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FLUID PROPERTIES — PART I

The ability to accurately measure and control flow is essential to maintain the process conditions required to maximize plant production and product quality. In most process applications, proper regulation of flow rates ensures control of process reaction rates as well as the regulation of other variables such as pressure, level and temperature. Often, flow measurements are used as indicators of overall process performance.

Flow is one of the most difficult process variables to measure accurately. One of the simplest methods for determining a fluid's rate of flow is the weight per unit time method, which assumes a basic premise of fluid mechanics: mass is a conserved quantity. The mass entering a system is equal to the mass leaving the system when both are measured over the same time interval. In practice, using the weight per unit time method to measure flow requires catching the fluid in a container and weighing it over a given interval of time. However, there are many instances in which such requirements are impractical. Two such examples include applications involving gases that cannot ordinarily be condensed into liquids; and closed-loop processes commonly associated with chemical applications. Consequently, other methods must be used to obtain accurate flow measurements. These methods must take into consideration two basic properties of fluid, density and viscosity, and their effect on the accuracy of flow measurement. The discussion of

density and information pertaining to fluids in a static phase are presented in this chapter; viscosity is discussed in Chapter 2.

Density

All substances have density. Density is a measurement of the proximity of the molecules that make up a substance. In the simplest terms, density is mass per unit of volume. This can be expressed as:

$$\rho = \frac{m}{V}$$

where:

- ρ = density
- m = mass
- v = volume

Often, density is the property that distinguishes one substance from another. For instance, it is density that causes the same volume of different substances to differ in weight. Figure 1-1 illustrates the impact of density on weight. Two substances of equal volume, a cubic foot of iron and a cubic foot of water, are arranged on

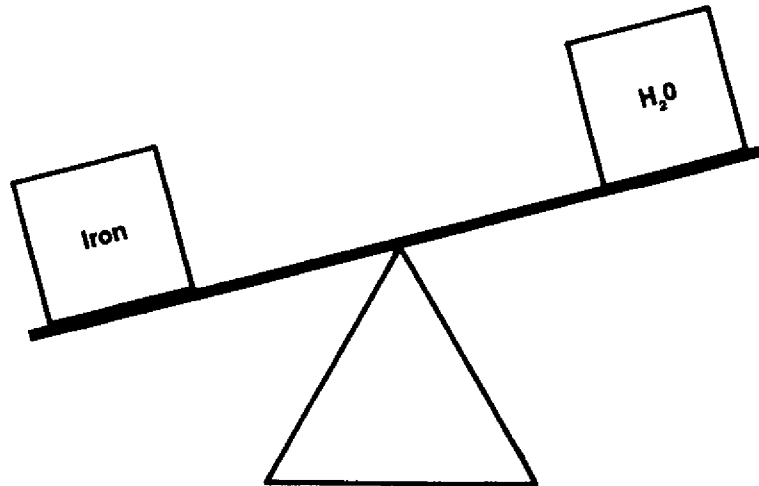


Figure 1-1. Relationship of Density to Weight

a balance scale. It is the greater density of the iron that causes it to weigh more than an equal volume of water. The relationship of density to weight applies to all forms of matter: solids, liquids and gases.

Density is typically expressed in pounds per cubic foot. In some instances, a conversion to grams per cubic centimeter may be useful. The following equation can be used to convert density to pounds per cubic foot or grams per cubic centimeter.

$$1 \text{ lb/ft}^3 = 0.0160262 \text{ g/cm}^3$$

For example, given a 2.04 cubic foot container, the density of 100 pounds of liquid that occupies 1.53 cubic feet is:

$$\begin{aligned} \rho &= \frac{m}{V} \\ &= \frac{100 \text{ lb}}{1.53 \text{ ft}^3} \\ &= 65.359 \text{ lb/ft}^3 \end{aligned}$$

To express this value in grams per cubic centimeter, the calculation is extended:

$$(65.359 \text{ lb/ft}^3)(0.0160262 \text{ g/cm}^3) = 1.0475 \text{ g/cm}^3$$

Effects of Temperature and Pressure on Density

The density of a substance is affected by variables such as temperature and pressure. These effects vary according to the physical properties of the substance. For example, the effects of temperature on the density of solids and gases varies widely. Gases are most affected; solids are least affected; with liquids generally ranging somewhere in between. The effects of pressure on the density of solids and liquids are considered negligible because both are relatively noncompressible. However, the effect of pressure on the density of gases is very pronounced. Consequently, systems designed to measure the flow of gases must include compensation for both variables in order to ensure accurate results.

The density formula ($\rho = m/V$) can be used to illustrate the effect of temperature on a liquid. It is understood that heating a substance causes it to expand, increasing its volume. According to the formula, the density of a constant mass must decrease as its volume increases. Conversely, as the temperature of a substance decreases, the substance contracts. Therefore,

the density of a constant mass increases as its volume decreases.

Volumetric expansion, which affects the density of a liquid, can be expressed as:

$$V = V_0 (1 + \beta [\Delta t])$$

where β is the cubical coefficient of expansion of the liquid that is consistent with the temperature units used.

So, if a liquid has a cubical expansion coefficient factor of 0.9×10^{-3} per degree Celsius, its change in density due to a rise in temperature of 10 degrees Celsius is:

$$\begin{aligned} V &= V_0 (1 + [0.9 \times 10^{-3} \text{ } ^\circ\text{C}] \times [10^\circ \text{C}]) \\ &= 1.009 V_0 \end{aligned}$$

Since the mass is the same before and after the increase in temperature, the change in density is inversely proportional to the change in volume. This is expressed mathematically as

$$\begin{aligned} \frac{\rho}{\rho_0} &= \frac{V_0}{V} \\ &= (1.009)^{-1} \\ &= 0.991 \end{aligned}$$

The net decrease in density is 0.9 percent.

The same equation can be used to describe volumetric expansion, using the following relation:

$$\beta = 3 \times \alpha$$

where α is the linear coefficient of the solid.

The density of gases varies significantly with temperature. Increasing the temperature of a gas at a constant pressure increases the activity and motion of the gas molecules in relation to one another. The increased activity results in the expansion of the gas, which in turn, requires a larger volume. Because the same mass occupies more space, its density decreases.

This phenomenon is described in Charles' Law, which states that for an ideal gas or mixture of gases at constant pressure, the volume is directly proportional to the absolute temperature.

$$V = \text{constant} \times T$$

To compare the volumes of an ideal gas at constant pressure and at different temperatures, the following equation is used:

$$\frac{V}{V_0} = \frac{T}{T_0}$$

For example, to determine the impact of a 10 degree Celsius rise in temperature on the volume of a gas at constant pressure and a temperature of 15° Celsius, the first step is to calculate absolute temperature on the Celsius scale. This is done by adding 273 to the 15° Celsius temperature reading since 273 represents absolute zero on that scale:

$$\begin{aligned} \frac{V}{V_0} &= \frac{T}{T_0} \\ &= \frac{(273 + 15 + 10)}{(273 + 15)} \\ &= 1.035 \end{aligned}$$

Given that information, it can be determined that volume increases by 3.5% as a result of 10° Celsius increase in temperature.

As previously noted, pressure also affects the density of a substance. Although the effects of pressure on the density of liquids and solids is of little significance, its effect on gases cannot be ignored. Increasing the pressure on a gas causes it to compress; decreasing the pressure causes it to expand. When compressed, the same mass is contained in a smaller space, causing a decrease in volume and an increase in density. Conversely, decreasing pressure increases volume and decreases density. This principle is described in Boyle's Law which states that for any ideal gas or mixture of ideal gases at a constant temperature, the

4 Flow

volume is inversely proportional to the absolute pressure.

$$V = \frac{\text{constant}}{P}$$

Boyle's Law can also be stated in another form:

$$\frac{V}{V_0} = \frac{P}{P_0}$$

This formula can be used to compare the volumes of an ideal gas at different pressures while maintained at a constant temperature.

To determine the impact of an increase in pressure of 5 psi on the volume of an ideal gas at a constant temperature with a pressure of 28 psi, the first step is to calculate absolute pressure. This is done by adding 14.7 to the measured pressure.

$$\begin{aligned} \frac{V}{V_0} &= \frac{P_0}{P} \\ &= \frac{(28 + 14.7)}{(28 + 5 + 14.7)} \\ &= \frac{42.7}{47.7} \\ &= 0.895 \end{aligned}$$

Based on this calculation it can be determined that the volume of the gas decreased to 89.5% of its original volume due to an increase in pressure of 5 psi. Stated another way, it could be said that the volume of the gas decreased by 10.5% due to an increase in pressure of 5 psi.

Charles' and Boyle's Laws can be combined to form the Ideal Gas Law. An "ideal gas" is defined as any gas which responds to changes in pressure or temperature or both at the same time and follows the Ideal Gas Law. This is expressed mathematically as follows:

$$\frac{V}{V_0} = \frac{P_0 \times T}{P \times T_0}$$

In cases where the temperature and pressure variations are small, the two act almost independently of one another. Reasonably accurate estimates can be obtained by adding the percentage of temperature and pressure deviations from a given set of conditions.

So, the net change in volume caused by a 10.5 percent decrease in volume caused by increased pressure and a 3.5 percent increase in volume caused by an increase in temperature is:

$$\begin{aligned} \frac{V}{V_0} &= 0.895 \times 1.035 \\ &= 0.926 \end{aligned}$$

The net change in volume as a result of the changes in temperature and pressure, is a decrease of 7.4 percent (100% - 92.6%). This amount could have also been estimated by adding the individual percentage deviations. Adding plus 3.5 percent (the increase in volume due to the increase in temperature) to minus 10.5 percent (the decrease in volume as a result of an increase in pressure) equals a 7 percent "estimated" decrease in volume, which is close to the calculated change.

Specific Gravity

Another term commonly used to express the density of fluids is specific gravity. While density is a stand-alone measurement, specific gravity is a ratio comparing the density of a fluid at a specific temperature to the density of water or air at the same temperature. The specific gravity of liquids and gases can be represented by the following equations.

$$\text{Specific Gravity} = \frac{\text{Density of a liquid}}{\text{Density of water at standard conditions}}$$

$$\text{Specific Gravity} = \frac{\text{Density of a gas}}{\text{Density of air at standard conditions}}$$

Since the units in the equation cancel each other out, the resulting value is a dimensionless number. This

makes it possible to use the value of the specific gravity of a fluid in combination with measurements in any units.

Many industries use different standard conditions to calculate specific gravity. This results in a variety of numerical values. For this reason, density is more commonly used to describe gases. However, to avoid error, standard conditions should be defined when density is to be calculated from the specific gravity. Typically, liquid specific gravity is referenced to 60° F and 14.696 psi. Since other standard temperatures may also be used, the following information may be helpful.

$$\begin{aligned} \text{Density of water at } 60^\circ \text{ F} &= 62.33630 \text{ lb/ft}^3 \\ &= 0.9990121 \text{ g/cm}^3 \end{aligned}$$

$$\begin{aligned} \text{Density of water at } 68^\circ \text{ F} &= 62.31572 \text{ lb/ft}^3 \\ &= 0.9982019 \text{ g/cm}^3 \end{aligned}$$

$$\begin{aligned} \text{Density of air at } 60^\circ \text{ F} &= 14.696 \text{ psia} \\ &= 0.0764 \text{ lb/ft}^3 \end{aligned}$$

$$\begin{aligned} \text{Density of air at } 68^\circ \text{ F} &= 14.696 \text{ psia} \\ &= 0.07528 \text{ lb/ft}^3 \end{aligned}$$

Changes in temperature will affect the specific gravity of a substance. This effect can be demonstrated by comparing the specific gravities of a liquid at 60° F and at 68° F. At 60° F, a liquid has a density of 1.095 grams per cubic centimeter. Its specific gravity can be calculated as follows:

$$\begin{aligned} \text{SG} &= \frac{1.095 \text{ g/cm}^3}{0.9990121 \text{ g/cm}^3} \\ &= 1.096 \end{aligned}$$

When the temperature is raised to 68° F, the density changes to 1.094 grams per cubic centimeter. This change is reflected in the following calculation:

$$\begin{aligned} \text{SG} &= \frac{1.094 \text{ g/cm}^3}{0.9990121 \text{ g/cm}^3} \\ &= 1.095 \end{aligned}$$

Therefore, the specific gravity of liquids and gases will decrease as temperature increases.

FLUID PROPERTIES — PART II

Fluid properties such as density apply to fluid in a static phase. Viscosity is a property that applies to fluids in motion. Viscosity can be described as a measure of how freely a liquid flows.

The force that causes fluids to flow is created by a change or difference in pressure. While there are many types of pressure, the study of fluid flow and flow measurement is primarily concerned with static pressure, dynamic pressure, and differential pressure.

Static pressure is an important variable in the measurement of fluid flow. It can be defined as the pressure exerted by fluids at rest. Static pressure is independent of the kinetic energy of the fluid. As illustrated in Figure 2-1, the liquid in the tank is exerting static pressure against the walls of the tank.

Dynamic pressure is the increase in pressure above static pressure that results from the transformation of the fluid's kinetic energy into potential energy. In other words, it is the pressure above static pressure caused by the movement of fluids. Dynamic pressure can be produced by gravity, as in the case of an elevated water tank (see Figure 2-2), or mechanically, as in the case of a pump.

Differential pressure is the pressure difference between two related pressures. Differential pressure can be determined by measuring two related pressures and calculating the difference between the two measurements. This difference is the differential pressure

value. Differential pressure is frequently used to determine fluid flow rate.

Flow

While a study of flow measurement requires an understanding of what causes fluid to flow, accurate measurement systems must also take into account the flow profiles of fluids.

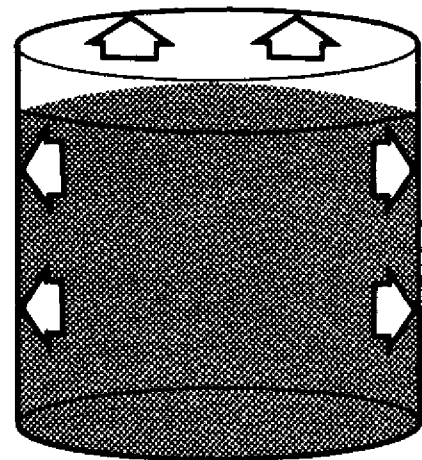


Figure 2-1. Static Pressure

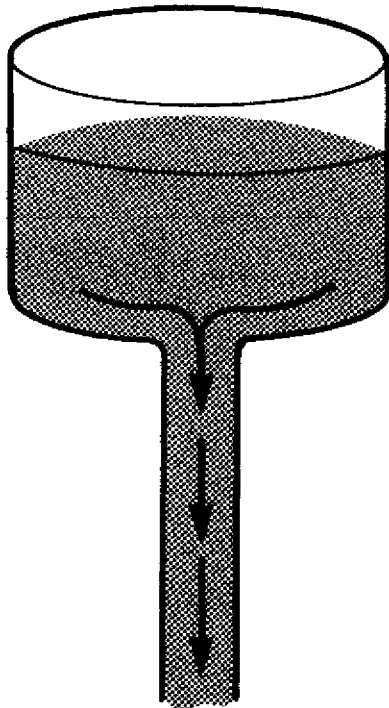


Figure 2-2. Dynamic Pressure

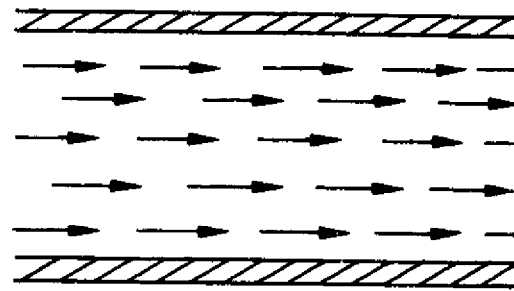
Fluids may move in smooth patterns, agitated or turbulent patterns, or the patterns may be a combination of these characteristics. Figure 2-3 shows a comparison of three types of flow: laminar flow, turbulent flow and transitional flow.

Figure 2-3A represents a smooth, layered flow, which is described as laminar flow. In laminar flow, the fluid particles move along parallel paths. If laminar flow could be observed, it would appear as several streams of liquid flowing smoothly alongside each other.

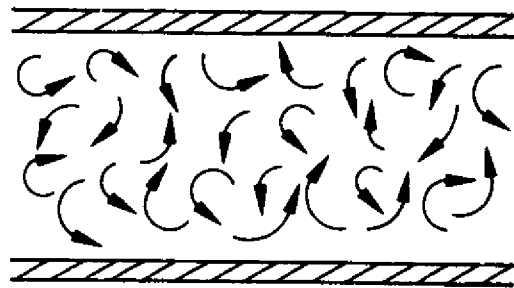
Figure 2-3B represents a turbulent flow pattern. In comparison to laminar flow, turbulent flow is agitated and disturbed. Turbulent flow appears to have small, high frequency fluctuations that travel in all directions forming eddies.

