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## INTRODUCTION

### Scope

This design guideline helps engineers to understand the functions and types of flow measurement instrumentation available.

The selection method of the flow measurement instrument depends on the application. This guideline assist engineers to size flow measurement instrumentation (Orifice plate, Venturi tube, Pitot tube, nozzle, Rotameter, vane meter, positive displacement flow meter and etc) with the engineering calculation. Just key in the required data into the spread sheet provide in this package the calculation result will be obtained.

All the important parameters used in the guideline are explained in the definition section which will help the reader understand the meaning of the parameters used.

This design guideline discusses the method of selection of the several types of the flow measurement instrumentation, such as from the differential pressure flow meter, variable area flow meter, positive displacement flow meter, turbine flow meter, electromagnetic flow meter and etc. This are also included in the introduction and theory sections.

In the theory section, selections of the flow meters are included and the general theories applied for the sizing for each type of the flow meters are included. This will aid the engineer from the selection through sizing.

In the application section, several case studied are shown and discussed in detail all the way to applied the theory for the calculation. The case studied will aid the engineers to do the selection and sizing for the several flow meters base on their own system.

In the final section included is the example of the Data Sheet which is generally used in industrial and the Calculation Spreadsheet for the engineering design of this guideline.

## Flow Measurement

The importance of flow measurement in the industry has grown in the past 50 year, not just because it was widespread use for accounting purposes, such as custody transfer of fluid from supplier to customers, but also because of its application in manufacturing processes. Examples of the industrial involvement in flow measurement includes food and beverage, oil and gas industrial, medical, petrochemical, power generation, and water distribution and etc.

Flow measurement is the determination of the quantity of a fluid, either a liquid, or vapor, that passes through a pipe, duct or open channel. Flow may be expressed as a rate of volumetric flow (such as gallons per minute, cubic meters per minute, cubic feet per minute), mass rate of flow (such as kilograms per hour, pounds per hour), or in terms of a total volume or mass flow (integrated rate of flow for a given period of time).

Fluid flow measurement can be divided into several types; each type requires specific considerations of such factors as accuracy requirements, cost considerations, and use of the flow information to obtain the required end results. Normally the flow meter is measure flow indirectly by measuring a related property such as a differential pressure across a flow restriction or a fluid velocity in a pipe. A number of different fundamental physical principles are used in flow measurement devices.

There is various kind of the flowmeter available in market; they can be classifier types as

i) Difference pressure flow meter
   a. Orifice plate, (Figure 1)
   b. Venturi tube (Figure 2),
   c. Pitot tube and
   d. Nozzle (Figure 3)

ii) Variable area flowmeter
   a. Rotameter (Figure 4),
   b. Movable vane meter, and
   c. Weir, flume

iii) Positive displacement flowmeter
   a. Sliding-vane type PD meter,
   b. Tri-rotor type PD meter,

c. Birotor PD meter,
d. Piston type PD meter,
e. Oval gear PD meter,
f. Nutating disk type PD meter,
g. Roots PD meter,
h. The CVM meter ,and
i. Diaphragm meter

