INTRODUCTION

Measuring fluid flow is one of the most important aspects of process control. In fact, it may well be the most frequently measured process variable. This bulletin describes the nature of flow and factors affecting it. Devices commonly used to measure flow are presented, as is a discussion on accuracy and how it is typically specified. For quick reference, a table listing the primary characteristics of flow metering devices is included along with a conversion chart for the various measurement units encountered in dealing with flow.

Flow is generally measured inferentially by measuring velocity through a known area. With this indirect method, the flow measured is the volume flow rate, \( Qv \), stated in its simplest terms:

\[
Qv = A \times V
\]

In this equation, \( A \) is the cross-sectional area of the pipe and \( V \) is the fluid velocity.

FACTORS AFFECTING FLOW RATES IN PIPES

The major factors affecting the flow of fluids through pipes are:

- the velocity of the fluid.
- the friction of the fluid in contact with the pipe.
- the viscosity of the fluid.
- the density of the fluid.

Fluid velocity depends on the head pressure which is forcing the fluid through the pipe. The greater the head pressure, the faster the fluid flow rate (all other factors remaining constant), and consequently, the greater the volume of flow. Pipe size also affects the flow rate. For example, doubling the diameter of a pipe increases the potential flow rate by a factor of four times.

Pipe friction reduces the flow rate of fluids through pipes and is, therefore, considered a negative factor. Because of the friction of a fluid in contact with a pipe, the flow rate of the fluid is slower near the walls of the pipe than at the center. The smoother, cleaner, and larger a pipe is, the less effect pipe friction has on the overall fluid flow rate.
Viscosity ($\mu$), or the molecular friction within a fluid, negatively affects the flow rate of fluids. Viscosity and pipe friction decrease the flow rate of a fluid near the walls of a pipe. Viscosity increases or decreases with changing temperature, but not always as might be expected. In liquids, viscosity typically decreases with increasing temperature.

However, in some fluids viscosity can begin to increase above certain temperatures. Generally, the higher a fluid’s viscosity, the lower the fluid flow rate (other factors remaining constant). Viscosity is measured in units of centipoise. Another type of viscosity, called kinematic viscosity, is measured in units of centistokes. It is obtained by dividing centipoise by the fluid’s specific gravity.

Density ($\rho$) of a fluid affects flow rates in that a more dense fluid requires more head pressure to maintain a desired flow rate. Also, the fact that gases are compressible, whereas liquids essentially are not, often requires that different methods be used for measuring the flow rates of liquids, gases, or liquids with gases in them.

It has been found that the most important flow factors can be correlated together into a dimensionless parameter called the Reynolds number, which describes the flow for all velocities, viscosities, and pipeline sizes. In general, it defines the ratio of velocity forces driving the fluid to the viscous forces restraining the fluid, or:

$$R_D = \frac{VD\rho}{\mu}$$

At very low velocities of high viscosities, $R_D$ is low and the fluid flows in smooth layers with the highest velocity at the center of the pipe and low velocities at the pipe wall where the viscous forces restrain it. This type of flow is called laminar flow and is represented by Reynolds numbers below 2,000. One significant characteristic of laminar flow is the parabolic shape of its velocity profile (Figure 1).

At higher velocities or low viscosities the flow breaks up into turbulent eddies where the majority of flow through the pipe has the same average velocity. In the “turbulent” flow the fluid viscosity is less significant and the velocity profile takes on a much more uniform shape. Turbulent flow is represented by Reynolds numbers above 4,000. Between Reynolds number values of 2,000 and 4,000, the flow is said to be in transition.