Transitional flow, which is illustrated in Figure 2-3C, exhibits characteristics of both laminar and turbulent patterns. In some cases, transitional flow will oscillate between laminar and turbulent flow.

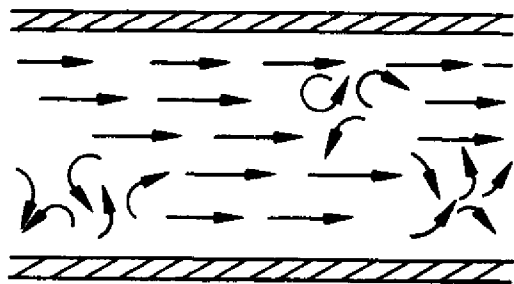
The degree of frictional resistance generated by the three types of flow patterns varies. Laminar flow offers



A. Laminar flow



B. Turbulent flow



C. Transitional flow

Figure 2-3. Comparison of Types of Flow

the least amount of frictional resistance to fluid flow, whereas turbulent flow causes a great deal of frictional resistance. The degree to which transitional flow tends toward one pattern or the other is a major factor in determining the amount of friction the flow generates.

Viscosity

Viscosity is the property that determines how freely fluids flow. Viscosity can be further described as the property of a fluid that contributes to laminar or turbulent flow characteristics. Fluids have various degrees

of viscosity. Such variations result from internal friction between the particles of the substance. If the molecules slide easily over one another, the substance has a relatively low viscosity. A substance with a higher viscosity has a higher resistance to flow. Two substances with different viscosities are water and oil. Water pours freely, while oil pours more slowly.

In any situation, a fluid's flow profile will depend in part on the viscous forces that resist flow and the forces that act to keep flow moving at a constant rate. For example, fluid traveling through a pipe must overcome the resistance generated by two forces: the internal friction determined by the viscosity of the liquid; and the friction occurring between the liquid surfaces and the walls of the pipe. If the flow is laminar, it can be assumed that there is less frictional resistance at the center of the flow where the molecules are sliding against each other, than at the pipe walls where friction occurs between the liquid and pipe surfaces.

If the flow is laminar, the viscous force causes the flow to slow as it approaches the pipe walls. Theoretically, this flow is parabolic, with the central core having a higher velocity and the outermost area having a lower velocity. This is illustrated in Figure 2-4.

Turbulent flow is less affected by viscous forces along the walls of the pipe. Due to relatively low viscous forces, turbulent flow exhibits a more uniform profile than laminar flow. However, the fluid layer next to the wall remains laminar even in the case of fully developed turbulent flow.

Effect of Temperature on Viscosity

Temperature has a significant effect on the viscosity of a substance. Relatively small changes in tempera-

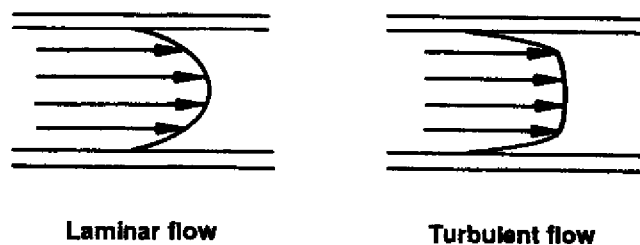


Figure 2-4. Flow Profiles

ture may produce significant changes in a fluid's viscosity. Generally, changes in temperature have an inverse effect on viscosity. If the temperature of a fluid decreases, its viscosity will increase. On the other hand, if the temperature of the fluid increases, its viscosity will decrease. For example, if molasses stored at room temperature is placed in a refrigerator, its viscosity will increase and it will become harder to pour. However, if the molasses is heated, its viscosity will decrease.

If the viscosity of a liquid at one temperature is known, its viscosity at another temperature may be estimated by using the generalized viscosity curve for liquids (see Figure 2-5). The value is expressed in centipoise (cP), a unit of viscosity measurement. For example, if the viscosity of a liquid at 50° C is 25cP, the viscosity of the liquid at 0° C can be determined using the generalized viscosity curve for liquids.

The initial viscosity is indicated where the generalized viscosity curve intersects at 25μ cP and 50° C. As each division represents 50° C, the estimated viscosity at 0° C is approximately 400 cP. This example illustrates the magnitude of the effect on a substance's viscosity even with small temperature changes.

Reynolds Number

Flow is often measured in terms of velocity. Therefore, when different portions of the flow are moving at different velocities, measurement accuracy will be affected. Further, as stated earlier, the flow profile depends on a combination of factors, including the forces that resist flow and the forces that act to keep flow moving at a constant rate. The relationship between these forces is expressed by the Reynolds number: a ratio of inertial to viscous forces specific to flow conditions.

$$R_D = \frac{\text{inertial forces}}{\text{viscous forces}} = \frac{\rho \times v \times D}{\mu}$$

Like specific gravity, the Reynolds number is dimensionless and is not absolute for a given liquid substance, but varies with the conditions of flow. The following equations are used to calculate the Reynolds number for liquid and gas flow through a pipe, given that ρ is in pounds per cubic foot and D is in inches.

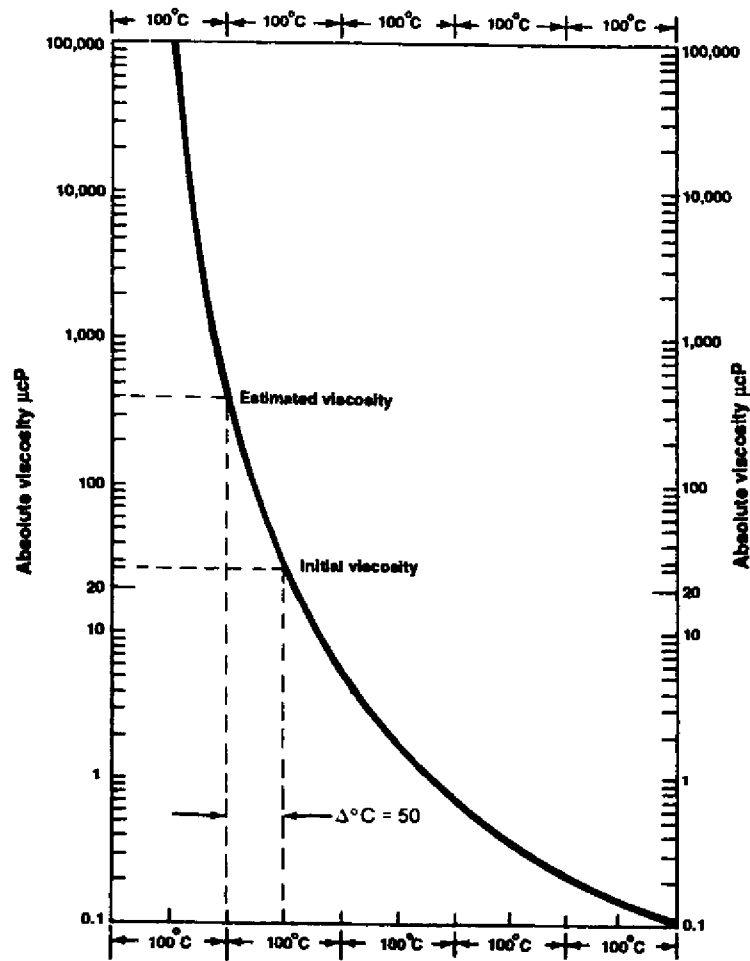


Figure 2-5. Generalized Viscosity Curve for Liquids

Liquid:
$$R = \frac{3160 \times Q_{gpm} \times SG}{\mu P \times D}$$

Gas:
$$R = \frac{379 \times Q_{acfm} \times \rho}{\mu P \times D}$$

where:

where:

- 3160 = units constant
- Q_{gpm} = flow in gallons per minute
- SG = specific gravity
- μP = viscosity in centipoise
- D = inside pipe diameter

- 379 = units constant
- Q_{acfm} = flow in cubic feet per minute
- ρ = density

It is understood that the Reynolds number only reflects fluid effects and disregards such factors as pipe roughness, pipe obstructions and pipe bends. However, boundary limitations have been established that serve

as estimates for practical applications. The boundaries that follow are not established by controlled laboratory experiments. When the Reynolds number is less than 2000, flow is in the laminar region. When the Reynolds number is greater than 4000, flow is considered to be in the turbulent region. When the Reynolds number is in the range of 2000 to 4000, flow is transitional.

Viscosity is the factor which most affects the value of the Reynolds number. In cases where small changes in temperature cause relatively large changes in viscosity, corresponding changes in the Reynolds number will also occur. These changes affect whether the flow is in the laminar, turbulent or transitional regions. The Reynolds number is often a significant factor in determining how well a specific fluid-measuring device will perform and which applications are most appropriate to its use.

MEASURING FLOW

Measuring the flow of a substance, requires a thorough, detailed understanding of the process and the substance being measured. Process applications may involve the flow of gases, liquids, or solids; singly or in combination. These substances may flow through pipes or open channels depending on the nature of the process. Two factors that determine the method of flow measurement or the flowmeter most suited to an application are the quantity of the flow, and the type of substance being measured.

The flow rate of a substance can be described using a number of terms including feet per second, gallons per minute, cubic feet per minute and tons per hour. The unit chosen to indicate flow rate is an important factor

in flow measurement applications, and varies according to the indicating requirements specific to the process. There are several methods used to measure flow, including flow rate, volumetric flow rate, and mass flow rate.

Flow Rate

The measurement unit used to express the rate of flow actually refers to the velocity of the flow, or how rapidly the substance moves. A flow rate is a measure of the distance a particle of a substance moves in a given period of time.

Feet per second is a unit commonly used to measure

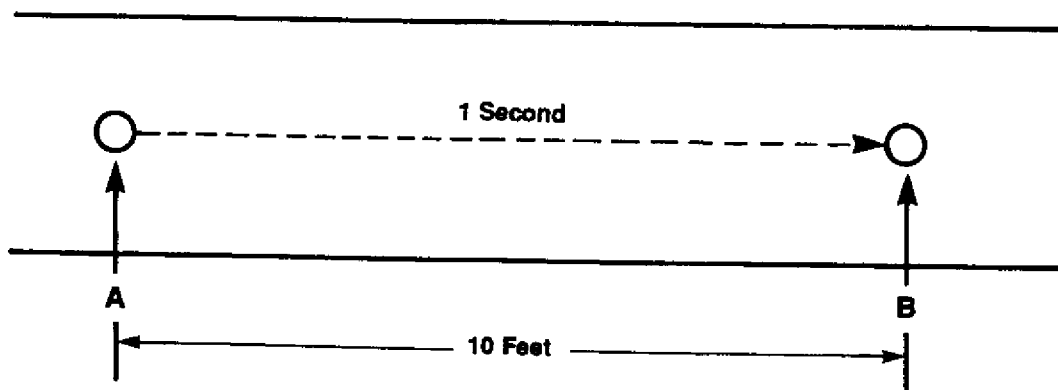


Figure 3-1. Flow Rate

flow rate. An application of this method is illustrated in Figure 3-1. If a molecule of the fluid in the pipe takes one second to move from Point A to Point B, and the distance between these points is ten feet, the flow rate of the fluid in the pipe is 10 feet per second (10 ft/sec.).

In addition to calculating the flow rate between points, it may also be necessary to calculate the total volume of fluid that passes through the pipe over a specified period of time.

Volumetric Flow Rate

The method of measurement used to indicate the volume of fluid that passes a point over a period of time is volumetric flow rate. Volumetric flow rate is usually expressed in gallons per minute (GPM) or cubic feet per second.

One means of measuring volumetric flow is to transfer a specific volume of fluid from one vessel to another and time the procedure. If two minutes are required to transfer 500 gallons of fluid from one vessel to the other, the volumetric flow rate is 250 gallons per minute or 250 GPM. In general, this method has limited practical applications. A more widely used method of measuring volumetric flow rate is typically adopted when two factors, flow velocity and pipe inside diameter, are known. Tables are available to determine the inside diameters for pipes of different sizes.

Volumetric flow rate can be calculated using the formula:

$$Q = A \times v$$

where:

- Q = volumetric flow rate
- A = cross-sectional area of the pipe
- v = flow velocity

For example, in an application in which a fluid has a flow velocity of 14 feet per second through a pipe with an inside diameter of two and one-half feet, the volumetric flow rate is determined to be 68.7 cubic feet per second, using the following equation:

$$\begin{aligned} Q &= A \times v \\ &= (\pi r^2) \times 14 \text{ ft/sec.} \\ &= 4.90625 \text{ ft}^2 \times 14 \text{ ft/sec.} \\ &= 68.7 \text{ ft}^3/\text{sec.} \end{aligned}$$

Mass Flow Rate

Another system of flow measurement that can be used to determine the flow rate of a process is mass flow rate. Mass flow rate determines the amount of mass that passes a specific point over a period of time. Mass flow rate applications determine the weight or mass of the substance flowing through the system.

Provided the volumetric flow rate and the fluid density of the process substance is known, mass flow rate can be calculated using the following equation:

$$W = Q \times \rho$$

where:

- W = mass flow rate
- Q = volumetric flow rate
- ρ = density

Therefore, if a process fluid with a density of 65.4 lb/ft³ has a volumetric flow rate of 59 cubic feet per second, the mass flow rate could be determined as follows:

$$\begin{aligned} W &= 59 \text{ ft}^3/\text{sec.} \times 65.4 \text{ lb/ft}^3 \\ &= 3858.6 \text{ lb/sec.} \end{aligned}$$

When mass flow rate is measured, the effect of temperature and pressure on the density of the fluid must be considered. This is especially true in processes involving gases. In such cases, means must be established to compensate for the changes in density caused by other process variables.

HEAD-TYPE DIFFERENTIAL PRESSURE FLOWMETERS

There are several types of instruments used to measure flow. Differential pressure or head-type flowmeters represent one widely used class of flow-measuring instruments. These instruments are generally considered simple, reliable and highly accurate. Consequently, they are often the instrument of choice for liquid flow measurement applications as well as most gas applications.

The rate of flow using a head flowmeter device is determined by measuring the pressure drop across a constriction. Differential pressure is measured and flow rate is inferred from the measured difference in the two related pressures.

Bernoulli's Law

Head-flow type flow measurement is based on the principle that energy cannot be created or destroyed. Consequently, as illustrated in Figure 4-1, the same volume of fluid will pass by Point A and Point B over the same period of time. However, if the fluid flow passes through a constriction, the flow velocity must increase if flow rate is to remain constant. Therefore, to maintain the flow rate between Points A and B, the total energy of the fluid must also remain constant.

The conservation of energy principle was used by Bernoulli to formulate an equation describing fluid flow. Bernoulli states that the sum of the pressure head

(static energy), the velocity head (kinetic energy), and the elevation head (potential energy) at one point is equal to their sum at any other point. Therefore, the energy of the fluid is conserved by continuity and flow across a constriction in the pipe. According to Bernoulli, the flow rate at each cross section can be determined by the following equation:

$$\frac{P}{\rho \times g} + \frac{v^2}{2g} + y = \text{constant}$$

where:

- P = pressure causing the fluid to move

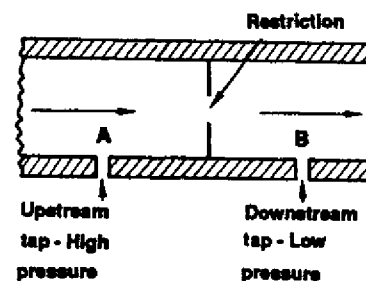


Figure 4-1. Head Flow Meter Principle

- v = flow velocity
- g = acceleration of gravity
- ρ = density of the fluid
- y = elevation head of the fluid

The sum of the three pressures described by Bernoulli equals the total pressure or stagnation pressure. This stagnation pressure, like the total energy of the fluid, must remain constant. Therefore, if a horizontal pipe line has a constant elevation, total energy would simply be the sum of potential energy plus the kinetic energy.