iv) Turbine flowmeter

v) Electromagnetic flowmeter

vi) Ultrasonic flowmeter
a. Doppler
b. Transit- Time

vii) Coriolis (Mass) flowmeter

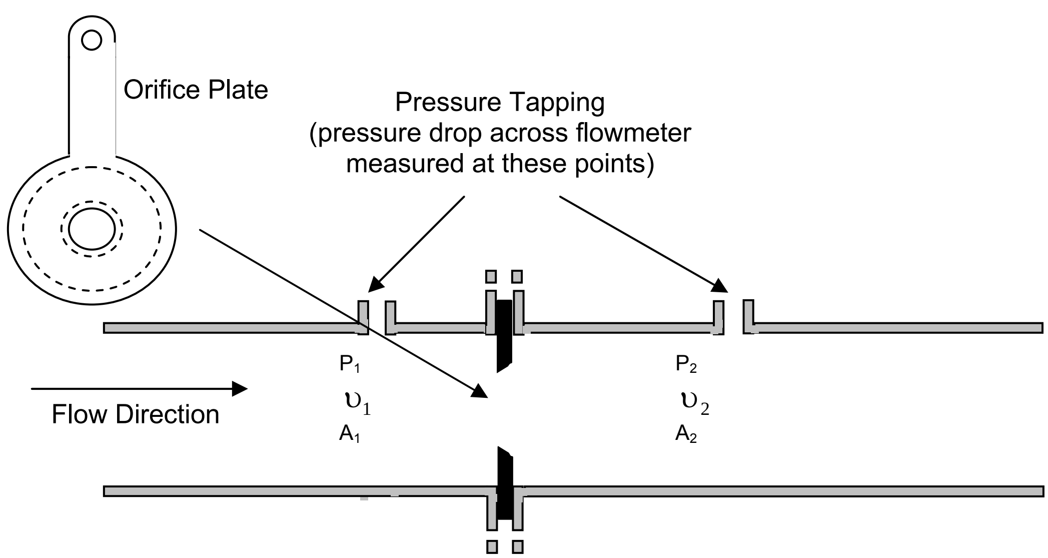


Figure 1: A Concentric Sharp Edged Orifice Plate Flowmeter

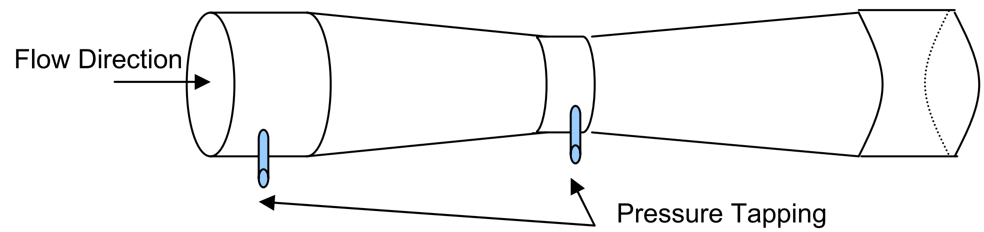


Figure 2: A Venturi Tube Flowmeter

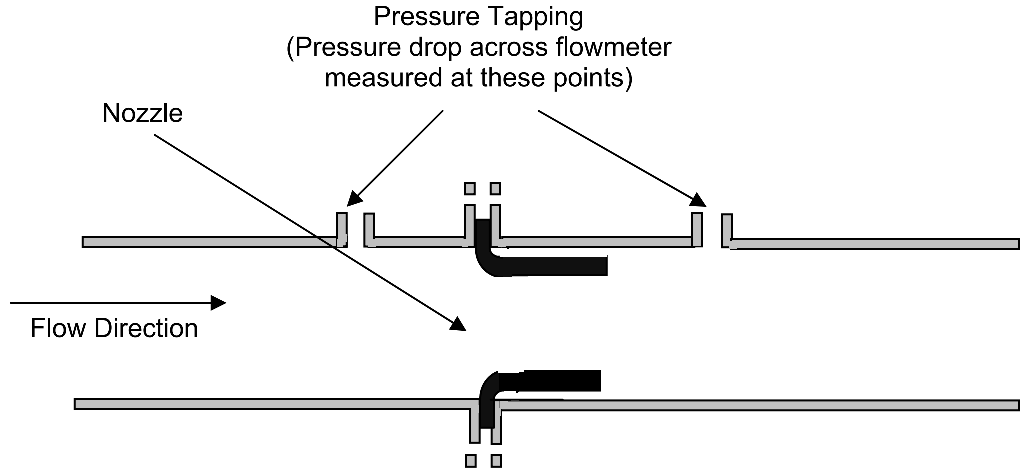


Figure 3: A Nozzle Flowmeter

When selecting the flowmeter for the specific applications, certain studied have to be carried out. Review the certain meters service record and reference to industry standards and users within an industry are important points to review in choosing the best meter for the given applications.