**FIGURE 1. Velocity Profiles**

**MEASUREMENT OF FLUID FLOW IN PIPES**

Of the many devices available for measuring fluid flow, the type of device used often depends on the nature of the fluid and the process conditions under which it is measured. Flow is usually measured indirectly by first measuring a differential pressure or a fluid velocity. This measurement is then related to the volume rate electronically. Flowmeters can be grouped into four generic types: positive displacement meters, head meters, velocity meters, and mass meters.
Positive Displacement Meters

Positive displacement meters measure the volume flow rate (Qv) directly by repeatedly trapping a sample of the fluid. The total volume of liquid passing through the meter in a given period of time is the product of the volume of the sample and the number of samples. Positive displacement meters frequently totalize flow directly on an integral counter, but they can also generate a pulse output which may be read on a local display counter or by transmission to a control room. Because each pulse represents a discrete volume of fluid, they are ideally suited for automatic batching and accounting. Positive displacement meters can be less accurate than other meters because of leakage past the internal sealing surfaces. Three common types of displacement meters are the piston, oval gear, and nutating disc.

Head Meters

Head meters are the most common types of meter used to measure fluid flow rates. They measure fluid flow indirectly by creating and measuring a differential pressure by means of an obstruction to the fluid flow. Using well-established conversion coefficients which depend on the type of head meter used and the diameter of the pipe, a measurement of the differential pressure may be translated into a volume rate.

From the Equation of Continuity, assuming constant density (incompressible fluid) it can be seen that:

\[ Qv = V_1A_1 = V_2A_2 \]

This equation is one of the most important relationships in fluid mechanics. It demonstrates that for steady, uniform flow, a decrease in pipe diameter results in an increase in fluid velocity. In addition, from Bernoulli’s equation on the conversation of energy, it is further seen that total head pressure (H) must remain constant everywhere along the flow or:

\[ \left( \frac{P}{\rho} \right) + \left( \frac{V^2}{2} \right) = H = \text{Constant} \]

The first term of the equation is called “potential head” or “potential energy”. The second term is known as the “velocity head” or “kinetic energy”. Because potential and kinetic energy together are constant, it is clear that an increase in velocity as described by the Equation of Continuity must also be accompanied by a decrease in potential energy or line pressure. It is this relationship between velocity and pressure that provides the basis for the operation of all head-type meters.

Head meters are generally simple, reliable, and offer more flexibility than other flow measurement methods. The head-type flowmeter almost always consists of two components: the primary device and the secondary device. The primary device is placed in the pipe to restrict the flow and develop a differential pressure. The secondary device measures the differential pressure and provides a readout or signal for transmission to a control system. With head meters, calibration of a primary measuring device is not required in the field. The primary device can be selected for compatibility with the specific fluid or application and the secondary device can be selected for the type or readout of signal transmission desired.

Orifice Plates

A concentric orifice plate is the simplest and least expensive of the head meters (Figure 2). Acting as a primary device, the orifice plate constricts the flow of a fluid to produce a differential pressure across the plate. The result is a high pressure upstream and a low pressure downstream that is proportional to the square of the flow velocity. An orifice plate usually produces a greater overall pressure loss than other primary devices. A practical advantage of this device is that cost does not increase significantly with pipe size.

![FIGURE 2. Thin Plate Orifice Meter](FLOW-0475A)
Venturi Tubes

Venturi tubes exhibit a very low pressure loss compared to other differential pressure head meters, but they are also the largest and most costly. They operate by gradually narrowing the diameter of the pipe (Figure 3), and measuring the resultant drop in pressure. An expanding section of the meter then returns the flow to very near its original pressure. As with the orifice plate, the differential pressure measurement is converted into a corresponding flow rate. Venturi tube applications are generally restricted to those requiring a low pressure drop and a high accuracy reading. They are widely used in large diameter pipes such as those found in waste treatment plants because their gradually sloping shape will allow solids to flow through.

Flow Nozzles may be thought of as a variation on the venturi tube. The nozzle opening is an elliptical restriction in the flow but with no outlet area for pressure recovery (Figure 4). Pressure taps are located approximately 1/2 pipe diameter downstream and 1 pipe diameter upstream. The flow nozzle is a high velocity flowmeter used where turbulence is high (Reynolds numbers above 50,000) such as in steam flow at high temperatures. The pressure drop of a flow nozzle falls between that of the venturi tube and the orifice plate (30 to 95 percent).