Similarly, stagnation pressure would equal static pressure plus dynamic pressure, as shown in the following equation:

$$P_t = P + 1/2\rho \times v^2$$

The equation of continuity provides a relation between the velocity and the fluid flow rate for incompressible fluids. In a pipe, this may be represented as:

$$Q = A_1 \times v_1 = A_2 \times v_2$$

According to this relationship, when the pipe narrows, the velocity of the fluid must increase to maintain the same volumetric flow rate (see Figure 4-2). When this

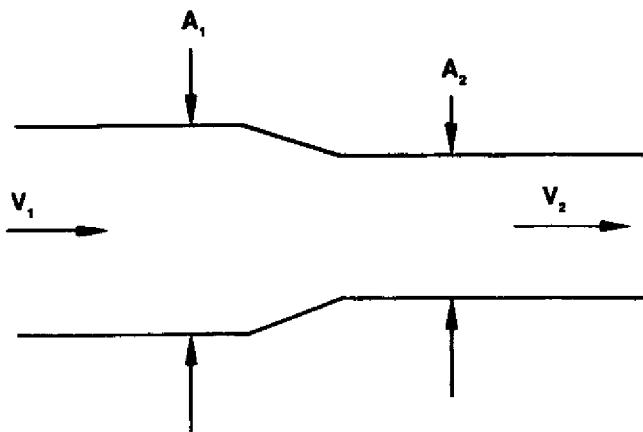


Figure 4-2. Equation of Continuity in a Pipe

occurs, the kinetic energy and dynamic pressure change proportionally. This means that some of the potential energy has been converted to kinetic energy. Also, since the dynamic pressure has increased, there will be a corresponding decrease in static pressure. For example, if a liquid has a velocity of 10.0 ft/sec in a 2 inch schedule 40 pipe, the velocity of that liquid in a 3 inch schedule 40 pipe can be calculated as follows:

$$Q = A_1 \times v_1 = A_2 \times v_2$$

$$Q = 1/4 \pi \times (2.067 \text{ in})^2 \times (10 \text{ ft/sec}) = 1/4 \pi \times (3.068 \text{ in})^2 \times v_2$$

$$v_2 = (2.067 \text{ in}/3.068 \text{ in})^2 \times (10 \text{ ft/sec})$$

$$= 4.54 \text{ ft/sec}$$

Combining Bernoulli's equation with the equation of continuity, results in the following formula:

$$P_1 + 1/2\rho \times v_1^2 = P_2 + 1/2\rho \times v_2^2$$

When this formula is rearranged to solve for differential pressure ($P_1 - P_2$), the change in the differential pressure is proportional to the square of the velocity or flow rate. Thus, the flow through an orifice plate can be represented by:

$$Q = \text{constant} \times (\Delta P/\rho)^{1/2}$$

The Greek letter delta (Δ) is used to represent differential, therefore, ΔP represents differential pressure. The constant adjusts for the dimensional units, non-ideal fluid losses and behavior, discharge coefficients, pressure tap location, gas expansion factor, and the Reynolds number.

It should be noted that this principle has been illustrated assuming an incompressible fluid. However, the relationship is valid with some modification for compressible fluids as well. When used in applications involving compressible fluids, factors accounting for the change in density and energy loss from friction must also be included.

All head-type differential pressure flowmeters operate on the conservation of energy principle. The

primary sensing element creates a differential pressure by constricting the fluid flow, while a secondary element measures this differential pressure.

Converting this measured differential pressure to flow rate is fairly complex. The following equation expresses the relationship between differential pressure and flow:

$$Q = CA \sqrt{2gh}$$

where:

- Q = flow
- C = orifice coefficient
- A = cross-sectional area of the restriction
- g = gravitational constant
- h = head or differential pressure

The value of C depends on the diameters of the pipe and the orifice. For circular pipes and circular restrictions, the Beta ratio is the ratio between the diameter of the restriction and the inside diameter of the pipe. The ratio between the velocity in the pipe and the velocity at the restriction is equal to the ratio of areas, or Beta squared. For configurations which are non-circular, it is defined as the square root of the ratio of the area of the restriction to the area of the pipe or conduit. Values for C for several calibrated restrictions are shown in Figure 4-3.

This square root or "square law" relationship of flow to differential pressure makes some disadvantages of head-type flowmeters apparent. Measurement of flows of less than 30 percent of maximum may be less accurate than a measurement at a higher percent of maximum flow. The square root relationship also makes integrating or totalizing of flows cumbersome and the accuracy of totalized flow somewhat questionable. In addition, this relationship represents a nonlinear effect on loop gain in flow control systems, requiring controller readjustment at different rates of flow. The nonlinear effect results in a loss of accuracy below 50 percent of the measurement span.

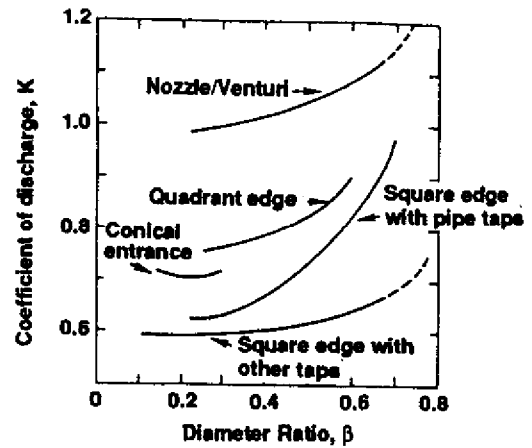


Figure 4-3. Coefficient/ β (Beta) Ratio

Orifice Plate

The most common and the simplest differential producer is the orifice plate. Orifice plates are easy to construct, install, inspect, and to replace, if damaged. The simplicity of this device also permits substitutions to be made easily if changes in flow rates are required.

An orifice plate is usually composed of stainless steel. An opening of a predetermined size and shape is machined into the plate according to strict tolerances. Then, the orifice plate is inserted perpendicular to the process flow. This abruptly reduces the stream size, creating a head-producing constriction. Differential pressure is then measured at pressure taps installed upstream and downstream from the orifice plate.

The placement of the pressure taps is critical to flow measurement. Proper tap placement will provide correct differential pressure measurement to accurately determine flow rate. When an orifice plate is installed in the flow path, turbulent flow swirls on both sides of the plate. The exact point of smallest flow diameter on the down stream side of the orifice plate is indefinite. Even after the flow has passed the orifice, the flow continues to decrease in the cross-sectional area (see Figure 4-4). This causes the velocity to increase.

The point of narrowest constriction, and the point closest to the lowest static pressure, is called the vena contracta. Since this point will produce the greatest difference in the two related pressures, it is theoretically

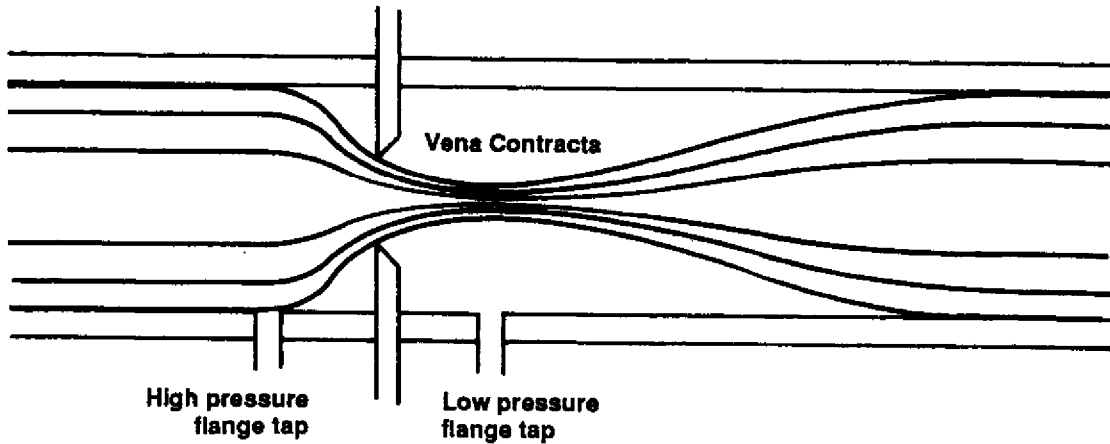


Figure 4-4. Flow Pattern with Orifice Plate

the best location for a downstream tap. However, the area immediately downstream of the vena contracta is extremely unstable. Therefore, positioning a tap at this location will adversely affect measurement accuracy.

When used, pipe taps should be positioned at a distance equal to eight pipe IDs (inside diameters) downstream from the face of the orifice, and at five pipe IDs upstream from the face of the orifice. When flange taps are used, they should be positioned in the flange one inch upstream of the face of the orifice plate and one inch downstream from the back of the orifice plate. The orifice plate should be installed in a line to allow a straight run of a minimum of eight pipe IDs on the upstream side of the orifice, and five pipe IDs on the downstream side of the orifice. This arrangement is referred to as an orifice run, and it will reduce any turbulence that could affect measurement accuracy. Vena contracta taps are located a distance of one pipe ID upstream from the orifice and at the plane of minimum pressure, or the vena contracta. The locations of these various orifice taps are shown in Figure 4-5.

One advantage of orifice plates is that they are capable of metering either gases or liquids with high degrees of accuracy. Since orifice plates are applicable for a wide range of processes, several designs are used. Different types of orifice plate designs are illustrated in Figure 4-6.

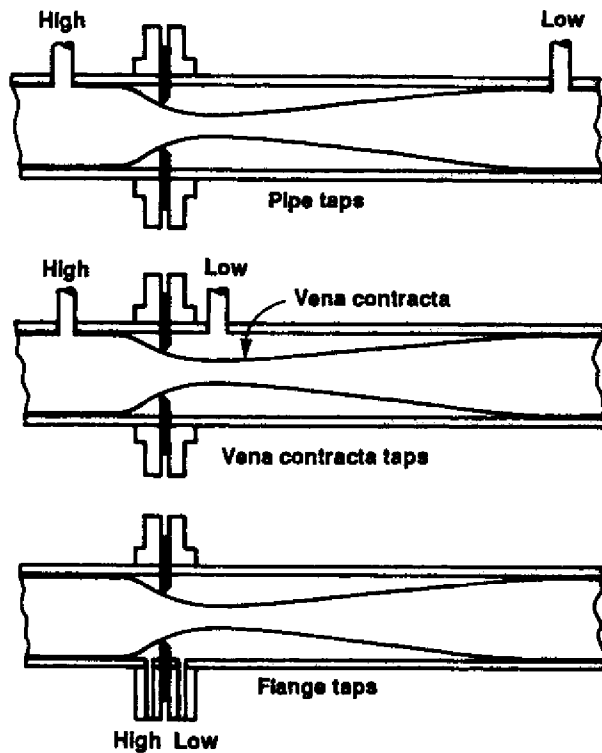


Figure 4-5. Tap Locations in Orifice Installations

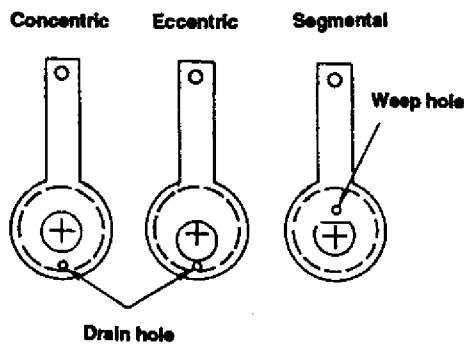


Figure 4-6. Orifice Plate Designs

The most common type of orifice plate is the concentric bore. This design is suitable for most clean fluids. With this type of orifice plate, a circular hole is machined in the plate so that when the plate is installed, the hole will be in the center of the pipe.

An eccentric bore plate is used to minimize measurement inaccuracies that can be caused by solids settling out of the liquid. With this type of plate, the position of the machined hole is off-center. The eccentric bore is positioned so that the bottom of the hole is even with the inside wall of the pipe, allowing the solids to be swept through the orifice plate. For gas applications, this bore is installed at the top of the pipe. When the flow rate of liquids that contain solids is being measured the particles in the liquid can settle on the bottom of the pipe.

This causes the pipe area to become smaller and the pipe is no longer round. This affects the pressure drop across the orifice which will affect the flow measurement. When solids are very heavy, a segmental orifice plate may be used. In these applications, the rounded part of the orifice is located at the bottom of the pipe when the flow rate of liquids is being measured; the rounded part is located at the top of the pipe when the device is used to measure the flow rate of gases.

Both eccentric bore plates and segmented plates allow particulate matter to flow through the orifice plate instead of building up in front of it and affecting the accuracy of flow measurement. The segmental orifice plate can also be used in process applications that measure the flow of slurries, although its accuracy is less reliable under those conditions.

Orifice plates may also be provided with small vent holes, or weep holes, located either at the top or the bottom of the plate. In gas applications where the measured fluid is saturated, condensation can occur. The condensate can build up in front of the plate, causing errors in the flow rate measurements. The weep hole is positioned in the bottom of the plate to permit liquid condensate to drain through without introducing error. In liquid applications, the weep hole is positioned at the top of the plate to permit entrained vapor to flow through the orifice plate and reduce errors in flow measurement.

Because orifice plates have no moving parts, they require very little maintenance. However, weep holes and pressure taps may become clogged with foreign matter. These conditions can cause measurement inaccuracies to occur. Bore wear will also eventually affect measurement accuracy. When any of these conditions exist, the orifice plate should be removed and cleaned, or replaced.

Venturi Tubes

Another widely used head-type differential pressure device is the venturi tube (see Figure 4-7). The venturi tube places a constriction in the flow path that acts on the same principle as that of the orifice plate. In basic forms, the venturi tube consists of a converging conical inlet, a cylindrical throat, and a diverging recovery cone. With a venturi tube, the velocity of flow gradually increases as the fluid passes through the inlet. This results in an increase in velocity and a decrease in static pressure. The cylindrical throat, positioned where flow rate is stable, measures this decreased static

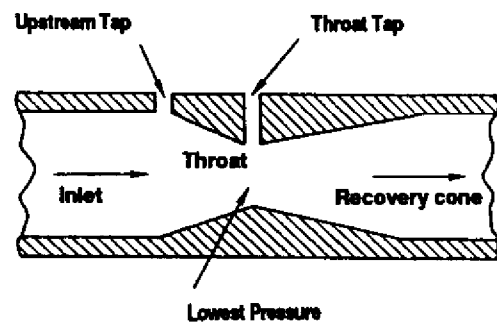


Figure 4-7. Venturi Principle

pressure. Static pressure then increases and recovers in the diverging recovery cone. Pressure taps used to measure the difference in pressure in the venturi tube are usually positioned at one-half pipe diameter upstream of the inlet cone and at the middle of the throat.

The walls and throat of a venturi tube are smooth, with no sudden changes in contour to prevent solids from becoming trapped. These design elements or features cause venturi tubes to be better suited for the measurement of dirty fluids and slurries which would tend to build up in front of, or clog an orifice plate. However, in processes containing solids, it is difficult to prevent pressure taps from becoming plugged. To minimize buildup of materials, the venturi tube is sometimes modified to an eccentric configuration (see Figure 4-8) in which the bottom of the throat is in the same horizontal plane as the bottom of the connecting pipe. This modification allows unobstructed passage of solids through the venturi.

In general, the performance and limitations of orifice plates and venturi tubes are comparable. Both are equipped to provide highly accurate differential pressure measurements in support of flow measuring systems.

Flow Nozzles

Flow nozzles are another type of differential head producing device used with differential pressure flowmeters. Flow nozzles are a restriction consisting of an elliptical contoured inlet and a cylindrical throat section. A flow nozzle is illustrated in Figure 4-9. Pressure taps used to measure the difference in static pressure created by a flow nozzle are commonly located one pipe diameter upstream and one-half pipe diameter downstream from the inlet face of the nozzle.

Flow nozzles are well suited for measurement of steam flow and other high velocity fluid flows where

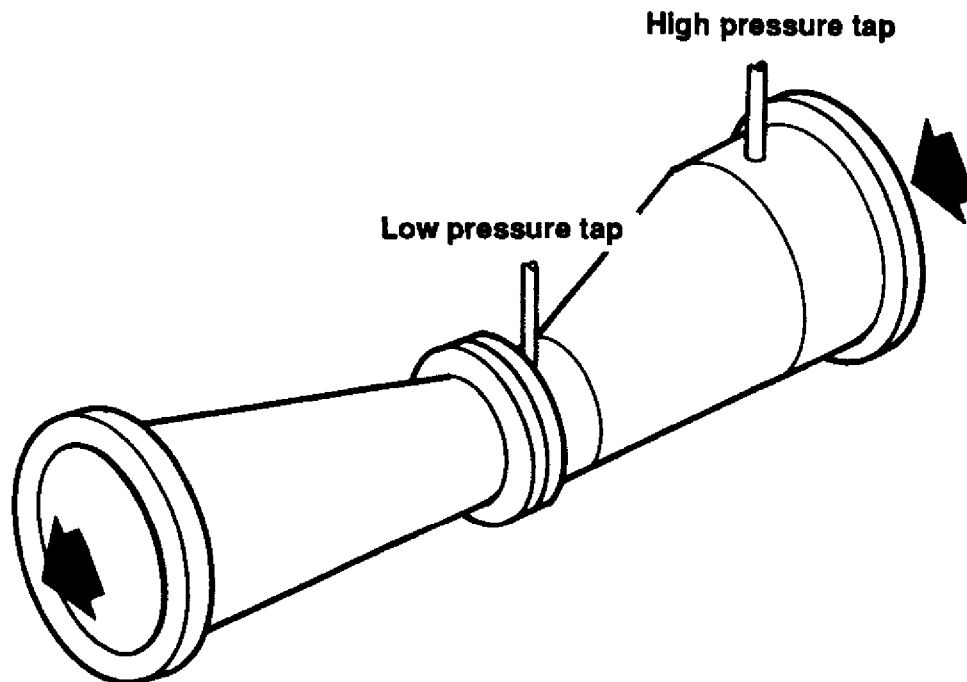


Figure 4-8. Eccentric Venturi Tube

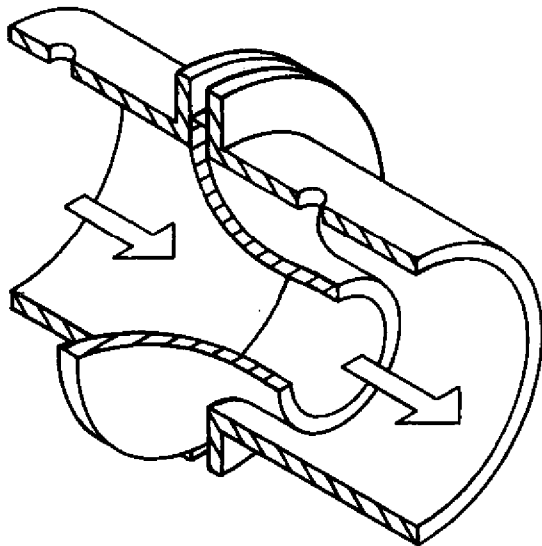


Figure 4-9. Flow Nozzle

erosion may be a problem. Unlike the orifice plate, the exact contour of the flow nozzle is not critical to measurement. So flow nozzles can be expected to retain their precise calibration longer than orifice plates. Like venturi tubes, flow nozzles are also suited for process applications involving slurries.

