A Comparison of Liquid Petroleum Meters for Custody Transfer Measurement

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Introduction

Petroleum products bought and sold on the world wide market may be transported over thousands of miles and change ownership many times from the well head to the end user. Each time the product changes ownership, a “custody transfer” is completed and both buyer and seller expect their asset share to be accurately measured. The dynamic measurement provided by meters is a convenient and accurate means to measure valuable petroleum products. Selecting the right meter for the job with a high level of confidence is imperative to ensure accurate measurement at the lowest the cost of ownership.

Meter Selection

Typical petroleum applications where measurement is required include: production, crude oil transportation, refined products transportation, terminal loading, fuel oil tank truck loading and unloading, aviation and lube oil blending. Each of these applications is unique and a specific type of meter may be better suited for each application. Selecting the correct meter for a specific measurement task is dependant on the following operating conditions:

- **System characteristics –** Pressure and temperature are typically specified but other characteristics such as pulsating flow from a PD pump or valve operation / location should also be considered as they may cause measurement errors for some types of meters.
- **Product characteristics** – The basic product characteristics of viscosity, specific or API gravity, chemical characteristics and lubricating quality must be specified. Also, any contaminates such as particulates, air or water contained in the product must be identified and noted in an application analysis.
- **Flow range** – This is the minimum and maximum flow rate over which the meter will operate. The flow range can also be expressed as the ‘turndown range’, which is the ratio of the maximum to the minimum flow rate (e.g., a flow range of 10 bph to 100 bph is a 10:1 turndown range).
- **Viscosity Range** – Just as the flow range can be expressed as a turndown range, so can the maximum to the minimum viscosity be expressed as a turndown range.
- **Accuracy** – The Accuracy of a liquid flow meter depends predominantly on the flow range and the viscosity range of the products over which the meter operates. The following formula relates Flow Turndown Range to Viscosity Turndown Range to yield a Measurement Turndown Range (MTR). Comparing the MTR of various meter types for specific operating conditions provides a guide to selecting the meter with the best potential accuracy for the application.

Measurement Turndown Range =
Flow Turndown Range x Viscosity Turndown Range

or

MTR = FTR x VTR

Meter Accuracy Requirements and Criteria

Accuracy requirements for the wholesale and retail trade are normally defined by the weights and measures regulations in the country or jurisdiction in which the sale is conducted. Sales within the petroleum industry that are not normally defined by weights & measures, but by a contract between the trading parties, are known as Custody Transfer transactions. A typical contract may define a specific measurement standard such as one of the American Petroleum Industry (API) Standards. Currently API recognizes four types of dynamic measuring devices – Positive Displacement (PD) Meters, Turbine Meters, Coriolis Mass Flow Meters (CMFM’s) and recently approved Liquid Ultrasonic Flow Meters (LUFM’s). The API Standards are based on “best practice” and define the proper application of a specific flow meter. Contracts are also based on other recognized standards but all these standards have one thing in common - they all strive to minimize measurement error for a specific application.

Error is defined as the difference between the measured quantity and the true value of the quantity. There are four (4) types of errors:

Spurious error – merely mistakes or blunders that must be identified and eliminated

Random error – variations at constant conditions, normally evenly distributed about a mean, which can be statistically analyzed and eliminated

Constant systemic error – a bias that is particular to an installation. These errors include hydraulic and zero calibration effects

Variable systemic error – a bias that varies with time and includes bearing wear or changes in tolerances.

Note: *Systemic errors can only be determined and accounted for by onsite proving at operating conditions.*

The criteria associated with custody transfer and all accurate measurement includes:

- **Repeatability** – the variation of meter factor under stable operating conditions, i.e., constant flow rate, temperature, pressure, and viscosity. The typical requirement is that a meter must repeat within +/- 0.05%

in 5 consultative runs. A more general statement is the meter should be repeatable within +/- 0.027% at 95% confidence level. This more general statement allows a wider repeatability test tolerance. For example, a repeatability of +/ - 0.12% in 10 consecutive runs or a repeatability of +/- 0.17% in 15 consecutive runs both meet +/- 0.027% at 95% confidence level. This latter definition of repeatability is important in testing Coriolis and Ultrasonic Flow meters, because sampling type meters normally require more runs to satisfy the repeatability requirement.

- **Linearity** – the variation of meter factor over a flow range at constant temperature, pressure and viscosity.
- **Stability or Reproducibility** – the variation of meter factor over time. Unlike repeatability runs where conditions can be kept nearly constant, operating conditions over time may have wider variations. Therefore, it is important that the meter selected have minimum sensitivity to operational variations to achieve required accuracy. For example, if heating oil with a viscosity range of 2 cSt to 10 cSt over the operating temperature range (see Appendix A) is being loaded at 100 to 500 gpm, the meter must be stable over a 5:1 flow range and a 5:1 viscosity range which is a measurement range of 25:1.
- **On-site Verification** or proving has always been, and remains, fundamental to custody transfer measurement. It is the only sure method to determine and correct for both constant and variable systemic errors.