Pitot Tubes

In general, a pitot tube for indicating flow consists of two hollow tubes that sense the pressure at different places within the pipe. These tubes can be mounted separately in the pipe or installed together in one casing as a single device. One tube measures the stagnation or impact pressure (velocity head plus potential head) at a point in the flow. The other tube measures only the static pressure (potential head), usually at the wall of the pipe. The differential pressure sensed through the pitot tube is proportional to the square of the velocity. To install a pitot tube, you must determine the location of maximum velocity with pipe traverses. Although a pitot tube may be calibrated to measure fluid flow to ±1/2 percent, changing velocity profiles may cause significant errors. Pitot tubes are primarily used to measure gases because the change in the flow velocity from average to center is not as substantial as in other fluids. Pitot tubes have found limited applications in industrial markets because they can easily become plugged with foreign material in the fluid. Their accuracy is dependent on the velocity profile which is difficult to measure.
Target Meters

A target meter consists of a disc or a “target” which is centered in a pipe (Figure 5). The target surface is positioned at a right angle to the fluid flow. A direct measurement of the fluid flow rate results from the force of the fluid acting against the target. Useful for dirty or corrosive fluids, target meters require no external connections, seals, or purge systems. Much data is necessary, however, to determine the optimum size of the target and calibration is essential for its proper operation.

![FIGURE 5. Target-Type Meter](FLOW-0460A)

Elbow Tap Meters

An elbow tap operates by using a 45 degree pipe elbow in the fluid flow. A high pressure tap is taken from the outside of the elbow and a low pressure tap is taken from the inside of the elbow. This provides a differential pressure which is proportional to the flow rate. Measuring the differential pressure depends on the centrifugal force of the fluid flowing through the elbow. Hence, gas with its low density is not a good application for elbow taps. This also explains why a short curvature in the elbow develops a much greater differential pressure than a long curvature. The pressure drop of an elbow tap is no greater than that of the elbow. Though repeatable, accuracy of an elbow tap meter is only within ±5 percent.

Rotameters

Rotameters (also known as variable-area flowmeters) are typically made from a tapered glass tube that is positioned vertically in the fluid flow (Figure 6). A float that is the same size as the base of the glass tube rides upward in relation to the amount of flow. Because the tube is larger in diameter at the top of the glass than at the bottom, the float resides at the point where the differential pressure between the upper and lower surfaces balance the weight of the float. In most rotometer applications, the flow rate is read directly from a scale inscribed on the glass; in some cases, an automatic sensing device is used to sense the level of the float and transmit a flow signal. These “transmitting rotameters” are often made from stainless steel or other materials for various fluid applications and higher pressures. Rotameters may range in size from 1/4 inch to greater than 6 inches. They measure a wider band of flow (10 to 1) than an orifice plate with an accuracy of ±2 percent, and a maximum operating pressure of 300 psig when constructed of glass. Rotameters are commonly used for purge flows and levels.

![FIGURE 6. Rotameter-Type Area](FLOW-0476A)
Velocity Meters

When using velocity to measure a fluid flow rate, the primary device generates a signal proportional to fluid velocity. The equation \( QV = \frac{A}{H} \times V \) illustrates that the generated signal is linear with respect to the volume flow rate. Velocity meters are usually less sensitive than head meters to velocity profile, some are obstructionless, and because they provide linear output with respect to flow, there is no square-root relationship as with differential pressure meters. This eliminates the potential inaccuracies associated with square-root extraction and explains the greater rangeability of velocity meters in comparison to most head meters.