Difference fluid properties (viscosity, type of fluid, velocity profiles, flow profiles, Reynolds number) are the important cause of the differential flow measurement available in market. A lot of flowmeter techniques have been developed with each suit to a particular application, only few flowmeter can used for widespread application and no one single can use for all applications.

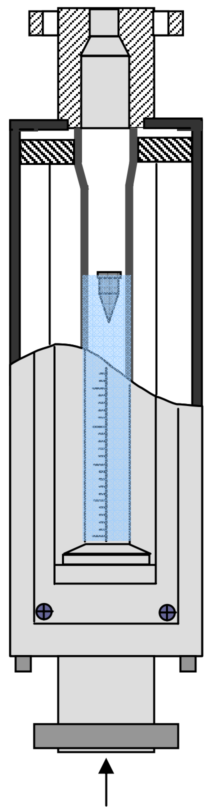


Figure 4: A Cross Sectional of Rotameter

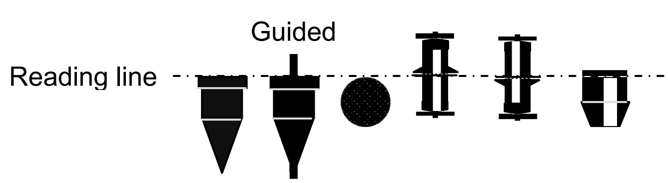


Figure 5: Typical Rotameter Bob Geometries

## DEFINITION

**Beta Ratio-** The ratio of the measuring device diameter to the meter run diameter (i.e., orifice bore divided by inlet pipe bore) or can be define as ratio of small to large diameter in orifices and nozzles.

**Capacity -** Is the water handling capability of a pump commonly expressed as either gallon per minute (gal/min) or cubic meter per minute ($m^3$/min).

**Coriolis Flowmeter -** Direct mass measurement sets Coriolis flowmeters apart from other technologies. Mass measurement is not sensible to changes in pressure, temperature, viscosity and density. With the ability to measure liquids, slurries and gases, Coriolis flowmeters are universal meters.

**Diameter Ratio (Beta) -** The diameter ratio (Beta) is defined as the calculated orifice plate bore diameter (d) divided by the calculate meter tube internal diameter (D).

**Differential Pressure-** The drop in pressure across a head device at specified pressure taps locations. It is normally measured in inches or millimeters of water.

**Differential Pressure Flowmeter-** A flowmeter in which the pressure drop across an annular restriction placed in the pipeline is used to measure fluid flow rate. The most common types use an orifice plate, Venturi tube, or nozzle as the primary device.

**Differential Pressure Transmitter-** Secondary device that measures the differential pressure across the primary device and converts it into an electrical signal.

**Discharge Coefficients-** The ratio of the true flow to the theoretical flow. It corrects the theoretical equation for the influence of velocity profile, tap location, and the assumption of no energy loss with a flow area between 0.023 to 0.56 percent of the geometric area of the inlet pipe.

**Electromagnetic Flowmeter -**An electromagnetic flowmeter operate on Faraday's law of electromagnetic induction that states that a voltage will be induced when a conductor moves through a magnetic field. The liquid serves as the conductor and the magnetic field is created by energized coils outside the flow tube.

**Manometer-** A device that measures the height (head) of liquid in a tube at the point of measurement.

**Mass Meter-** Meter that measures mass of a fluid based on a direct or indirect determination of the fluid's weight rate of flow.

**Measurement-** The act or process of determining the dimensions, capacity, or amount of something.

**Meter Factor (MF) -** The meter factor (MF) is a number obtained by dividing the quantity of fluid measured by the primary mass flow system by the quantity indicated by the meter during calibration. For meters, it expresses the ratio of readout units to volume or mass units.