Elbow-Tap Flowmeters

Elbow-tap flowmeters operate on the principle that when a fluid moves around a curved path, the acceleration of the fluid around the curved path creates a centrifugal force. A typical elbow-tap flowmeter is shown in Figure 4-10. In operation, the centrifugal force results in a higher pressure on the outside of the elbow than on the inside of the elbow. Thus a differential pressure is produced which is proportional to the square of the flow through the elbow.

Pressure taps installed on opposite sides of the elbow can be used to measure the difference in pressure. This differential can be used to calculate flow rate.

A major advantage of elbow-tap flowmeters is the ease with which they can be installed. Because most piping configurations contain elbows, taps can be installed economically. When placed in an existing pipe

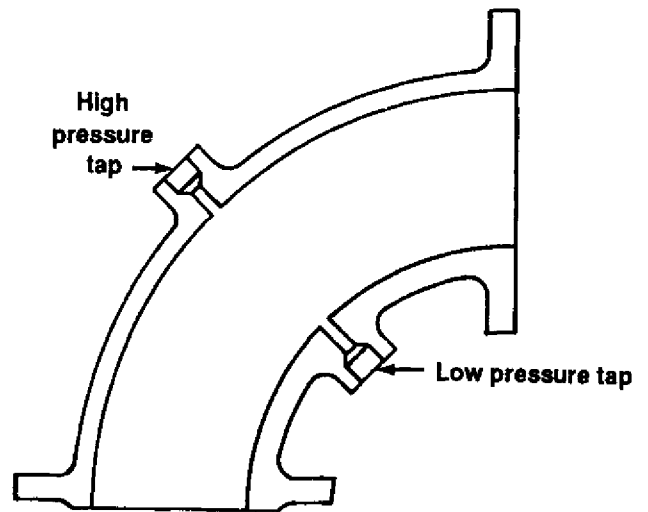


Figure 4-10. Elbow-tap Flowmeter

elbow, there is no added pressure loss. However, elbow-tap flowmeters are less accurate than other head-type measurement devices. In addition, elbow taps develop relatively low differential pressure and may be unsuitable for flow measurement applications with low velocity fluids.

Pitot Tubes

Basically, a Pitot tube consists of two pressure taps in a flow stream (see Figure 4-11). The low pressure tap

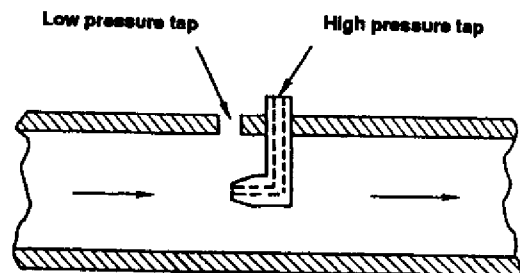


Figure 4-11. Pitot Tube

is perpendicular to the flow path and measures the static head. The high pressure tap is inserted into the flow stream and faces directly into the flow path. By measuring the differential pressure created by the Pitot tube, flow rate can be calculated.

A Pitot tube causes a negligible pressure loss in the flowing stream. However, this device can be difficult to position properly in the flow stream and is subject to plugging in slurry applications.

MAGNETIC, THERMAL AND ULTRASONIC FLOWMETERS

Magnetic Flowmeters

Magnetic flowmeters are widely used to measure the flow rate of conductive liquids in process applications. Recent technological developments have made them relatively easy to install and, often, more economical than other designs. A primary advantage of this type of instrument is that magnetic flowmeters provide virtually unobstructed flow. Because the flow path is relatively unobstructed, they are well suited to use with high viscosity fluids and process liquids containing solids. Important applications include flow measurement of sludge in sewage treatment plants, slurries in mining operations and liquid metals in various industrial processes.

In addition, magnetic flowmeters do not create pressure drop. Velocity is measured directly, and, thus, variations in density do not affect their accuracy. Further, these instruments are free of Reynolds number constraints; they may be used for measuring the velocity of liquids with any flow profile.

In general, magnetic flowmeters are accurate, reliable, measurement devices that do not intrude into the system. Often, these instruments can be maintained without shutting down the process. Further, since they produce an electrical output, this type of flowmeter is compatible with electronic control systems.

Principle of Operation

Magnetic flowmeters operate on the principle of Faraday's Law of Electromagnetic Induction. This law states that the voltage (E) induced in a conductor moving through a magnetic field at a right angle to the field is directly proportional to the number of conductors, or, as in this case, the distance between the probes (D), the intensity of the magnetic field (B) and the velocity of the motion of the conductor (v).

$$E = \text{constant} \times D \times B \times v$$

When these three factors are present, an electrical voltage is induced in a conductor that is moving through a magnetic field and at right angles to the field. The faster the conductor moves through the magnetic field, the greater the voltage induced in the conductor.

Figure 5-1 demonstrates how a magnetic flowmeter applies this principle. The flowmeter itself consists of a straight length of pipe. This is called the metering section; it is made of nonmagnetic material. In this case, the process fluid serves as the conductor. The direction of the induced voltage will be perpendicular to both the motion of the conductor and the magnetic field. The magnetic field is produced by either electromagnetic coils or permanent magnets that are positioned on opposite sides of the short length of the

non-magnetic pipe.

As the fluid passes through the magnetic field, a voltage is generated. Two electrodes projecting through the metering tube lining pick up the induced voltage. Wires connected to the electrodes can be attached to a meter that will measure the amount of

voltage produced. Since the magnetic field is constant, the induced voltage is directly proportional to the velocity of the liquid and, thus, to the volumetric flow rate of the liquid passing through the meter. This measured voltage can be used to calculate flow rate.

In pipes, the induced voltage can be determined

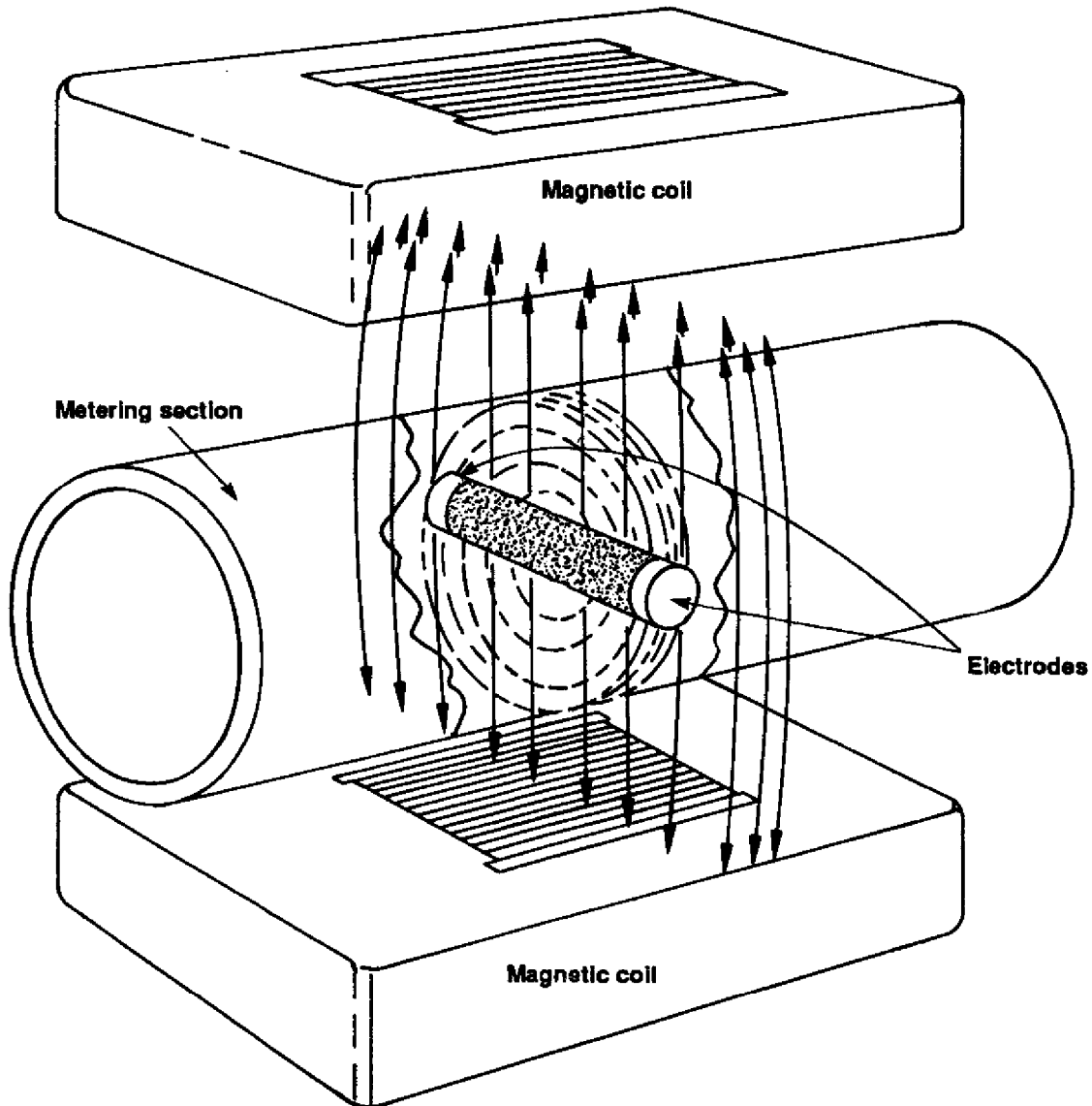


Figure 5-1. Magnetic Flow Principle

from Faraday's equation:

$$E = \text{constant} \times B \times D \times v$$

$$E = (\text{constant} \times B \times 4/\pi \times D) \times Q$$

where Q is determined by the equation $Q = A \times v$ and A is $\pi \times D^2/4$.

All the terms in parentheses are held constant in a magnetic flowmeter. Therefore, the induced voltage output is linearly proportional to the changes in flow rate (Q). This rate of flow can be calculated and indicated as flow rate, volumetric flow rate or mass flow rate.

AC Magnetic Flowmeters

Alternating current (AC) magnetic flowmeters excite the electromagnetic field with AC current. A typical AC magnetic flowmeter is shown in Figure 5-2.

Two problems must be considered when using AC flowmeters to measure flow. The first is signal distortion and interference caused by extraneous voltages or noises. Noise may either be induced by or already present in the system. Because voltages induced by the

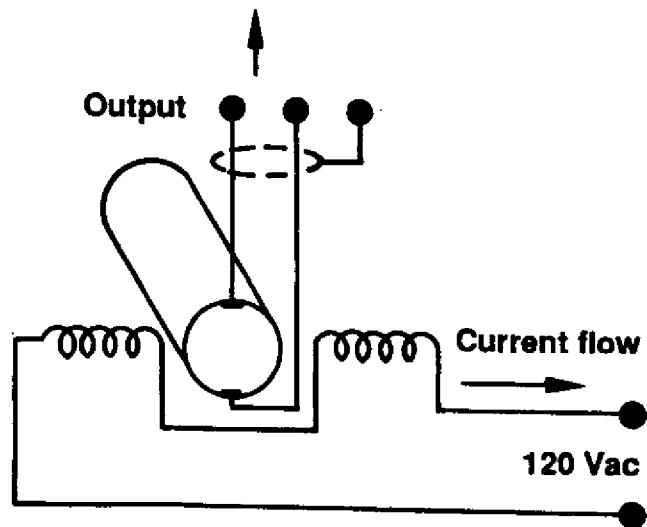


Figure 5-2. AC Flowmeter

electromagnetic field are relatively small in comparison to the extraneous voltages, measurement accuracy can be seriously affected.

Noise may be produced within the meter or within the process. The liquid itself may bear trace voltages induced from exposure to a source of electromagnetic interference upstream, or a static charge may be produced by friction. Stray voltages caused by this noise, can be picked up by the electrodes and introduce substantial inaccuracies in the measurement. Such sources of noise can be partially eliminated with a zero adjustment in the measuring instrument. The zero must be adjusted when the flowmeter is full of process fluid at zero flow.

The second problem that can adversely affect the accuracy of AC flowmeter measurements is that the sensitivity of the electrodes may be reduced if the electrodes become coated with a non-conductive material, either from electrolytic by-products of the process or by clinging process material. Buildup usually occurs gradually, but the effects over time can be significant.

Some magnetic flowmeters are available with removable electrodes. This option allows the electrodes to be inspected periodically and cleaned, if necessary, without dismantling the meter. Ultrasonic cleaning systems are also available to remove accumulated non-conductive material from electrodes without opening the system.

DC Magnetic Flowmeters

Direct current (DC) magnetic flowmeters excite the electro-magnetic field with a DC current. A typical arrangement of a DC magnetic flowmeter is shown in Figure 5-3. When the liquid flows through the magnetic field, a voltage is induced in the liquid. The voltage is picked up at the electrodes. The voltage measured represents the sum of the flow induced in the moving conductor and the noise present in the system. To eliminate the effect of noise, the device is zeroed when there is no process flow and the electrodes only detect extraneous voltages. With flow restored, the output of the meter will only indicate voltage induced by the process.

DC magnetic flowmeters are not subject to inaccuracies due to the coating of electrodes. As long as

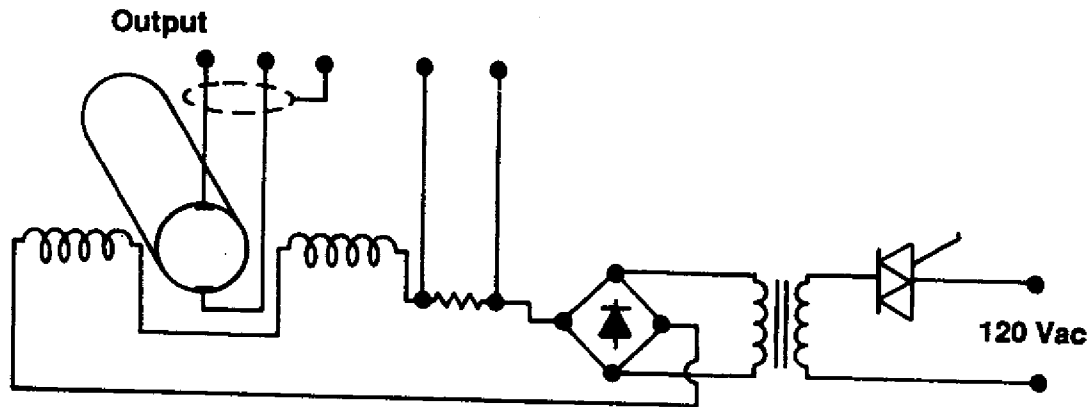


Figure 5-3. DC Magnetic Flowmeter

electrode sensitivity remains high enough for a DC flowmeter to operate, its performance is relatively unaffected. Miniature DC magnetic flowmeters are also widely used in miniaturized electronic circuits. These instruments weigh less and have reduced power requirements.

Thermal Flowmeters

In a thermal flowmeter, flow rate is measured either by monitoring the cooling action of the flow on a heated element placed in the flow or by the transfer of heat energy between two points along the flow path. Hot wire anemometers and the calorimetric flowmeters are two common types of thermal flowmeters.