Positive Displacement Meters

Dynamic fluid flow meters can be classified as either direct volumetric meters or inference type meters. A Positive Displacement (PD) meter (Figure 1) directly measures volumetric flow by continuously separating (isolating) the flow stream into discrete volumetric segments. Inference meters determine volumetric flow rate by measuring some dynamic property of the flow stream. Turbine meters, both conventional and helical types, fall in the latter category along with Coriolis mass meters and ultrasonic meters.

Operating Principle

The PD meter measures flow by momentarily isolating segments of known volume and counting them. For example in a rotating vane PD meter, as the rotor turns, isolated chambers are formed between blades, rotor, base, cover and housing. Like a revolving door, known segments of fluid pass through the measurement chamber and are counted.

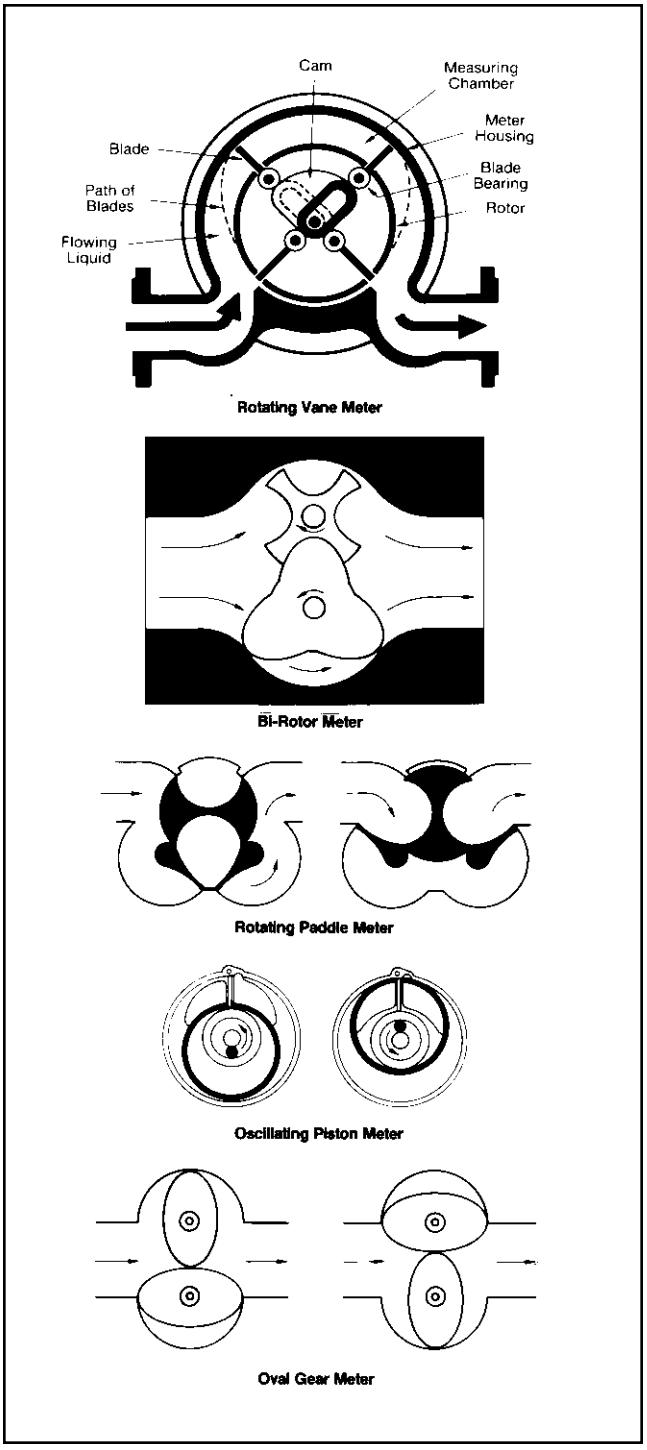


Figure 1 — PD Meter Types

PD Meter Accuracy Theory

There are two factors which affect the accuracy of a PD meter - measuring chamber volume displacement and slippage through the capillary seals (clearances).

Volume Displacement

The volume displacement of a PD meter is determined by the size of the volumetric measurement chamber. The two factors that influence the physical volume displaced and the meter's accuracy are temperature and coatings. Changes in temperature affect the displacement of the meter because of the thermal expansion or contraction of the materials in the measurement chamber. Most PD meter designs are not highly sensitively to temperature and can operate within the allowable measurement accuracy over a fairly wide temperature range.