Turbine Meters

A turbine meter uses a multi-bladed rotor that is supported by bearings within a pipe section perpendicular to the flow (Figure 7). Fluid drives the rotor at a velocity that is proportional to the fluid velocity and, consequently, to the overall volume flow rate. A magnetic coil outside the meter produces an alternating voltage as each blade cuts the coil’s magnetic lines of flux. Each pulse, therefore, represents a discrete volume of liquid. Since the rotor is usually made of stainless steel, it is compatible with many fluids. However, the bearings, which are necessary to support the rotor and which must allow it to spin freely at high speeds, require a fairly clean process. Turbine meters are typically available in pipeline sizes from less than \( \frac{1}{2} \) inch through 12 inches. They have fast response and good accuracy.

Electromagnetic Flowmeters

The operating principle of magnetic flowmeter system is based upon Faraday’s Law of electromagnetic induction, which states that a voltage will be induced in a conductor moving through a magnetic field.

**Faraday’s Law:** \( E = kBDV \)

The magnitude of the induced voltage \( E \) is directly proportional to the velocity of the conductor \( V \), conductor width \( D \), and the strength of the magnetic field \( B \). Figure 8 illustrates the relationship between the physical components of the magnetic flowmeter and Faraday’s Law. Magnetic field coils placed on opposite sides of the pipe generate a magnetic field. As the conductive process liquid moves through the field with average velocity \( V \), electrodes sense the induced voltage. The width of the conductor is represented by the distance between electrodes. An insulating liner prevents the signal from shorting to the pipe wall. The only variable in this application of Faraday’s law is the velocity of the conductive liquid \( V \) because field strength is controlled constant and electrode spacing is fixed. Therefore, the output voltage \( E \) is directly proportional to liquid velocity, resulting in the linear output of a magnetic flowmeter.
**Vortex Meters**

The operating principle of a vortex flowmeter is based on the phenomenon of vortex shedding known as the von Karman effect. As fluid passes a bluff body, it separates and generates small eddies or vortices that are shed alternately along and behind each side of the bluff body (Figure 9). These vortices cause areas of fluctuating pressure that are detected by a sensor. The frequency of vortex generation is directly proportional to fluid velocity.

The output of a vortex flowmeter depends on the K-factor. The K-factor relates the frequency of generated vortices to the fluid velocity. The formula for fluid velocity is as follows:

\[
\text{Fluid Velocity} = \frac{\text{Vortex Frequency}}{\text{K-factor}}
\]

The K-factor varies with Reynolds number, but it is virtually constant over a broad flow range (Figure 10). Vortex flowmeters provide highly accurate linear flow rates when operated within this flat region.
Ultrasonic Meters

Ultrasonic flowmeters use sound waves to determine the flow rate of fluids. Pulses from a piezoelectric transducer travel through a moving fluid at the speed of sound and provide an indication of fluid velocity. Two different methods are currently employed to establish this velocity measurement.

The first ultrasonic meters used a transit-time method, in which two opposing transducers are mounted so that sound waves traveling between them are at a 45 degree angle to the direction of flow within a pipe. The speed of sound from the upstream transducer to the downstream transducer represents the inherent speed of sound plus a contribution due to the fluid velocity. In a simultaneous measurement in the opposite direction, a value (determined electronically) is representative of the fluid velocity, which is linearly proportional to the flow rate. While the transit-time method works well in most fluids, it is essential that they be free of entrained gas or solids to prevent scattering of the sound waves between transducers.

Another type of ultrasonic meter uses the Doppler effect. This type of ultrasonic meter uses two transducer elements as well, but each is mounted in the same case on one side of the pipe. An ultrasonic sound wave of constant frequency is transmitted into the fluid by one of the elements. Solids or bubbles within the fluid reflect the sound back to the receiver element. The Doppler principle states that there will be a shift in apparent frequency or wavelength when there is relative motion between transmitter and receiver. Within the Doppler flowmeter, the relative motion of the reflecting bodies suspended within the fluid tends to compress the sound into a shorter wavelength (high frequency). This new frequency measured at the receiving element is electronically compared with the transmitted frequency to provide a frequency difference that is directly proportional to the flow velocity in the pipe. In contrast to the transit-time method, Doppler ultrasonic meters require entrained gases or suspended solids within the flow to function correctly.