Either type can be used to measure mass flow rate, making both types especially suitable for gas applications. However, neither instrument is grouped with mass flowmeters because they do not measure mass directly. Rather, mass is inferred from the thermal behavior and properties of the fluid.

Hot Wire Anemometers

Hot wire anemometers have probes inserted into the process flow. These probes are usually connected in a typical bridge circuit. In the configuration shown

in Figure 5-4, one of two probes is heated to a specific temperature. The second probe measures the temperature of the fluid. As the flow increases, it causes a heat loss in the heated probe. Consequently, more current is required to maintain the probe at the correct temperature. The increase in current flow reflects the energy necessary to compensate for the heat loss from the probe that was caused by the changing fluid flow. This change in current flow can be measured and used to calculate mass flow rate.

Proper operation requires that thermal conductivity (the ability of the heat to be conducted from the probe to the fluid) and heat capacity (the quantity of heat that a given mass requires to raise its temperature a specified amount) are assumed to be constant.

Calorimetric Flowmeters

Calorimetric flowmeters work on the principle of heat transfer by the flow of fluid. Typically, calorimetric flowmeters are comprised of elements arranged consecutively along the direction of the flow. Figure 5-5 illustrates this configuration. A heating element is placed in the flow. A sensor is positioned to measure the temperature upstream of the device; a second measuring device reads the temperature of the flow downstream from the heater. The rate of flow is

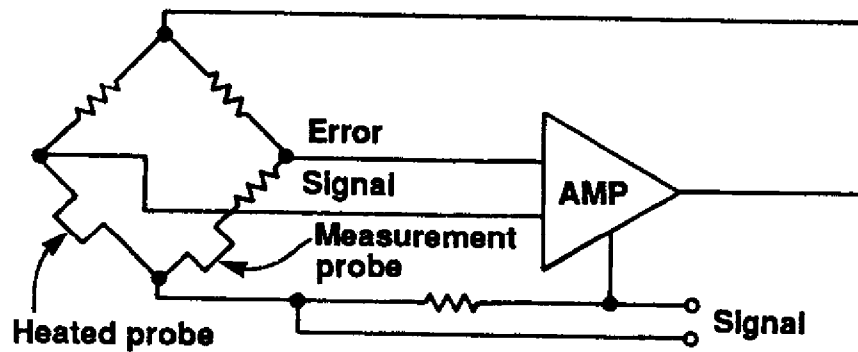


Figure 5-4. Diagram of Thermal Operating Principle

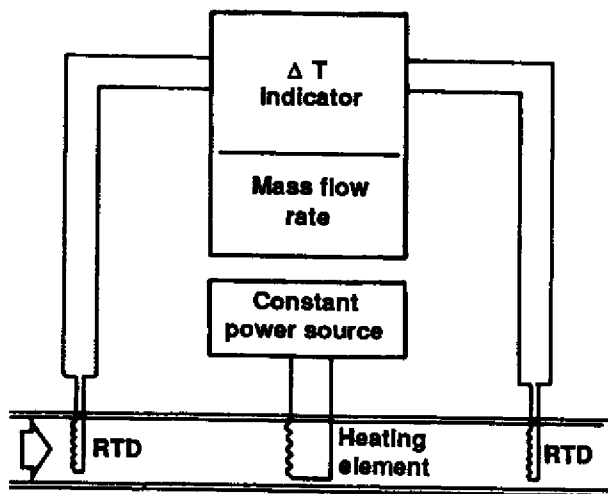


Figure 5-5. Calorimetric Flowmeter

determined by the difference in the two temperatures.

With a constant power input, this difference in temperature is a linear function of the mass flow and the heat capacity. The flowmeter can then be calibrated to indicate directly in mass flow units.

Applications of thermal flowmeters are limited to use with fluids that have known heat capacities. Usually these are clean gases or clean mixtures of pure gases of known composition where heat capacity is known and is constant during flowmeter operation. Liquid applications are less common because liquids generally contain more impurities than gases.

Thermal flowmeter designs can measure fluid flow at temperatures as high as 450° Celsius, although most have a temperature rating between 100 and 150 degrees Celsius. Pressure ratings are normally limited by the pressure rating of the flange or connection.

Conductive surfaces of a thermal flowmeter can become contaminated and should be routinely cleaned to maintain performance levels. In addition, thermal flowmeters are sensitive to the thermal conductivity between the probes and the fluid, and any change will affect the measurement. Therefore, these devices are generally not applied to abrasive fluid service where sensor wear may be a factor. Some thermal flowmeters are available with replaceable sensors.

Ultrasonic Flowmeters

Ultrasonic flow instruments measure the velocity of sound as it passes through the fluid flowing in a pipe. Some designs allow measurements to be made external to the pipe, while others require that the sensor be in contact with the flowstream. Thus, the sensor may be clamped onto the pipe or may be mounted in a section of pipe which is installed in the system.

Ultrasonic devices use sound waves or vibrations to detect the flow in a pipe. The measurement is based on the time of flight of the sound waves. Pulses are transmitted along and against the fluid flow. The transmitted beam is usually projected at an angle in the pipe. There are usually two transducers, one is located upstream of the other. The time of transit of the ultrasonic beam is measured and used to calculate the

flow through the pipe.

Two types of transducers are generally used in ultrasonic flowmeter applications: clamp-on transducers and inserted transducers. Clamp-on transducers are attached to the exterior of the pipe (see Figure 5-6A). Since the transducers are not in contact with the process fluid, the materials of construction are not a consideration. Clamp-on transducers are capable of operating faster than inserted transducers. This is because the sonic echo is away from the receiver in clamp-on applications and not caught up in an "echo change" as is the case with inserted transducers that face each other.

Inserted, or wetted ultrasonic transducers (see Figure 5-6B) are considered more accurate than the clamp-on type. Direct contact with the liquid results in a superior signal-to-noise ratio. However, variations in sonic velocity due to changes in fluid properties will affect the performance of the flowmeter.

In addition, since the transducer is in contact with the process fluid, the materials of construction must not react with the process. Stainless steel is typically used for ultrasonic transducers. Some designs allow for

removal of the transducer while fluid is flowing in the pipe. Others require that the pipe be drained before removing the transducer.

Clamp-on transducers can be designed to operate in the shear or axial beam mode. These modes are illustrated in Figure 5-7. In the shear mode, the ultrasonic energy is focused into the liquid so that the signal at the receiver shifts positions as the flow varies. As a result, if the sonic properties of the liquid vary, the signal can miss the receiver and not be sensed.

Axial beam injection (see Figure 5-7) avoids this problem by focusing the energy axially along the length of the pipe, covering the receiver with the signal. Thus, the flowmeter is less sensitive to changes in the sonic properties of the liquid.

Time of flight type devices can measure flows of clean liquids as well as liquids that contain up to 30 percent solids. Clamp-on designs, however, require that the pipe be sonically conductive, since the ultrasonic energy is transmitted to and received from the liquid through the pipe wall. There must be no air gap, or interface, between the transmitter and the pipe wall or the sensor and the pipe wall.

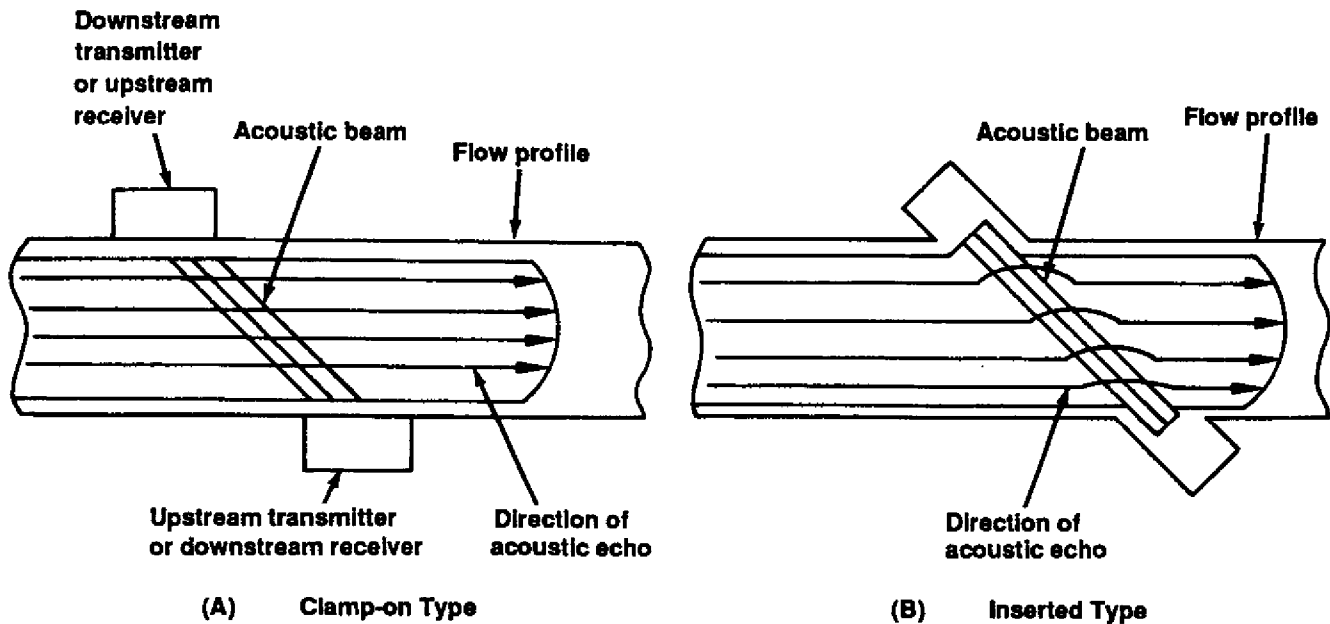
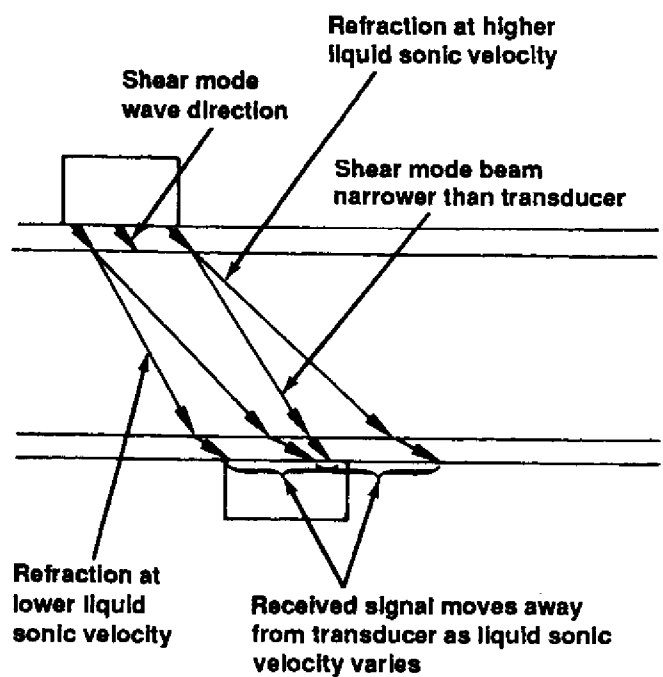
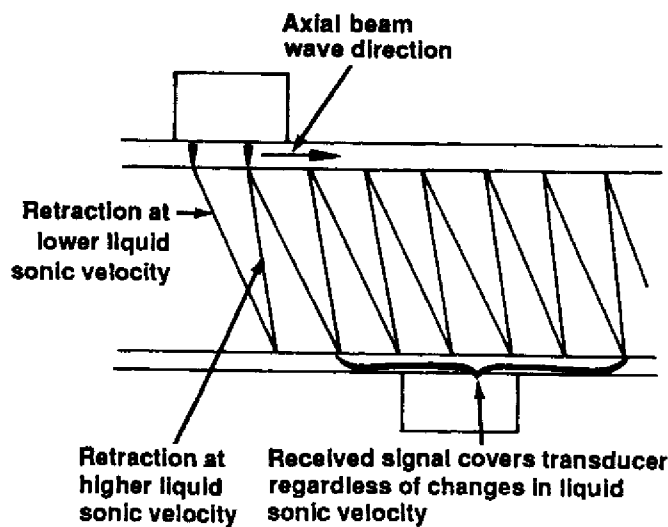


Figure 5-6. Time of Flight Flowmeters



(A) Shear Mode



(B) Axial Mode

Figure 5-7. Wave Propagation

MASS FLOWMETERS

In some industrial processes, accurate measurement of mass flow is required. Mass is defined as a measure of the quantity of matter in a body. Mass is one of the three fundamental quantities, the others being length and time, upon which all physical measurements are based. Often mass is thought of as weight, but these quantities are dissimilar. Weight is the measure of the effect of earth's gravity on mass and varies over the earth's surface.

Mass is independent of both the physical properties of matter and the ambient condition in which the measurement is taken. Thus, mass can be measured in two ways. True mass flow measurement is one that is a direct measurement of the mass, independent of the properties and the state of the fluid. A mass flowmeter is an instrument in which the reaction of the sensing element is proportional to the true mass flow rate. In such a device, mass is determined by measuring force and acceleration. These instruments are based on the precepts of Newton's second law: an unbalanced system of forces acting on a body produces an acceleration in the direction of the unbalanced force that varies in inverse proportion to the mass of the body.

Inferential mass flow measurement is dependent on a combination of the independent measurements of density and velocity. A volumetric flow rate is measured and then converted to mass flow, hence, an inferential, rather than direct, measurement of flow is made.

If a variation in density is characteristic of the process, these measurements may not accurately reflect the true mass of the flow and must be corrected by calculation.

Angular Momentum Mass Flowmeter

The angular momentum mass flowmeter is a true mass flowmeter since the reaction of the primary element is proportional to the momentum of the flow stream.

In this type of device (see Figure 6-1), fluid passes

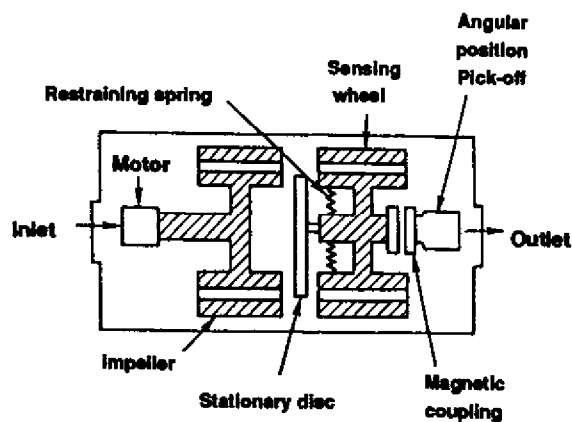


Figure 6-1. Angular Momentum Flowmeter

through an impeller and a turbine mounted in series in a pipeline. The impeller is driven at a constant speed by a small motor. As it is rotated, it causes the fluid entering the impeller to take on its rotational velocity. When exiting the impeller, the fluid has an angular velocity equal to that of the impeller in addition to the normal axial momentum of the stream.

The fluid then enters a turbine that is restrained by a calibrated spring and does not rotate. The turbine removes the angular momentum from the stream and this movement is transferred to the turbine. The torque produced by the turbine on the calibrated spring is directly proportional to the mass flow. Conversely, if the torque produced by the stream on the turbine is kept constant by varying impeller rotational speed, the rotational speed is inversely proportional to the mass flow.

Coriolis Flowmeters

The Coriolis flowmeter is a true mass flowmeter which operates on the physical principle of the effects

of the earth's rotation on a mass. This effect is referred to as the Coriolis acceleration and produces a Coriolis force. It is the Coriolis force that makes water in a vortex swirl clockwise in the northern hemisphere and counterclockwise in the southern hemisphere.

An illustration of this principle is shown in Figure 6-2. Consider the person standing at the center of the rotating platform shown in Figure 6-2A. Since the person is standing in the same place, his distance from the center of rotation is constant, and the rotational speed of the turntable is constant, the force exerted on the person in this plane is zero.