**Meter Static-** Meters that measure by batch from a flowing stream by fill and empty procedures.

**Non-pulsating (see pulsation) -** Variations in flow and/or pressure that are below the frequency response of the meter.

**Orifice Plate-** A thin plate in which a circular concentric aperture (bore) has been machined. The orifice plate is described as a .thin plate and with sharp edge, because the thickness of the plate material is small compared with the internal diameter of the measuring aperture (bore) and because the upstream edge of the measuring aperture is sharp and square.

**Pipeline Quality-** Fluids that meet the quality requirements of contaminant as specified in the exchange contract such as clean, non-corrosive, single phase, component limits, etc.

**Positive Displacement Flowmeter -**The positive displacement flowmeter measures process fluid flow by precision-fitted rotors as flow measuring elements. Known and fixed volumes are displaced between the rotors. The rotation of the rotors is proportional to the volume of the fluid being displaced.

**Pulsation-** A rapid, periodic, alternate increase and decrease of pressure and/or flow. The effect on a meter depends on the frequency of the pulsation and the frequency response of the meter.

## NOMENCLATURE

| | |
|---|---|
| $A_1$ | Sectional area of upstream pipe, $ft^2$ |
| $A_2$ | Sectional area of meter bore, $ft^2$ |
| C | Correction constant of the design of Pitot-static tube (from vendor of flowmeter), dimensionless |
| $c_d$ | Discharge coefficient, dimensionless |
| $D$ | Internal diameter of pipe, in |
| g | Acceleration of gravity, 32.2 $ft/s^2$ |
| $h_1$ | Height of flow for upstream, ft |
| $h_2$ | Height of flow for downstream, ft |
| $h_L$ | Head loss due to friction in meter, ft |
| k | Gas isentropic exponent, dimensionless |
| $P_1$ | Absolute pressure for upstream, psia |
| $P_2$ | Absolute pressure for downstream, psia |
| $Q_1$ | Mass flow, gal/min |
| q | Volumetric flow rate, $ft^3/s$ |
| $q_m$ | Mass flow rate, lbm/s |
| Re | Reynolds number, a dimensionless number |
| Y | Expansibility factor, for compressible fluid (Liquid =1) |

### Greek letters

| | |
|---|---|
| $\beta$ | Beta ratio, ratio of orifice bore diameter to pipe diameter |
| $\varepsilon$ | Equivalent roughness of the pipe wall material, in |
| $\rho$ | Weight density of fluid, $lbm/ft^3$ |
| $\mu$ | Absolute (dynamic) viscosity, cp |
| $\upsilon_1$ | Velocity for upstream, ft/s |
| $\upsilon_2$ | Velocity for downstream, ft/s |

## THEORY

### Selection Criteria of Flowmeter

To select a suitable flowmeter for a particular application it was not an easy task especially with the wide variety of flowmeters in the market. It requires considerable evaluation of the total cost, fluid state, flowing condition, Reynolds number, density, rangeability, mechanical installation constraints and accuracy requirements.

The design engineer should decide the design condition for mass, volume (operating standard) or energy. Beside that, pressure and temperature of the fluid should be providing as well for the flow meter and transmitter to compensate for process variations in these variables. A specific gravity or density analyzer may also be needed to account for variability in stream composition.

In considering the cost, it should consider the total cost involve, included equipment cost, total cost installation, maintained cost, and operating cost. Costs must be carefully evaluated, particularly as meter size or operating pressure changes. For instance, a small sized Venturi might be of comparable cost to an averaging pitot, but as the size increases the cost of the Venturi rapidly exceeds that of the averaging pitot for a given pipe size. Increasing design pressure has the same effect.

Accuracy

A term used frequently in flow measurement is accuracy. Accuracy is more abused than correctly used. Unfortunately, it is a sales tool used commercially by both suppliers and users of metering equipment. The supplier with the best number wins the bid. Likewise, the user will sometimes require accuracies beyond the capabilities of any meter available.

