| KLM Technology Group<br><br>Practical Engineering Guidelines for Processing Plant Solutions | KLM Technology Group<br><br>www.klmtechgroup.com | Page : 1 of 85<br><br>Rev: 02<br><br>Rev 01 March 2007<br>Rev 02 February 2014 |
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| KLM Technology Group<br>#03-12 Block Aronia,<br>Jalan Sri Perkasa 2<br>Taman Tampoi Utama<br>81200 Johor Bahru<br>Malaysia | **Fluid Flow Measurement Selection and Sizing<br>(ENGINEERING DESIGN GUIDELINE)** | Co Authors<br>Rev 01 A L Ling<br>Rev 02 Reni Mutiara Sari<br><br>Editor / Author<br>Karl Kolmetz |

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**Excel Format: (British & SI Unit)**



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# INTRODUCTION

## Scope

Measurement of a flowing fluid can be a challenge because it requires that the mass or volume of material be quantified as it moves through a pipe or conduit. Problems may arise due to the complexity of the dynamics of fluid flow. Flow measurements draw on a host of physical parameters that are also often difficult to quantify.

This design guideline includes the selection method of the flow measurement instrumentation depending on the applications. It also assist engineers to size some flow measurement instruments such as an orifice plate, Venturi tube, Pitot tube, Rotameter, vane meter, positive displacement flow meter and others with the engineering calculations, or by utilizing the spread sheet provided in this package.

All the important parameters use in the guideline are well explained in the definition section which will help the reader understand the meaning of the parameters and terms.

The theory section covers the selection of flow meters and the general theories applied for the sizing of each type of the flow meter. In the application section, several case studied are shown and discussed in detail step by step for the calculation. The case studied will aid the reader to complete the selection and sizing for the several flow meters base on their own system.

At the end of this guideline, example specification data sheets for the flow measurement instrumentation are included based on an industrial example. A calculation spreadsheet is included as well to aid the user to apply the theory of calculations.

## General Consideration

The importance of industrial flow measurement has grown in the past 50 years, not just because its 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 industries involved in flow measurement included food and beverage, oil and gas industrial, medical, petrochemical, power generation, and water distribution.

In custody transfer metering, being constantly aware that flow measurement equates to dollars, changes the perspective accordingly. The goal sought is that custody transfer measurement be converted to dollars ± zero. Quantities for custody transfer are treated as absolute when they are billed. The responsibility for this measurement, then, is to reduce all inaccuracies to a minimum so that a measured quantity can be agreed upon for exchanging custody. Control measurement may be accepted at ± 2%; operational measurement may require no more than ± 5%, as contrasted with the ± 0% target for custody transfer metering[5].

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 are various kinds of the flowmeters available in market; they can be classifier types as;

i) Difference pressure flow meter
   a. Orifice plate,
   b. Venturi tube,
   c. Pitot tube and
   d. Nozzle

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

iii) Positive displacement flowmeter
   - Tri-rotor type PD meter,
   - Birotor PD meter,
   - Piston type PD meter,
   - Oval gear PD meter,
   - Nutating disk type PD meter,
   - Sliding-vane type PD meter,
   - Roots PD meter,
   - The CVM meter ,and
   - Diaphragm meter

iv) Turbine flowmeter

v) Electromagnetic flowmeter

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

vii) Coriolis (Mass) flowmeter

viii) Vortex Shedding Meter

**Differential Pressure Flowmeter**

Approximately 40% of all liquid, gas, and steam measurements made in industry are still accomplished using common types of differential pressure flowmeters (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].

**Variable Area Flowmeter**

Variable area flowmeters refers to those meters in which the minimum cross-sectional area available to the flow through the meter varies with the flow rate. This type meters include the Rotameter and the movable vane meter used in pipe flows, and the weir or flume used in open-channel flows. The measure of the flow rate is a geometrical quantity such as the height of a bob in the Rotameter, the angle of the vane, or the change in height of the free surface of the liquid flowing over the weir or through the flume.

For pipe flows, variable area flowmeters are most suitable for low flow rates of gases or liquids at moderate temperatures and pressures. Favorable features include rugged construction, high reliability, low pressure drop, easy installation, and low cost. Disadvantages include measurement uncertainty of 1% or more, limited range (10:1), slow response, and restrictions on the meter orientation. A generally good price/performance ratio has led to widespread use of these meters in numerous scientific and medical instruments and in many industrial applications for flow monitoring.