However, as indicated in Figure 6-2B, a person walking radially outward on the rotating platform would experience the Coriolis force acting in the plane of rotation, and tangential to that plane as he attempted to move. Thus, he must lean toward, or direct the mass of his body against the force produced by the Coriolis acceleration. The Coriolis force is created as a result of the Coriolis acceleration acting on the person as he changes position in relation to the center of rotation of

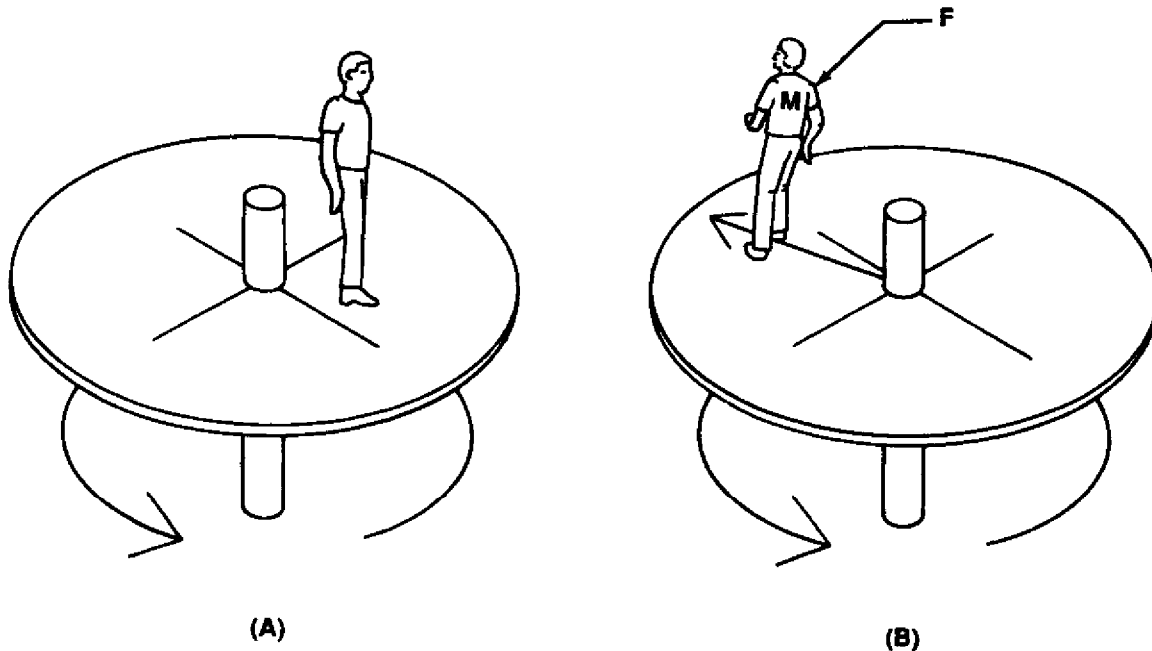


Figure 6-2. Coriolis Acceleration

the turntable. Since torque is equal to mass multiplied by acceleration, a measurement of the Coriolis force provides the means for a direct determination of mass flow.

One type of Coriolis mass flowmeter consists of an impeller with radial vanes. The meter is positioned so the vanes are in line with the flow (see Figure 6-3). The impeller, powered by a small motor turns at a constant rate. The vanes direct the flow in a direction that is radial and perpendicular to the axis of rotation.

As in the case of the person on the revolving platform, this results in a Coriolis acceleration which then exerts a force on the vanes. Force-sensing devices measure the torque produced, and, since the amount of torque is directly proportional to the mass flow rate, the value can be used to calculate the rate directly. This device has a quick response time, so it is especially applicable for processes with rapidly changing flows.

The vibrating U-tube is another type of mass flowmeter that uses the principle of Coriolis acceleration of a fluid. The U-tube offers no obstruction to the flow-path allowing it to measure liquids with varying physical properties. In addition, this type of flowmeter may

be used with liquids containing solids. Vibrating U-tube flowmeters are also suitable for measuring corrosive, abrasive and very viscous materials. They may also be used in gas applications where the gas has a density sufficient to generate the force necessary to produce a measurable deflection in the tube. As with other Coriolis mass flowmeters, there are no Reynolds number constraints. Figure 6-4 shows a device of this type. The flowmeter consists of a vibrating U-tube in which the Coriolis acceleration is created and measured.

In operation, process fluid flows through the tube. As it does, an oscillator vibrates the tube rapidly along the axis formed between its open ends. An angular motion is created in the tube, which can be equated to the rotating platform; while the flowing process fluid is equivalent to the person attempting to walk toward the edge. Thus, a Coriolis acceleration is induced, but, because the motion is oscillatory, the direction of the acceleration alternates.

Because of this alternation, the fluid in one arm of the tube flows away from the axis of rotation while in the other half, the same amount of fluid flows towards

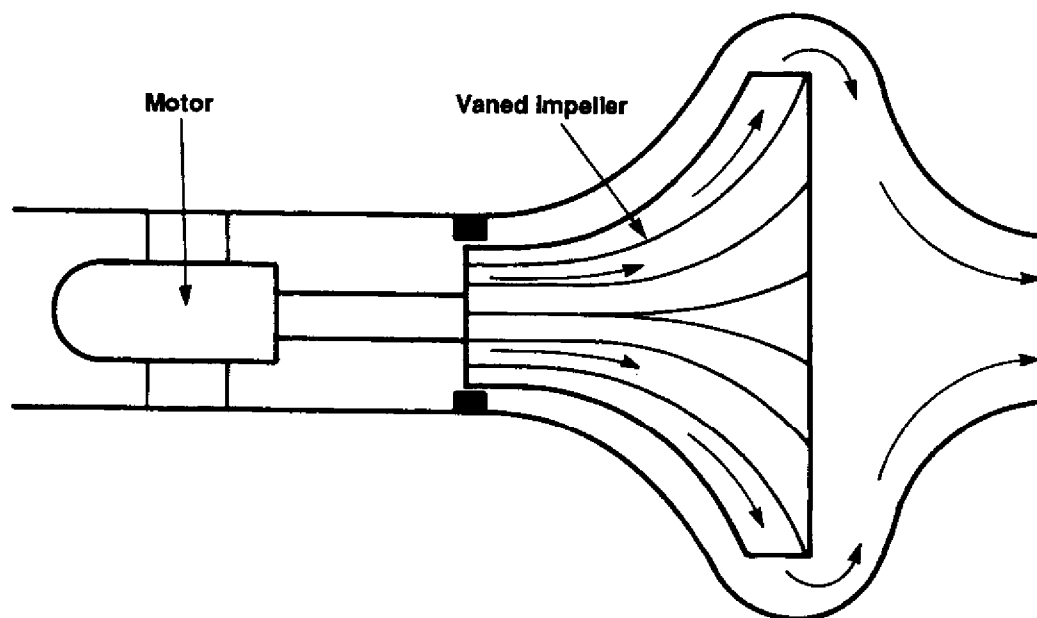


Figure 6-3. Coriolis Mass Flowmeter (Vaned Type)

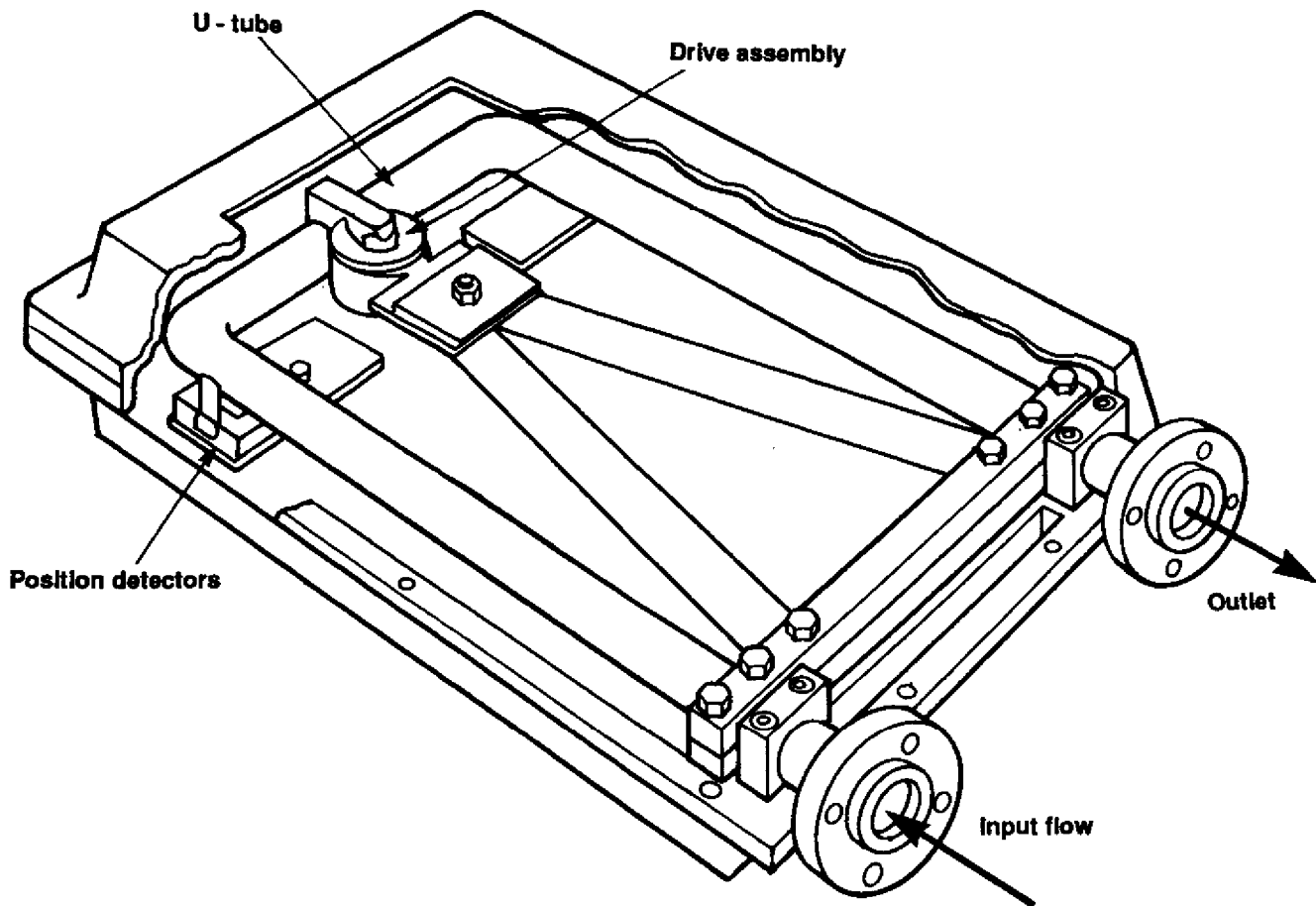


Figure 6-4. Vibrating U-Tube

the axis of rotation. At any given moment, the fluid in each half of the U-tube has an associated Coriolis acceleration that acts in opposite directions. These opposing Coriolis accelerations result in forces in the opposite directions, which produce a twisting motion in the tube (see Figure 6-5). The amount of motion which is directly proportional to the mass flow through the U-tube, is detected by a sensing device.

Hydraulic Wheatstone Bridges

The hydraulic wheatstone bridge mass flowmeter is a true mass flowmeter which uses differential pressure to measure the mass flow. In principle, it is the

hydraulic equivalent of the electrical wheatstone bridge. A typical configuration utilizing the wheatstone bridge principle is shown in Figure 6-6.

Four identical orifice plates are placed in a wheatstone bridge arrangement. A portion of the flow is pumped at a constant rate from one segment of the fluid loop to another segment of the loop. A differential pressure transmitter is then used to sense the flow signal. The differential pressure across the flowmeter system is proportional to the mass flow rate. It is important to note, however, that the fluid density at all points in the transducer must remain constant, limiting the use of this device to liquid applications.

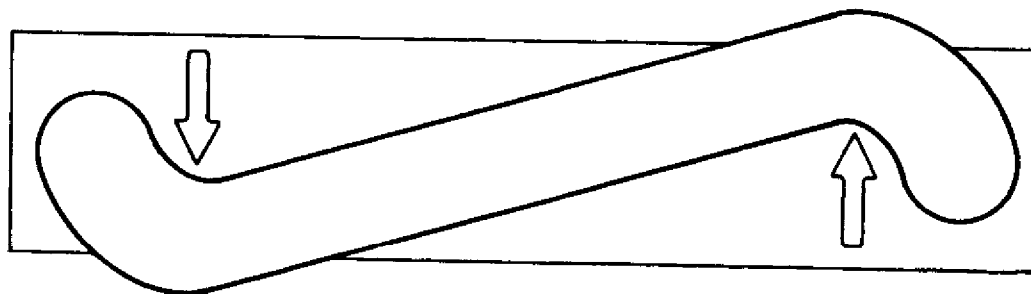


Figure 6-5. End View - Vibrating U-Tube

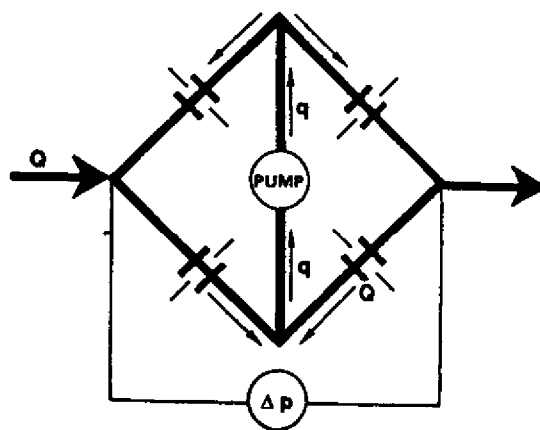


Figure 6-6. Wheatstone Bridge Configuration

POSITIVE DISPLACEMENT FLOWMETERS, AXIAL TURBINE FLOWMETERS AND ROTAMETERS

Positive Displacement Flowmeters

In many applications, positive displacement flowmeters provide significant advantages over meters of other classes. They are accurate, precise, have a wide flow range and are ideal for measuring low rates of flow. In addition, their operation requires no external power supply and they usually require only simple maintenance.

Positive displacement flowmeters operate by trapping a known quantity of fluid, and transferring the fluid from the inlet to the outlet connections. The measuring chamber follows a fixed path, and on each revolution the meter is filled at the inlet and discharged at the outlet. Thus, each volume of fluid displaces the previous volume. No volume of fluid is ever counted twice. Then the number of trapped volumes that pass through the meter is counted to measure the flow.

Positive displacement flowmeters also present serious disadvantages, however. Usually positive displacement meters are suitable only for clean liquids and gases. Abrasive particles in fluids can wear the closely machined parts and affect accuracy. In addition, the flowmeters may become plugged by solids. Placing a strainer upstream of the flowmeter can reduce this problem, although in high viscosity service, the pressure drop across the strainer may significantly affect the meter's accuracy.

Any gas present in the process liquid will also cause difficulties. Because of the nature of the operation of this class of flowmeter, it will read gas volumes as though they were liquid. A common means of resolving this problem is to position an air trap upstream of the flowmeter.

Nutating Disc Flowmeter

One of the earliest and most commonly used types of positive displacement flowmeters is the nutating disc. A typical nutating disc flowmeter is shown in Figure 7-1. The meter consists of a housing containing a disc which is allowed to wobble, or nutate. As fluid enters the inlet port of the meter, its movement in the chamber causes the disc to turn or nutate. As the disc turns, it transfers a fixed quantity of fluid from the inlet to the outlet. A counter drive pin attached to the disc moves a shaft that is connected to a counter meter to keep track of the volume of fluid that has passed through the meter.

For each disc nutation, a fixed volume of liquid passes through the meter. The total number of nutations, or turns, of the disc is a direct measure of the volume of liquid that passes through the meter.

Nutating disc flowmeters are generally applicable to clean, non-abrasive liquids. Slippage (leakage) can pose a problem in low viscosity applications. This type

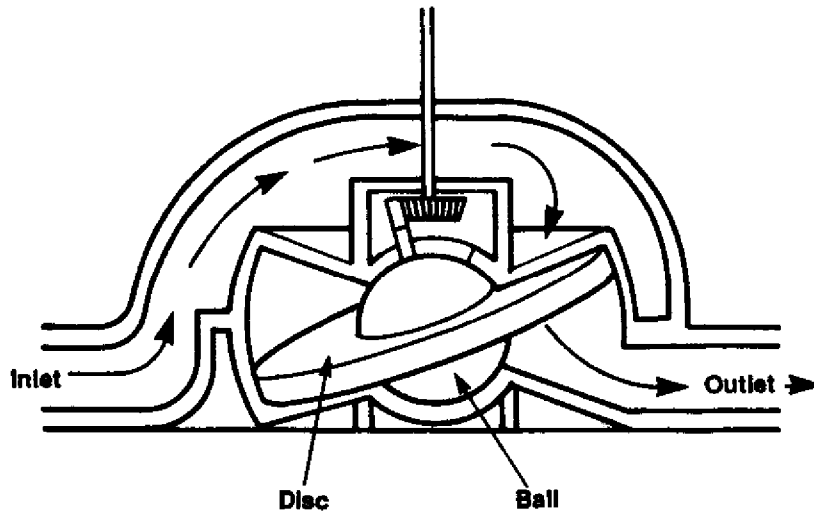


Figure 7-1. Nutating Disc

of flowmeter is commonly used to meter water for businesses and residences, due to its ability to measure low viscosity liquids reasonably well and economically.

