency is detected by a variety of means, including piezoelectric pressure transducers, strain gauges, self-heated resistance elements and ultrasonic beams.

9 Drag flow meters

Also referred to as target flow meters, drag flow meters [15, 7] (Fig. 3e) are based on the relationship between the drag force \( F_D \) on an immersed bluff object and the flow velocity. In general,

\[
F_D = \frac{1}{2} C_D \rho A V^2
\]

(7)

where \( C_D \) is the drag coefficient and \( A \) is the frontal area of the object, namely the area of its projection on a plane normal to the flow velocity. \( C_D \) is essentially constant for an object with sharp corners immersed in turbulent flow at sufficiently large Reynolds numbers, typically greater than about 1000. Thus, the volume flow rate through a pipe would be given as

\[
Q = k \sqrt{F_D}
\]

(8)

where \( k \) is a constant. In practice, the target, which is a disk-like object, is inserted in the pipe and mounted on a support instrumented with strain gauges or LVDTs (linear variable differential transformers), which measure the drag
force through deflection. Such instruments are very sensitive and bidirectional and can be used at high pressures and with a variety of fluids. As the target is usually positioned in the centre of the pipe, they do not get easily clogged by suspended impurities.

10 Turbine flow meters

\textit{Turbine flow meters} measure the volume flow rate of fluids in pipes as proportional to the angular velocity of an immersed vaned rotor \cite{9, 12, 7}. A very common type utilizes an axial turbine with its axis aligned with the pipe centre-line (Fig. 3f). The passage of each rotating blade is sensed electromagnetically by an externally mounted sensor and the flow rate is given by

\[ Q = kn \]  

\hspace{1cm} \text{(9)}

where \( n \) is the number of pulses per unit time provided by the sensor and \( k \) is a constant depending on the impeller design and size, the pipe diameter and the number of blades. Turbine flow meters are subject to significant pressure losses and are prone to cavitation, when used with high-speed, low-pressure liquids. A low-cost version, called the \textit{paddlewheel flow meter} (Fig. 3g), utilizes a partially immersed rotor, with its axis normal to the flow direction. Besides flow rate, turbine flow meters may also provide the total fluid volume that passed through over a time interval. The common domestic water meters are of the turbine type.

11 Ultrasonic flow meters

Ultrasonic flow meters \cite{2, 9, 13} utilize high-frequency (typically of the order of 10 MHz) pressure waves to compute the volume flow rate of liquids in pipes. There are two distinct types of such meters: the \textit{Doppler flow meters} and the \textit{time-of-flight flow meters}.

A representative Doppler flow meter consists of two piezoelectric crystals, a transmitter \( T \), which transmits an ultrasonic wave through the pipe, and a receiver \( R \), which receives the ultrasound reflected by solid particles or gas bubbles transported by the flowing fluid (Fig. 4a). The frequency \( f_r \) of the reflected sound is shifted from the frequency \( f_t \) of the transmitted sound by an amount \( \Delta f \), called the \textit{Doppler shift}, which is proportional to the velocity \( V \) of the reflector, as

\[ \Delta f = f_t - f_r = \frac{2f_t \cos \theta}{c}V \]  

\hspace{1cm} \text{(10)}

where \( c \) is the speed of sound. Such devices are calibrated to provide an output that is equal to the average velocity of the fluid in the pipe, assuming that the flow is fully developed. They are non-invasive and can be hand-held or strapped to the outside of a pipe.
A representative time-of-flight flow meter consists of two externally mounted pairs of piezoelectric transducers. Each transmitter emits sound waves towards the corresponding receiver, one of which is located downstream of its mate, while the other is upstream of it (Fig. 4b). Each transmitter emits a sound pulse each time the corresponding receiver receives the previous one. Because sound waves are transported by the flowing fluid, sound propagates faster downstream than upstream and the frequencies of pulsation of the two pairs differ by an amount

$$\Delta f = \frac{2 \cos \theta}{l} V$$

(11)

where $l$ is the distance between the transducers of each pair. This configuration makes the flow measurement independent of the speed of sound and, thus, flow temperature.

### 12 Electromagnetic flow meters

These instruments provide the volume flow rate of electrically conducting liquids in pipes. Their operation is based on *Faraday’s law of electromagnetic induction,*
which states that, when a conductor with length \( l \) moves with speed \( V \) in a direction normal to the direction of a magnetic field with magnetic flux density \( B \), an electric potential \( E \) is generated across it as

\[
E = BLV
\]  

(12)

Practical electromagnetic flow meters [7, 9, 2] consist of an insulated pipe section of the same diameter \( D \) as the pipe of interest, surrounded by an alternating or pulsed magnetic field and having two surface electrodes embedded on the wall across a diameter normal to the magnetic field direction (Fig. 4c). The voltage difference between these electrodes is related to the volume flow rate as

\[
E = \frac{4kB}{\pi D}Q
\]  

(13)

where \( k \) is a numerical coefficient. Electromagnetic flow meters have an accuracy that exceeds 0.5% and are not overly sensitive to the velocity profile. On the other hand, they are bulky, heavy and relatively expensive.