## Positive Displacement (PD) Meters

Positive displacement (PD) meters measure volumetric flow by continuously separating (isolating) a flow stream into discrete volumetric segments, counting them, and then returning it to the flowing stream. Positive displacement (PD) meters are used for measurement of liquids and gas, primarily liquids for pipeline uses. Two of the most common meters at residences are the water and gas meter, both of which are usually positive displacement meters.

Each design and working mechanism can be noticeably different from another; all positive displacement meters have three components a stationary fluid retaining wall (outer housing), a mechanism (internal mechanism) that momentarily entraps inlet fluid into a partitioned chamber before releasing it to the downstream side of the meter and the display or counter accessories that determines the number of entrapments of fluid in the dividing chamber and infers the flow rate and the total volume of flow through the meter.

Application for the low line pressure, design of the outer housing of the PD flowmeter is single walled, while for higher operating pressures, the housing is double walled where the inner wall is the containment wall for the entrapment chamber and the outer wall is the pressure vessel.

Difference designs it can be due to difference measurement applications. For liquid applications, PD meters work best for liquids with heavy viscosities. Almost all PD meters require precisely machined, high tolerance mating parts; thus, measured fluid must be clean for longevity of the meter and to maintain the measurement precision.

Positive displacement meters will measure with high accuracy over a wide range of flow rates, and are very reliable over long periods on clean fluids or with line filters. In general, PD meters have minimal pressure drop across the meter; hence, they can be installed in a pipeline with very low line pressures.

## Turbine Flowmeter

Turbine flowmeters measure the velocity of liquids, gases and vapors in pipes, such as hydrocarbons, chemicals, water, cryogenic liquids, air, and industrial gases. High accuracy turbine flowmeters are available for custody transfer of hydrocarbons and natural gas. This flowmeter can be applied to sanitary, relatively clean, and corrosive liquids in sizes up to approximately 24 inches. The flow of corrosive liquids can be measured with proper attention to the materials of construction of all wetted parts, such as the body, rotor, bearings, and fittings.

Applications for turbine flowmeters are found in the water, petroleum, and chemical industries. Water applications include distribution systems within and between water districts. Petroleum applications include the custody transfer of hydrocarbons. Miscellaneous applications are found in the food and beverage, and chemical industries.

## Electromagnetic Flowmeter

Electromagnetic flowmeter measures flow according to Faraday's law of magnetic induction. A full-flow electromagnetic flowmeter is a nonintrusive device that consists of a magnetic coil that encircles the pipe, and two electrodes drilled into the pipe along a diameter flush with the inner surface of the pipe so that the electrodes are in contact with the fluid but do not interfere with the flow and thus do not cause any head loss[fluid mechanical]. In fluid measurement, the “conductor" is the process fluid flow, the faster it flows, the greater the voltage induced across the electrodes of the meter.

## Ultrasonic Flowmeter

Ultrasonic flowmeters are normally used to measure flow for pure water, wash water, sewage, process liquids, oils, and other light homogeneous liquids. The basic requirement is that the fluid be capable of ultrasonic wave propagation and have a reasonably axis-symmetrical flow, which flow must be measured without any head losses or any pressure drop.

The basic operating principle of these meters is to detect flow through a pipe, ultrasonic flowmeters use acoustic waves or vibrations of a frequency >20 kHz. Depending on the design, they use either wetted or nonwetted transducers on the pipe perimeter to couple ultrasonic energy with the fluid flowing in the pipe.

Compared to electromagnetic flowmeters, it can suit for variety kind of flowing liquid, but electromagnetic flowmeters only for the liquid which have minimum electric conductivity. In addition, the cost of ultrasonic flowmeters is nearly independent of pipe diameter, whereas the price of electromagnetic flowmeters increases drastically with pipe diameter.

**Coriolis Meter**

Coriolis meters have become widely used in industrial environments because they have the highest accuracy of all types of flowmeters. These meters are used for both custody transfer and control measurement. Its can be used on liquids, gases and can handle corrosive fluids and fluids that contain solids. They measure mass directly, rather than inferentially weight (mass). If the desired measure is volume, then some correction for density at fluid base conditions must be made.

The meter consists of one or two flow tubes enclosed in sensor housing. These tubes are vibrated at their natural frequency by an electromagnetic drive coil located at the center of the bend in the tube. The vibration is similar to that of a tuning fork, completing a full cycle about 80 times each second.