Helical Gear Positive Displacement Flowmeter

Helical gear flowmeters are often used on extremely viscous liquid service where it is difficult to apply other flowmeters because of Reynolds number constraints. Although this design is somewhat tolerant of solids, helical gear flowmeters remain susceptible to overspeed and bearing damage.

Figure 7-2 illustrates a helical gear flowmeter. In this type of positive displacement flowmeter, two radially-pitched helical gears are used to continually trap liquid as it passes through the flowmeter. As the liquid passes through the meter, it causes the gears to turn. A sensing system, typically magnetic or optical, senses a pulse each time a portion of a revolution occurs. Flow through the flowmeter is proportional to the rotational speed of the gears.

Oscillating Piston Positive Displacement Flowmeters

Oscillating piston flowmeters are commonly used on higher viscosity liquid applications, as slippage can

pose a problem with low viscosity liquids, particularly if there is any wear on machined parts. In most cases, the design of the device further limits its use to the measurement of fluids with low flow rates, usually not exceeding 200 gpm.

The oscillating piston flowmeter illustrated in Figure 7-3 has a cylindrical measurement chamber. A partition plate separates the inlet port from the outlet port. A piston, positioned to fit off center in the chamber, is guided by a control roller so that it can slide around the inner walls of the chamber. The motion of the piston is oscillatory; the center of the piston moves around the control roller and the slot of the piston can only operate in one plane.

When a quantity of fluid enters the chamber it causes the piston to rotate on its shaft. As it does so, a specific volume of fluid is moved through the meter and discharged at the outlet port. Each revolution of the piston corresponds to the movement of a fixed volume of fluid through the meter. Thus, the rate of flow is proportional to the velocity of the piston. The motion of the piston can be transmitted to a magnetic sensing system. The sensing system can operate a flow indicator, a totalizer, or a transmitter.

Rotary Vane Flowmeters

Rotary vane meters are commonly used in both liquid and gas applications. Its widespread use is found

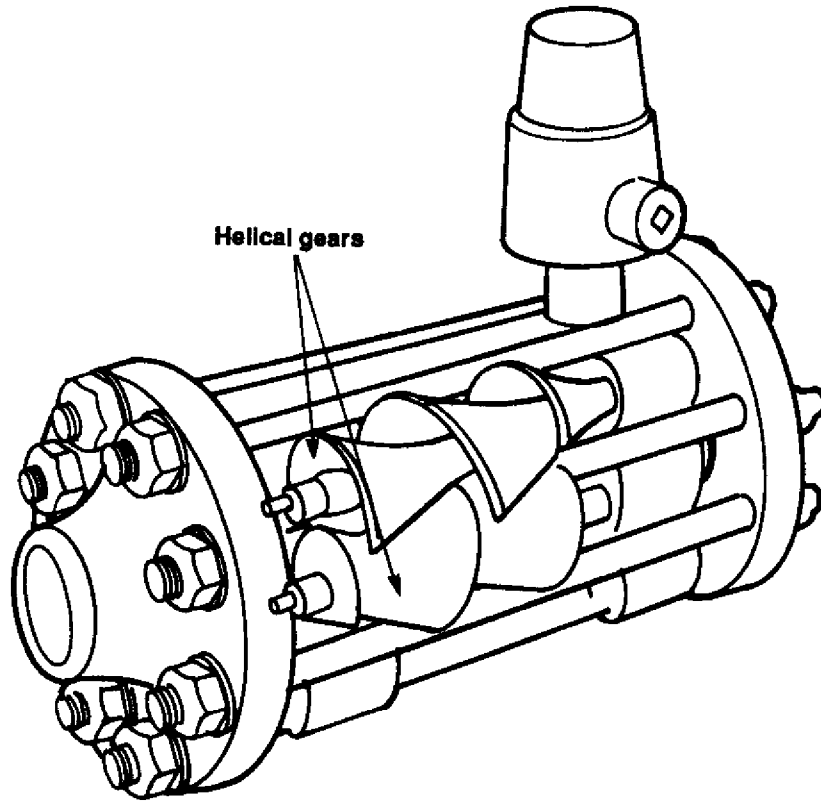


Figure 7-2. Helical Gear Positive Displacement Flowmeter

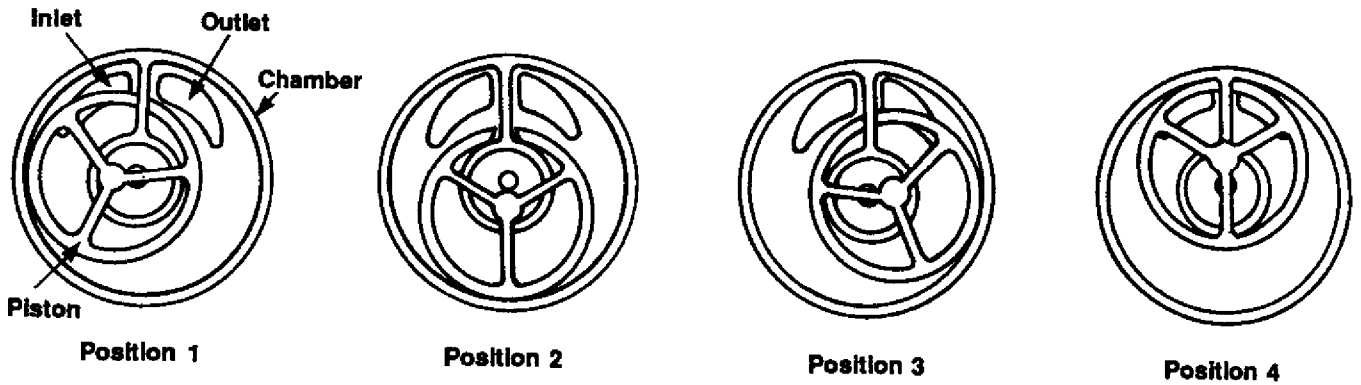


Figure 7-3. Oscillating Piston

in the petroleum industry, primarily for gasoline and crude oil metering. In a rotary vane flowmeter, spring-loaded vanes seal discreet quantities of fluid between the eccentric rotor and the housing of the instrument. These quantities of fluid are transported from inlet to outlet. A rotary vane flowmeter is shown in Figure 7-4.

As fluid enters the meter, the vanes are moved causing the rotor to turn. The vanes are spring loaded and able to slide freely in the rotor body as it turns. When the fluid enters the inlet port, the vanes extend against the housing wall to enclose the measuring chamber; they retract at the outlet to discharge the fluid into the system. Each complete revolution of the rotor moves several fixed volumes of fluid through the meter from inlet to outlet. Thus, the flow is proportional to the rotational velocity of the moving rotor.

Lobed Impeller and Oval Gear Flowmeters

Lobed flowmeters are used chiefly for gas service, although they may also be used for clean liquid

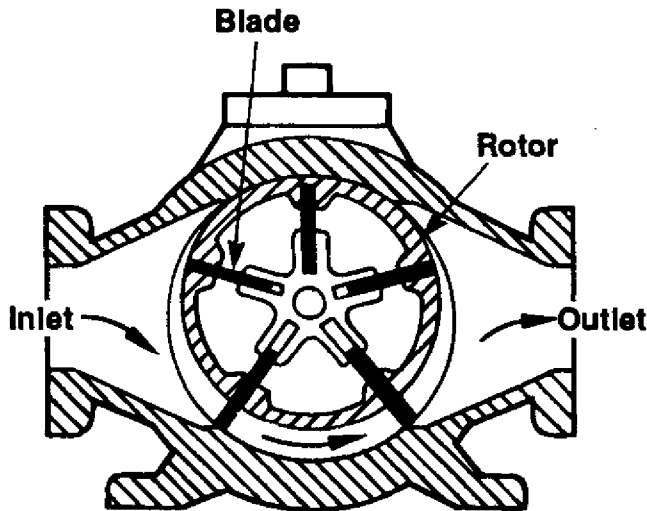


Figure 7-4. Rotary Flowmeter

applications. Oval gear meters, however, are used only for metering liquids to ensure that the gears remain wet and lubricated.

Lobed impeller and oval gear flowmeters operate in a similar fashion. In the lobed impeller flowmeter shown in Figure 7-5, two lobed impellers (rotors) are mounted on parallel shafts and are gear-synchronized to keep them correctly positioned in relation to each other. These lobes rotate in opposite directions, so as fluid enters the meter and causes the impellers to rotate, a measuring chamber is formed.

As with other meters of this class, a fixed volume of fluid is transferred from inlet to outlet with each revolution. A counter can be attached to one of the impeller shafts, which counts the number of revolutions of the impellers to give a measurement of total flow.

The oval gear flowmeter is a variation of the lobed impeller flowmeter. In this design, shown in Figure 7-6, the lobed impellers are replaced by a pair of meshed oval gears. The principle of operation for this

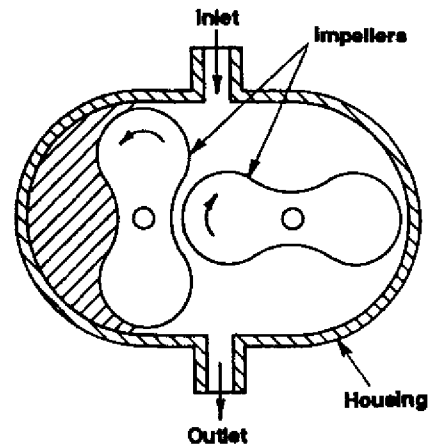


Figure 7-5. Lobed Impeller

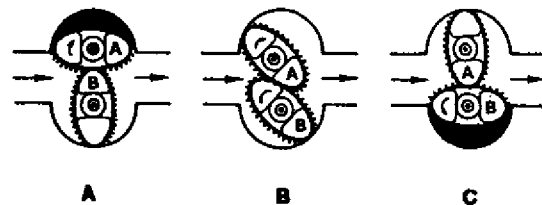


Figure 7-6. Oval Gear

type of meter is exactly the same as for the lobed impeller type. However, instead of being synchronized by an external gear the rotating gears keep the rotations synchronized. Again, by counting the number of revolutions made by the gears, an accurate measure of flow can be made.

Axial Turbine Flowmeters

Current-type flowmeters used in a pipeline are specifically designated turbine flowmeters. The current-type class differs only slightly in operating principle from positive displacement type flowmeters. In current-type meters, a discrete volume of fluid is not actually captured and transferred from inlet to outlet to measure flow rate as it is in a positive displacement meter. Rather, the total quantity of flow is inferred from the reaction of the turbine caused by the fluid flow.

Axial turbine flowmeters (see Figure 7-7) measure flow rate by measuring the velocity of the fluid flow in a pipe. Most designs incorporate a meter housing with end fittings for connection to a pipeline. A turbine rotor is mounted in the housing. Upstream of the rotor in the meter body is a section of straightening vanes which straighten the fluid flow as it enters the meter to ensure that it is free of swirls.

The fluid entering the meter causes the rotor to turn with velocity that is proportional to the fluid's flow velocity, and therefore, the flow rate. The rotor is linked to a sensing unit. As the rotor turns, either a counter records the number of revolutions or an electrical pulse is generated in a pick-up coil. This pulse is proportional to the rotational speed of the rotor and to the flow rate. Characteristically, turbine flowmeters develop a precisely known number of pulses for a given volume measured. This can be stated as:

$$\frac{\text{Cycles per time}}{\text{Volume per time}} = \frac{\text{Cycles}}{\text{Volume}} = \frac{\text{Meter}}{\text{Coefficient}}$$

Rotor designs used in axial turbine flowmeters vary from one model to another. Generally the rotor has a hub from which the flow vanes project. The hub rotates on sealed bearings. In turbine flowmeters used for gas service, the central hub is large. The large hub is used to create a venturi effect by decreasing the area in the pipe and, therefore, increasing the velocity of the gas. Since the torque driving the rotor depends on the gas density and the square of the velocity, it is important to increase velocity to ensure that there is sufficient torque to drive the rotor.

Turbine flowmeters are capable of a high degree of

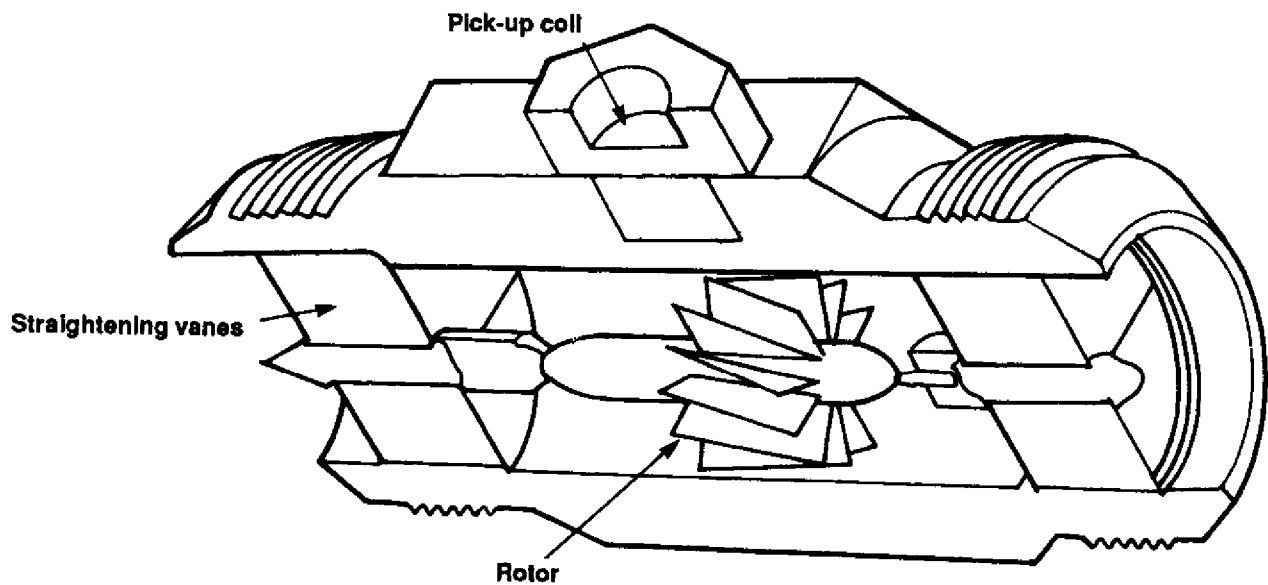


Figure 7-7. Axial Turbine Flowmeter

accuracy when calibrated and installed correctly. However, the moving parts, particularly the rotor bearings, are subject to wear. Normally, ball bearings are preferred but they can be used only in clean fluid applications. When dirty or corrosive fluids are metered, sleeve bearings are used.

Operation of this type of flowmeter is dependent upon the Reynolds number and, to some degree, the momentum of the fluid which must be of sufficient velocity to drive the rotor. Reynolds number constraints will vary with design, but, generally, most turbine flowmeters can operate and produce a linear reading in the turbulent range above a minimum Reynolds number varying between 4000 and 20,000.

Care must be taken not to operate the flowmeter at flows greater than those recommended by the manufacturer. Overspinning the rotor can destroy the bearings. Sudden surges of liquid flow, such as when a pump is started or a valve is opened, can also damage the flowmeter.

Turbine flowmeters are generally suitable for use with lubricating fluids operating within Reynolds number constraints. Exceptions include requirements to operate in gas service where close attention to bearing design is necessary due to the higher rotor velocities encountered.

Rotameters

Rotameters can be used in a variety of applications. They are capable of handling a wide range of liquids and can be used with slurries and gases.

Rotameters are variable area flowmeters. As in other flow instruments, flow measurement is based on the relationship between two known factors. One factor remains constant; a variation in the other factor indicates a variation in flow rate. In the rotameter, the variable factor is the area of the flowmeter opening, which changes proportionally with the flow rate. A typical rotameter is illustrated in Figure 7-8.