In pervious decades, accuracy was the term most commonly used to describe a meter's ability to measure flow. It was defined as the ratio of indicated measurement to true measurement. The antithesis of uncertainty and is an expression of the maximum possible limit of error at a defined confidence.

Why is accuracy is important for flow meter? The important point for custody transfers because it is related to money. A meter station measuring product worth $2 million a day, an inaccuracy of ± 0.2% represents $4,000 a day, or $1,460,000 a year and the amount that justifies considerable investment to improve flow measurement. The same error for a station measuring $1,000 worth of product a day represents only $2 a day, and the law of diminishing returns limits investment justifiable to improve measurement accuracy.

Flow Range and Rangeability

Flow range is the differential between the minimum and maximum flow rate over which a meter produces acceptable performance within the basic accurately specification of meter.

Rangeability is a flow meter's ability to cover a range of flow rates within specified accuracy limits. It is usually defined as the ratio of the maximum to minimum flow rates and is also known as meter turndown. This is important parameter when do selecting of the flowmeter (specific rangeability of respectively flowmeter are discussed in the following section). For example, a meter with maximum flow (100%) of 100 gallons per minute and minimum flow of 10 gal/min (within a stated tolerance such as ±0.5%) has a 10:1 rangeability or turndown of 10. It will be accurate ±0.5% from 10 to 100 gal/min.

Discharge Coefficient (C)

The discharge coefficient corrects the theoretical flow rate equation for the influence of velocity profile (Reynolds number). Specific discharge coefficients for various flow meter geometries have been determined by actual tests run by many different organizations (e.g., API, ASME, and ISO). The discharge coefficient is a very important factor in defining the shape of the flow path. It is heavily influenced by factors such as: the size of the orifice bore, the size of the pipe, fluid velocity, fluid density, and fluid viscosity.

Reynolds Number

The Reynolds number ($R_e$) is a useful tool in relating how a meter will react to a variation in fluids from gases to liquids. Since there would be an impossible amount of research required to test every meter on every fluid we wish to measure, it is desirable that a relationship of fluid factors be known.

$$R_e = \frac{50.6\, Q_1 \rho}{D\mu} \qquad \text{Eq (1)}$$

Which,

Re = Reynolds number, a dimensionless number
$\rho$ = weight density of fluid, Ibm/ft$^3$
$D$ = internal diameter of pipe, in
$Q_1$ = Mass flow, gal/min
$\mu$ = absolute (dynamic) viscosity, cp

## Differential Pressure Flowmeter

Approximately 40% of all liquid, gas, and steam measurements made in industry are still accomplished using common types of differential pressure flowmeter (orifice plate, Venturi tube, and nozzle). The operation of these flowmeters is based on the observation made by Bernoulli that if an annular restriction is placed in a pipeline, then the velocity of the fluid through the restriction is increased. The increase in velocity at the restriction causes the static pressure to decrease at this section, and a pressure difference is created across the element. The difference between the pressure upstream and pressure downstream of this obstruction is related to the rate of fluid flowing through the restriction and therefore through the pipe. A differential pressure flowmeter consists of two basic elements: an obstruction to cause a pressure drop in the flow (a differential producer) and a method of measuring the pressure drop across this obstruction (a differential pressure transducer). [4]

The basic concepts of differential meters have been known as: (a) flow rate is equal to velocity times the device area, (b) flow varies with the square root of the head or pressure drop across it. These are defined by the Bernoulli's equations which the relationship between fluid velocity (v), fluid pressure (P), and height (h) above some fixed point for a fluid flowing through a pipe of varying cross-section, and is the starting point for understanding the principle of the differential pressure flowmeter.