**Vortex Shedding Meter**

A vortex shedding meter consists of a sharp-edged bluff body (strut) placed in the flow that serves as the vortex generator, and a detector (such as a pressure transducer that records the oscillation in pressure) placed a short distance downstream on the inner surface of the casing to measure the shedding frequency[yunus].

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. Many flowmeter techniques have been developed with each suited to a particular application, only few flowmeter can used for widespread application and no one single can use for all applications.

## DEFINITION

**Accuracy -** The ability of a flow measuring system to indicate values closely, approximating the true value of the quantity measured.

**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).

**Coefficients Discharge -** 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.

**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.

**Custody Transfer -** Flow measurement whose purpose is to arrive at a volume on which payment is made/received as ownership is exchanged.

**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.

**Uncertainty -** Astatistical statement of measurement accuracy based on statistically valid information that defines 95% of the data points (twice the standard deviation).

## 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 designer should decide the design condition for mass, volume (operating standard) and energy. 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.

## 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.

For 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 accuracy is important for flow meter? It is the important point for custody transfers because it is related to money. For example, 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. This amount that justifies a considerable investment to improve flow measurement instrumentation. 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.

The accuracy of a flowmeter is the maximum deviation between the meter's indication and the true value of the flow rate or of the total flow. This is a measure of a flowmeter's performance when indicating a correct flowrate value against a correct value obtained by extensive calibration procedures. The subject of accuracy is dealt with in ISO 5725. The following two methods used to express accuracy have very different meanings:

### A. Percentage of measured value or actual reading

Accuracy based this method is stated tolerance according percentage of measured value or actual reading on various flow rate. For example, a flowmeter's accuracy is given as ±3% of actual flow of 1000 kg/h, the uncertainty of actual flow is between 970 kg/h and 1030 kg/h. Similarly at an indicated flowrate of 500 kg/h, the 'uncertainty' is between 485 and 515 kg/h.

### B. Percentage of full scale deflection (FSD)

A flowmeter's accuracy may also be given as a percentage of full scale deflection FSD, which means that the measurement error is expressed as a percentage of the maximum flow that the flowmeter can handle. Error stated in percentage FSD tends to be smaller than the error as a percentage of actual reading. For this example a value of ±0.3% FSD will be used on flow of 1000 kg/h, the uncertainty of actual flow is between 997 kg/h and 1003 kg/h. At an indicated flowrate of 50 kg/h, the error is still ±3 kg / h, and the actual flow is between 47 and 53 kg/h consequence, the error be ± 6%. As the flowrate is reduced, the percentage error increases.

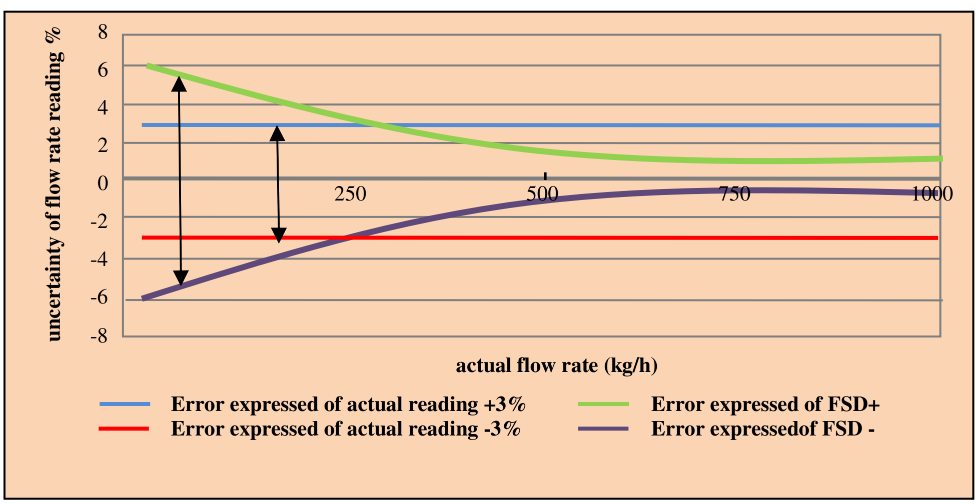


Figure 1: Range of error

## 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, lbm/ft$^3$

$D$ = internal diameter of pipe, in

$Q_1$ = Mass flow, gal/min

$\mu$ = absolute (dynamic) viscosity, cp

## Flow Measurement Devices

Eight principal flowmeter types have been defined to describe flow measurement. This section gives an overview of the flowmeters commonly used to measure the flow rate of liquids and gases flowing through pipes which are described below.

## I. Differential Pressure Flowmeter

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