The rotameter consists of a tapered glass tube which is incorporated into the piping system. The tube is positioned so its greatest diameter is uppermost and contains a float which moves up and down freely as the flow within the tube changes. Since the upward and downward forces on the float are in equilibrium, the

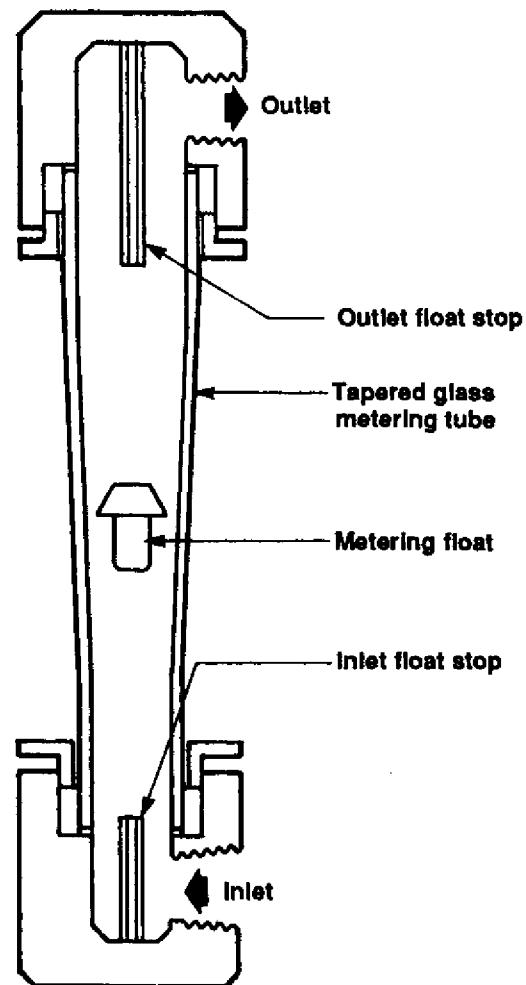


Figure 7-8. Area Flowmeter/Rotameter

float assumes a definite position at a given flow rate.

At a constant flow rate, the speed of the flow depends on the amount of area between the tube and the float. The only force which acts downward upon the float is its weight, which remains constant. One of the forces acting upward is the buoyancy of the float, which is the weight of the displaced fluid, and varies with fluid density. A second upward force, the pressure drop across the float, also remains constant. The viscous drag of the fluid passing the float is the third upward force acting upon the float.

While the pressure drop is constant, the tube is tapered, and the cross-sectional area for flow is variable. Increasing flow rates do not, therefore, increase the pressure drop across the float. Rather, they cause the float to take a higher position in the tube, thus providing a greater flow area. More simply, when the fluid flow is high, the float comes to rest near the top of the tube where there is a greater area. When the flow is low, the float moves down in the tube to a smaller area.

The relationship between the float placement and the fluid flow is linear. A scale attached to the rotameter allows direct measurement of flow rate. The scale, however, must be calibrated for each type of fluid, the design of the tube and the weight of the float.

Small rotameters with ball floats respond to Reynolds number changes, making them sensitive to changes in both viscosity and density. Larger rotameters are less sensitive to these variations.

Rotameters can be used to measure mass flow rate in processes involving low viscosity fluids because the action of the float is in part dependent on the density of the fluid in the system.

VORTEX SHEDDERS

Vortex shedders are a type of oscillatory flowmeter. Such flowmeters employ physical phenomena that cause discrete changes in some parameter that is a function of the flow through the flowmeter.

Theory of Operation

Vortex shedders are based on the phenomena of vortex shedding. This effect, which has been observed for centuries, was recorded by Leonardo di Vinci in 1531. However, it is only in recent years that vortex shedding has been used to detect and measure flow.

Figure 8-1 illustrates this phenomenon. Vortex shedding can occur whenever a blunt or flat-faced body, called a bluff body, is positioned in a flowing stream of gas or liquid. As fluid passes a bluff body at low velocity, the flow is able to follow the irregular contour. However, as the velocity increases, the fluid tends to separate into layers and swirl around the body to form vortices downstream of it. A vortex is an area of swirling motion with high local velocity and, thus, lower pressure than the surrounding fluid. The vortices swirl alternately clockwise and counterclockwise. As a vortex forms on one side of the body and creates a low pressure area, the effect of the spinning fluid behind the body starts a vortex on the opposite side. When a vortex on one side of the bluff body breaks away from the body, it is followed by a new one on the opposite side

of the body. That in turn also breaks away, followed by a new vortex on the opposite side. This alternating pattern of vortices is called a Von Karman vortex trail.

The alternate shedding of vortices is the basis of meter operation. Pressure decreases when a vortex is formed and increases when it is shed. This is true on both sides of the bluff body. It is this increase and decrease of pressure across the bluff body which is measured to determine a frequency of vortex formation. The frequency of the vortex generation is directly proportional to the fluid velocity and may be expressed as:

$$Q = A \times v$$

Strouhal observed that the frequency of vortices increased with flow rate in a linear fashion. Hence, the output of a vortex shedding flowmeter is dependent on the Strouhal number, which is a dimensionless number. This relationship is represented by:

$$f = St \times \frac{v}{\text{shedder width}}$$

It is important to note here that the Strouhal number is not a constant and can vary with the Reynolds number, since vortex shedding flowmeters are Reynolds number dependent.

While most designs use a single shedder, one design introduces additional bodies into the flow stream which are active in vortex formation. Here, the active bodies combine the von Karman phenomenon and the Coanda Effect to form strong and stable vortices. The Coanda Effect is another phenomenon of fluid

attachment in which a flowing stream will attach itself to one wall in the presence of two walls. Using this phenomenon, vortices are formed by alternately developing a stagnant zone between the shedder and each of the bodies, as illustrated in Figure 8-2.

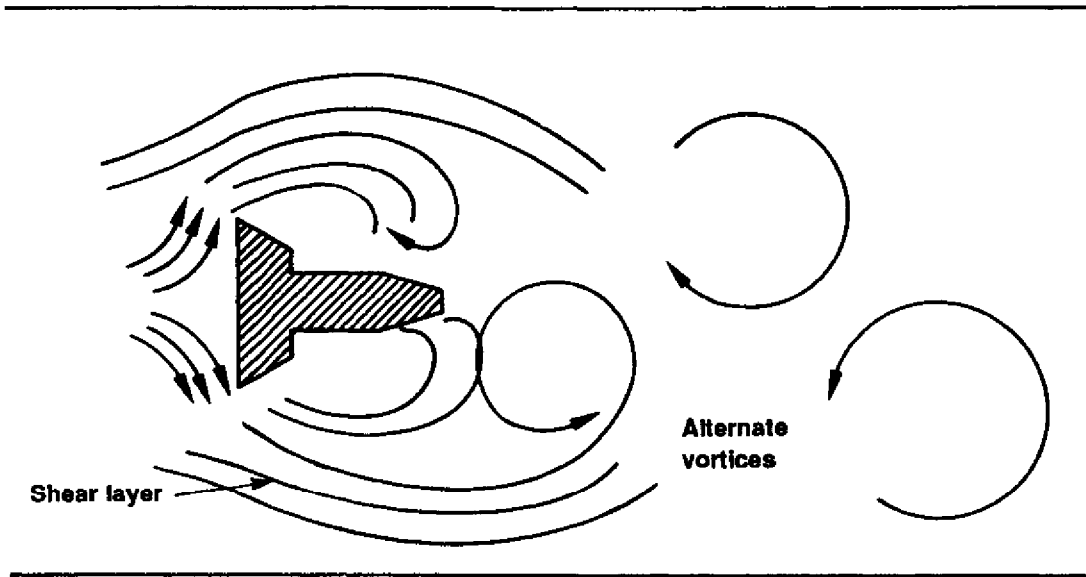


Figure 8-1. Vortex Shedding Principle

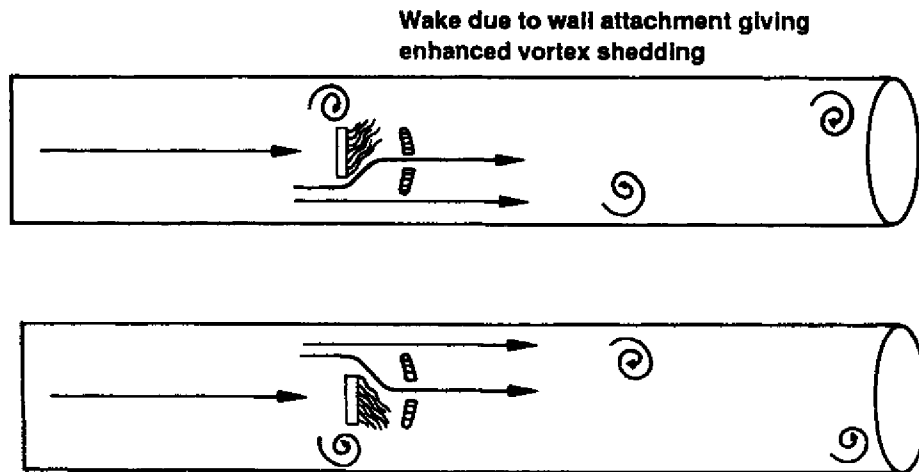


Figure 8-2. Vortex Shedding and Coanda Effect

Design

Figure 8-3 illustrates a typical vortex shedding flowmeter design. Vortex shedding flowmeters are generally comprised of three basic parts: a shedder, or bluff body, which generates the vortices; a sensor to sense the frequency of the vortices and produce a signal that can be measured; and, a transmitter to amplify and condition the signal. The frequency of the vortices can be sensed either by detecting and measuring the fluctuating pressure in the wake of the bluff body, or by measuring the changes in local velocity fluctuations around the bluff body.

Vortex shedding meters are fairly accurate in higher velocity liquids or gases, but their accuracy

decreases when applied to lower velocity applications. Accuracy is also lessened when used in high viscosity liquids.

It is important to note that vortex shedding meters are limited by Reynolds number constraints and must be used in fluids that exceed minimum velocity requirements to cause vortex formation.

The simplicity of its design and the fact that it has no moving parts in the flow stream are definite advantages of the vortex shedding flowmeter. In addition, the measurement accuracy of vortex shedders is unaffected by pipe vibrations.

On the other hand, vortex shedders are unable to handle dirty or abrasive fluids. These would quickly erode the bluff body and alter its vortex shedding

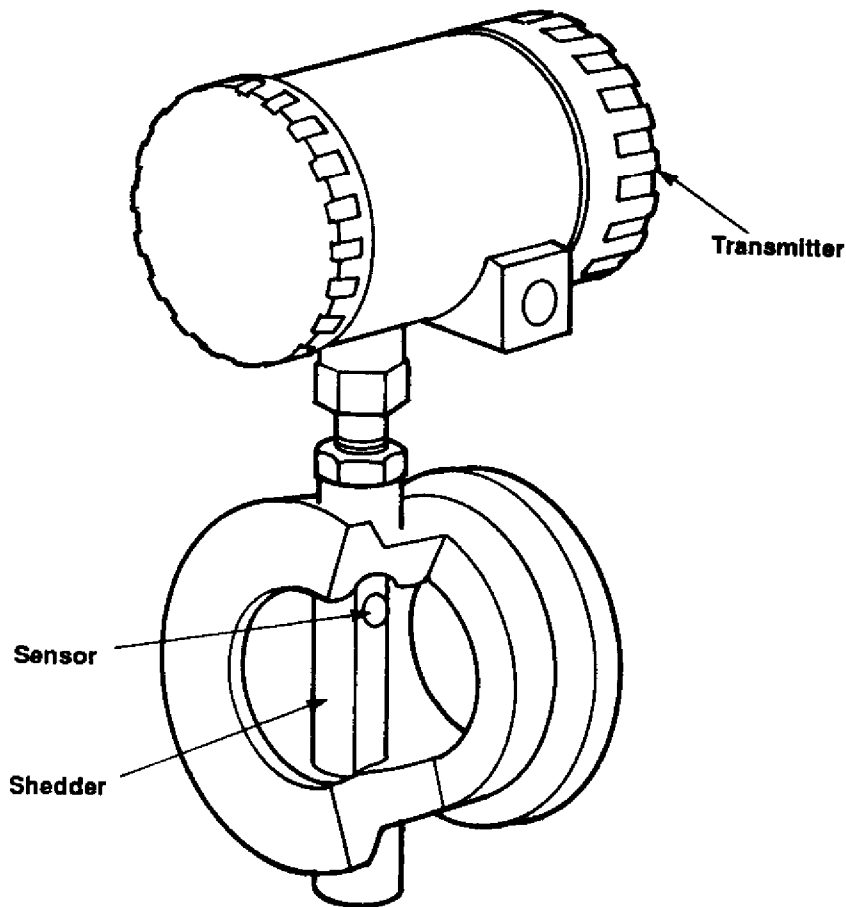


Figure 8-3. Vortex Shedding Flowmeter

characteristics. The bluff body also creates a pressure drop across the meter which may be unacceptable for some applications.

Vortex Precession Flowmeter

Another vortex detecting device should be noted here. This is the vortex precession flowmeter, sometimes referred to as a swirlmeter (see Figure 8-4). This type of meter also operates by detecting vortices. However, in this device, the fluid is forced into a swirl condition by swirl-producing vanes, or swirl blades.

The vortex that is formed as fluid enters the meter immediately precesses, or moves outward in a spiral motion. Precession is a natural phenomenon which occurs when a rotating fluid enters an enlarged space. Because of this phenomenon, the center of the vortex becomes displaced from the meter centerline and follows a helical path (precession) as it moves downstream through the enlargement. This precession causes fluctuations in fluid pressure and velocity. A sensor placed downstream from the swirl blades detects and measures the frequency of the precession. This frequency is linearly proportional to flow rate.

Vortex precession meters have an overall accuracy and range that is comparable to vortex shedding flowmeters. However, there is one major disadvantage

to their use. In using the vortex precession meter, the pressure loss that occurs is about five times greater than with the vortex shedder. This constraint significantly restricts its suitability for many types of processes.

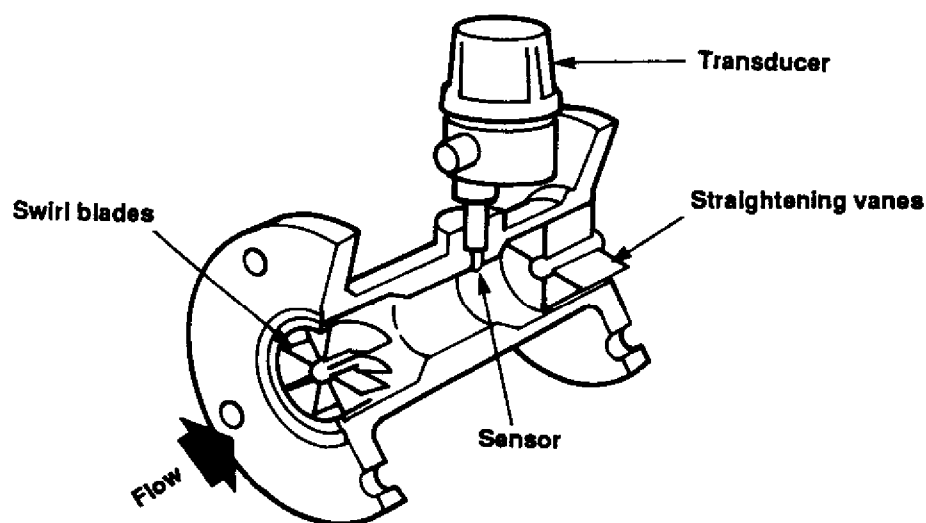


Figure 8-4. Vortex Precession Meter

QUIZ

QUIZ

1. For any ideal gas or mixture of ideal gases at a constant temperature, the volume is inversely proportional to the absolute pressure. This statement reflects
 - a. ideal gas law.
 - b. Charles' law.
 - c. Boyle's law.
 - d. Bernoulli's law.

2. The basic weight per unit time method assumes that
 - a. all substances have density.
 - b. mass is a conserved quantity.
 - c. decreasing pressure increases volume and density.
 - d. decreasing temperature increases volume and density.

3. When there is an increase in pressure of 8 psi in an ideal gas at a constant temperature with a pressure of 26 psi, volume decreases by
 - a. 12.5%.
 - b. 16.5%.
 - c. 83.5%.
 - d. 88.5%.

4. Orifice plates, flow nozzles, and venturi tubes are all examples of
 - a. variable area flowmeters.
 - b. head-type differential pressure flowmeters.
 - c. mass flowmeters.
 - d. positive displacement flowmeters.

5. The Reynolds number determines
 - a. the venturi effect.
 - b. if flow is laminar or turbulent.
 - c. the coriolis acceleration.
 - d. the viscosity of a fluid.

6. The three fundamental quantities in matter upon which all physical measurements are based are
 - a. density, viscosity, and specific gravity.
 - b. flow, volume, and temperature.
 - c. pressure, density, and specific gravity.
 - d. mass, length and time.

7. The effect of the earth's rotation on a mass is referred to as
 - a. coanda effect.
 - b. venturi effect.
 - c. coriolis effect.
 - d. specific gravity.

8. The principle of conservation of energy, that the same volume of fluid will pass between two points over the same given time period, is the basis of
 - a. Charles' law.
 - b. Bernoulli's law.
 - c. Archimedes' principle.
 - d. ideal fluid law.

9. Ultrasonic flowmeters operate on principles based on
 - a. Bernoulli's law.
 - b. Von Karmon effect.
 - c. time of flight.
 - d. coriolis effect.

10. Discreet volumes of fluid are metered, counted and totaled to measure flow in
 - a. mass flowmeters.
 - b. variable area flowmeters.
 - c. precession flowmeters.
 - d. positive displacement flowmeters.