While ultrasonic meters have several advantages, including freedom from obstruction in the pipe and negligible cost-sensitivity with respect to pipe diameter, their performance is very dependent on flow conditions. A fair accuracy is attainable with ultrasonic flowmeters when properly applied to appropriate fluids.

Mass Meters

True mass flowmeters measure the mass rate of flow directly as opposed to the volumetric flow rate. As a result, entrained air does not affect the accuracy of their measurement. Many so-called mass flowmeters, however, infer the mass flow rate via the equation:

\[ Q_m = Q_v \times \rho \]

In this equation, \( Q_m \) is the mass flow rate, \( Q_v \) is the volume flow rate, and \( \rho \) is fluid density. Such mass flowmeter instruments essentially combine two devices, one to measure fluid velocity and the other to measure density. These inputs are typically combined in a microprocessor, along with additional data, to provide an output indicative of the mass flow rate. In contrast, the following meters measure mass flow directly without the intermediate calculation from volume and density.

Thermal Meters

Thermal meters are commonly applied to gas streams only; in fact, to gas streams where the transfer of heat to and from the stream is a usual element of the metering process. Measuring this heat transfer supplies data from which a mass flow rate may be calculated. As mass meters, thermal meters operate independent of density, pressure, and viscosity.
Coriolis Meters

The Coriolis meter uses an obstructionless U-shaped tube as a sensor and applies Newton's Second Law of Motion to determine flow rate. Inside the sensor housing, the sensor tube vibrates at its natural frequency (Figure 11). The sensor tube is driven by an electromagnetic drive coil located at the center of the bend in the tube and vibrates similar to that of a tuning fork.

![FIGURE 11. Vibrating Coriolis Sensor Tube](image1)

The fluid flows into the sensor tube and is forced to take on the vertical momentum of the vibrating tube. When the tube is moving upward during half of its vibration cycle (Figure 12), the fluid flowing into the sensor resists being forced upward by pushing down on the tube.

![FIGURE 12. Fluid Forces in a Coriolis Sensor Tube](image2)

The fluid flowing out of the sensor has an upward momentum from the motion of the tube. As it travels around the tube bend, the fluid resists changes in its vertical motion by pushing up on the tube (Figure 12). The difference in forces causes the sensor tube to twist (Figure 13). When the tube is moving downward during the second half of its vibration cycle, it twists in the opposite direction. This twisting characteristic is called the Coriolis effect.

![FIGURE 13. Coriolis Effect](image3)

Due to Newton's Second Law of Motion, the amount of sensor tube twist is directly proportional to the mass flow rate of the fluid flowing through the tube. Electromagnetic velocity detectors located on each side of the flow tube measure the velocity of the vibrating tube. Mass flow is determined by measuring the time difference exhibited by the velocity detector signals. During zero flow conditions, no tube twist occurs, resulting in no time difference between the two velocity signals. With flow, a twist occurs with a resulting time difference between the two velocity signals. This time difference is directly proportional to mass flow.
ACCURACY IN MEASURING FLUID FLOW

Flow metering systems contain a number of components, each of which has its own accuracy rating. To understand the accuracy of a flow metering system, it is important to consider the accuracy rating of each component and understand how these individual ratings combine into a statement of accuracy for the entire system. Also, statement of accuracy should be accompanied by the flow rate range over which the accuracy applies. For example, a statement on accuracy might read: “The system has an accuracy of ±1 percent of rate over a range of 10 to 90 percent of maximum flow.” The following is a breakdown of the types of accuracy statements made concerning flow metering systems. It is generally expected that an accuracy specification includes the effects of linearity, hysteresis, and repeatability.