13 Coriolis flow meters

Coriolis flow meters [9, 2, 14, 12] were developed relatively recently, but have become increasingly popular in a variety of industries, due to their versatility and their capacity to measure true mass flow rate, essentially independent of fluid properties and flow conditions. There are several different geometrical designs, all based on the Coriolis force principle. Consider a fluid element with mass \( \delta m \) flowing with velocity \( V \) in a tube that rotates with angular velocity \( \omega \) about an axis normal to its own axis; assume that the fluid element is at a radial distance \( r \) from the axis of rotation and, during time \( \delta t = \delta r/V \), moves away from it to a radial distance \( r + \delta r \). Then, the angular momentum \((\delta m)\omega r^2\) of this fluid element would increase to \((\delta m)\omega (r + \delta r)^2 \approx (\delta m)\omega (r^2 + 2r\delta r)\). This increase of angular momentum is attributed to a torque \( rF_c \), where \( F_c = 2(\delta m)V\omega \) is called the Coriolis force. The direction of the Coriolis force is circumferential and opposite in sense to the direction of rotation, for outward motion. In vectorial notation, the Coriolis force is written as \( \vec{F}_c = 2(\delta m)\vec{V} \times \vec{r} \).

It is also written as \( \vec{F}_c = (\delta m)\vec{a}_c \), where \( \vec{a}_c \) is called the Coriolis acceleration. The flowing fluid receives this force from the tube walls; by reaction, the fluid applies a force upon the containing tube, which is equal in magnitude and direction to the Coriolis force, thus affecting the tube motion.

Practical flow meters do not rotate the tube but set it in vibration at its natural frequency by subjecting it to an alternating magnetic field. As representative of this class of instruments, Fig. 4d shows a sketch of the U-tube Coriolis flow meter. The fluid is passed through a bent tube, whose ends are clamped, while its tip is set to vibration. The instantaneous angular velocity, and therefore the Coriolis force, increase towards the tip. The two legs of the tube receive forces in opposite directions and, thus, the tube is twisted in one
sense during half of the cycle and in the opposite sense during the other half. The twist angle is measured by magnetic or optical position sensors sensing the time delay $\Delta t$ between the passage of the two legs through a transverse plane. This time delay is related to the mass flow rate as

$$\Delta t = \frac{8r_t^2 \cdot \rho}{K_s} m$$

where $r_t$ is the radius of the tube and $K_s$ is a constant that, ideally, depends only on the tube material. Small deviations from this relationship may be caused by multi-phase effects and other variations in fluid properties. Even so, Coriolis flow meters are suitable for conventional as well as contaminated and non-Newtonian fluids.

14 Thermal mass flow meters

*Thermal mass flow meters* are used to measure the mass flow rate of gases. They are not used for liquid flows due to the much higher power required to heat a liquid than a gas. For relatively low mass flow rates, the entire gas stream is passed through the meter, while, at higher flow rates, only part of the gas is heated by passing it through a bypass tube. There are two types of such instruments, the *heated tube flow meters* and the *immersion probe flow meters* [7].

In the heated tube flow meters, the flowing gas is passed through a piece of tube that is heated electrically and is instrumented with two temperature sensors, commonly thermocouples or resistance temperature detectors (RTD). The first sensor is located upstream of the heated section and the other one is downstream of it. The rate of heat transfer $\dot{H}$ to the fluid is

$$\dot{H} = \dot{m}C_P\Delta T$$

where $\dot{m}$ is the mass flow rate of the gas, $C_P$ is its specific heat under constant pressure and $\Delta T$ is the temperature difference across the heated section. Thus, the mass flow rate for a given gas can be measured from measurements of $\dot{H}$ and $\Delta T$. Manufacturers supply instruments with an output that has been calibrated in air, nitrogen or some other gas. When used with different gases, this output has to be corrected by multiplying it by the ratio of specific heats of the two gases.

Immersion probe flow meters consist of a probe with two RTDs connected in a Wheatstone bridge configuration. One RTD is used to measure the gas temperature, while the other is provided with a current so that it is heated to a temperature higher than the gas temperature by a fixed amount $\Delta T$. The electric power required to heat the second sensor is related to the mass-weighted velocity $\rho V$ of the gas by a non-linear relationship, called *King's law*. Electronic circuitry is employed to linearize the output so that it is proportional to $\rho V$.
a given gas. To obtain the mass flow rate, one has to multiply this output by the pipe cross-sectional area. Corrections for use with different gases are also available.

15 Selection of flow meter

Considering the diversity of designs and properties of flow meters and the wide ranges of flow conditions encountered in a fluid mechanics laboratories, it is advisable to compare carefully the different options that are available before purchasing a flow meter. Although it is possible that several devices may be equally suitable for a given application, it is also quite certain that several others would be totally unsuitable. As an aid towards the selection of the optimal flow meter, we provide the following table, which was based on information supplied by different manufacturers and contained in the website http://www.geocities.com/ull_km1980/flowmeterselectionguide.html

<table>
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<th>Flow meter type</th>
<th>dirty fluid</th>
<th>dyn. range</th>
<th>press. loss</th>
<th>uncertain.</th>
<th>upstr. pipe</th>
<th>visc. effect</th>
<th>cost</th>
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</table>

1 Y: yes, N: no
2 H: high, M: medium, L: low, VL: very low
3 percent of full scale (fs) or reading (r)
4 in diameters
References