Bernoulli's equation is defined as

$$\frac{(144)P_1}{\rho} + \frac{\upsilon_1^{\,2}}{2g} + h_1 = \frac{(144)P_2}{\rho} + \frac{\upsilon_2^{\,2}}{2g} + h_2 + h_L \qquad \text{Eq (2)}$$

which,

$P_1$ = Absolute pressure for upstream, psia
$P_2$ = Absolute pressure for downstream, psia
$\upsilon_1$ = Velocity for upstream, ft/s
$\upsilon_2$ = Velocity for downstream, ft/s
$h_1$ = Height of flow for upstream, ft
$h_2$ = Height of flow for downstream, ft
$g$ = Acceleration of gravity, 32.2 ft/s$^2$
$h_L$ = Head loss due to friction in meter, ft
$\rho$ = Density of measure fluid, lbm/ft$^3$

Assumption: (1) Fluid with constant density (incompressible fluid)
(2) Fluid is frictionless, which $h_L = 0$

By using a restriction in a pipe the flow rate can be measured. In a horizontal pipe the $h_2=h_1$, thus Equation (2) can be simplified as

$$\frac{(144)(P_1 - P_2)}{\rho} = \frac{\upsilon_2^{\,2} - \upsilon_1^{\,2}}{2g} \qquad \text{Eq (3)}$$

and for the mass balance conversion can be expressed as

$$\upsilon_1 A_1 \rho = \upsilon_2 A_2 \rho \qquad \text{Eq (4)}$$

which

$A_1$ = Sectional area of upstream pipe, $\frac{\pi D^2}{4x144}$, ft$^2$

$A_2$ = Sectional area of meter bore, $\frac{\pi d^2}{4x144}$, ft$^2$

Rearrange the Equation (4) and substitute $\upsilon_1$ into Equation (3) gives the volumetric flow rate (q) in ft$^3$/s;

$$q = \upsilon_1 A_1 = \frac{A_2}{\sqrt{1 - \frac{A_2^2}{A_1^2}}}\sqrt{\frac{2g(144)(P_1 - P_2)}{\rho}} \qquad \text{Eq (5)}$$

In considering the effect from friction loss and non-idealities and type of meter from the flowmeter the discharge coefficient has to add into the Equation (5) and for the compressible fluid the expansion factor has to take into considering as well. Then the equation can be expressed as

$$q = \frac{c_d Y A_2}{\sqrt{1 - \beta^4}}\sqrt{\frac{2g(144)(P_1 - P_2)}{\rho}} \qquad \text{Eq (6)}$$

which,

$c_d$ = Discharge coefficient, dimensionless

$\beta$ = beta ratio, ratio of orifice bore diameter to pipe diameter ($\frac{d}{D}$)

Y = Expansibility factor, for compressible fluid (Liquid =1)

$A_2$ = Area of the meter bore, $\frac{\pi d^2}{4x144}$, $ft^2$

$P_1$-$P_2$ = Differential pressure for upstream and downstream, psi

g = Acceleration of gravity, 32.2 $ft/s^2$

Orifice Plate

*I) Design and Construction*

An orifice plate is a restriction with an opening smaller than the pipe diameter which is inserted in the pipe; the typical orifice plate has a concentric, sharp edged opening, as shown in Figure 1. Because of the smaller area the fluid velocity increases, causing a corresponding decrease in pressure. The flow rate can be calculated from the measured pressure drop across the orifice plate, $P_1$-$P_2$ by using the Equation (6).

The orifice plate is commonly used as an instrument to meter or control the rate of flow of the most common or Newtonian fluids. These comprise all gases, including air and natural gas, and many liquids, such as water, and most hydrocarbons. With no moving parts and a simple design, the orifice is easily machined, and thus has been a popular flow-measuring device.

The orifice meter is one of a category of meters that require a pressure drop larger than the pressure drop in normal piping for proper measurement. If insufficient pressure drop is available for measurement, then a head meter cannot be used accurately. The general disadvantages of the orifice plate are its limited range, cause high pressure loss in system and sensitivity to flow disturbances.

Orifice plates have several differences design, which are Segmental, Eccentric, Quadrant Edge and typical design Concentric Sharp Edged (Table 1) for special measurement application.