Percent of Rate

Percent of rate accuracy states that throughout a given range, the uncertainty of flow in ±gallons per minute (gpm) decreases as the flow rate decreases (Figure 14). For example, a maximum flow of 100 gpm at ±2 percent of rate would allow uncertainty between 98 gpm and 102 gpm at the full rate of flow, ±1 gpm uncertainty at half flow (49 to 51 gpm), and ±2/5 gpm uncertainty at 20 gpm flow (19.6 to 20.4 gpm). A percent of rate accuracy statement usually applies to meters that measure fluid velocity to determine the flow rate. Examples of meters using a percent of rate accuracy are electromagnetic meters, turbine meters, and vortex meters.

Percent of Upper Range Value

When describing flow accuracy using percent of upper range value (URV), the uncertainty remains constant over the specified range (Figure 14). In the above 100 gpm example, but with ±2 percent of URV, uncertainty at full flow is 98 to 102 gpm; at half flow it is 48 to 52 gpm; and at 20 gpm uncertainty may vary from 18 to 22 gpm. The amount of uncertainty is constant over the range of flow. Therefore, the uncertainty is a greater percent of the actual flow rate at low flows than at higher flow rates. Percent of URV is suitable for describing the accuracy of head-type flow metering systems.

Repeatability

In many process flow applications, repeatability of a flowmeter is of greater importance than its accuracy. In a flow control loop, for example, if the flowmeter gives a stable, repetitive reading, the true accuracy of the measurement is usually not as meaningful. Repeatability does not imply that a flow measurement is accurate or correct, but that it is the same each time.

System Accuracy

The accuracy of the entire flow metering system can best be determined if all the components are rated according to the same type of accuracy statement (percent of rate or percent of maximum flow). If system accuracy varies at different flow rates, then overall system accuracy should be calculated at various flow rates. The usual method to produce a usable system accuracy statement is to calculate the square root of the sum of the square of each component’s accuracy rating, or:

\[ \pm \sqrt{\text{Accuracy A}^2 + \text{Accuracy B}^2 + \ldots + \text{Accuracy n}^2} \]

This equation partially accounts for the fact that errors will probably not all be either positive or negative simultaneously, and that, therefore, the overall accuracy rating will not reflect a “worst case” condition.
### TABLE 1. Volumetric Flow Rate

<table>
<thead>
<tr>
<th>cu ft/sec</th>
<th>cu ft/min</th>
<th>liters/min</th>
<th>cu meters/ min</th>
<th>cu meters/ hour</th>
<th>gal/min</th>
</tr>
</thead>
<tbody>
<tr>
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<td>60</td>
<td>1699</td>
<td>1.699</td>
<td>101.95</td>
<td>448.83</td>
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<td>0.02832</td>
<td>1.699</td>
<td>7.481</td>
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<tr>
<td>5.855 x 10^{-4}</td>
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<td>1</td>
<td>0.001</td>
<td>0.06</td>
<td>0.2642</td>
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<tr>
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<td>1000</td>
<td>1</td>
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<td>264.2</td>
</tr>
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### TABLE 2. Gravimetric Flow Rate

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<thead>
<tr>
<th>lb/sec</th>
<th>lb/min</th>
<th>lb/hr</th>
<th>gm/sec</th>
<th>gm/min</th>
<th>Kg/hr</th>
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<tbody>
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<td>0.01667</td>
<td>1</td>
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<td>2.205</td>
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<td>16.67</td>
<td>1</td>
</tr>
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</table>

### TABLE 3. Volume

<table>
<thead>
<tr>
<th>Gallons (U.S.)</th>
<th>Cubic Feet</th>
<th>Cubic Inches</th>
<th>Barrels (oil)</th>
<th>Cubic Centimeters</th>
<th>Liters</th>
<th>Imperial Gallons</th>
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<tbody>
<tr>
<td>1</td>
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### TABLE 4. Velocity

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<th>meter/min</th>
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<td>1.667</td>
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