Crude oils which contain paraffin wax can coat the inside of the measurement chamber. This reduces volumetric displacement and changes the meter's factor. Some meter designs, like the rotary vane PD meter, are more suitable for these applications. The blades of the rotary vane PD meter sweep away the build-up of wax from the walls of the measuring chamber with each rotation of the rotor. PD meters can provide stable measurement at a high degree of accuracy in these applications if the meter is proven frequently after initial start-up until meter factor stability is established.

Slippage

All PD meters have moving and stationary parts which require clearances between them. In most PD meter designs, there is no contact between parts but the tolerances are very tight and the liquid forms a capillary seal. Flow through the meter is caused by differential pressure across the measuring chamber. Flow through the meter not accounted for in the measurement chamber but which flows though these clearances is commonly known as slippage.

Slippage through the clearances of a PD Meter can be characterized by the Equation in Figure 2.

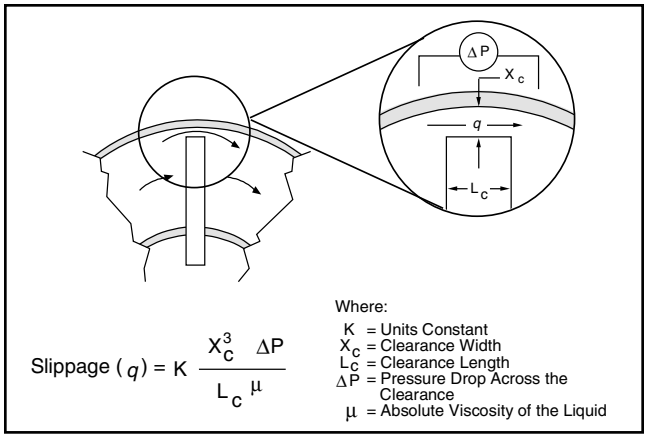


Figure 2 — Slippage across meter clearances

The slippage equation stipulates that for PD meter accuracy it is essential that the meter have low differential pressure and tight clearances with wide land areas. In addition to meter design and manufacture quality, a key determinate to slippage is viscosity. As the viscosity of the fluid increases, flow though the measuring element clearances decreases. At a certain viscosity, about 10 to 20 cSt depending on the type and size of meter, the amount of slippage is nil and the meter factor is constant. Figure 3 shows the affect of viscosity on slippage.

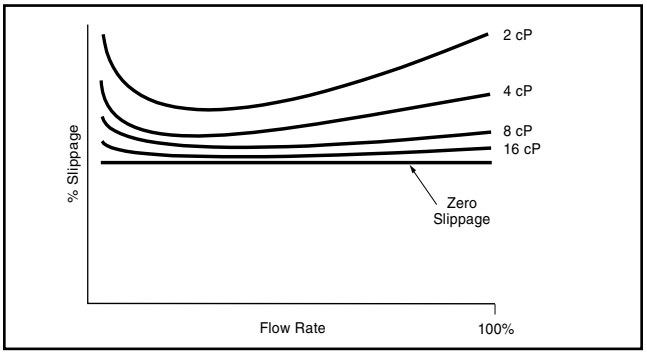


Figure 3 — Effect of Viscosity on PD measurement

Application Advantages of PD Meters

PD meters are highly versatile and have been used for custody transfer petroleum application since their introduction in the 1930's. Because of their high accuracy, stability, reliability, mechanical output and ease of proving, they are still widely used in the petroleum industry. Other meter technologies have displaced PD meters for high volume, low viscosity applications like refined product or light crude oil pipelines. PD meters still have a measuring advantage in some applications, which include:

- **Batching –** For small to medium batch application, PD meters provide excellent measurement accuracy and are easily verified with calibrated can type provers. PD meters remain one of the best meters for terminal and bulk plant loading applications especially for diesel, jet fuel and heating oils in cold climates. They are also the leading meter choice for petroleum delivery trucks and aviation refueling systems.
- **Medium to high viscosity products –** PD meters are one of the few meters that have highly stable meter factors on medium to high viscosity products. As noted by the slippage equation, as the viscosity increases the slippage decreases and the meter becomes more linear over a wider measurement range.
- **Master Meters –** PD meters make excellent master meters because they are not affected by flow profile and other installation conditions. In some applications, such as loading terminals that utilizes turbine meters as the primary flow measurement device, a PD Master Meter is used to prove the line meters. The PD master meter is first proven on a specific product using a calibrated can or a dynamic prover before it is used to calibrate the line meters.

PD meters, if applied on non-abrasive products, provide excellent service with relatively little maintenance. Many of the maintenance problems associated with PD meters are actually problems with accessories like mechanical counters, calibrators, mechanical temperature compensators and set-stop valves. Today's PD meters,

Flow Turndown Range vs Viscosity

Linearity	Viscosity cP					
	100 to 400	**20 to 100**	**5 to 20**	**2 to 5**	**0.8 to 2**	**0.5 to 0.8**
+/- 0.15%	50:1	30:1	20:1	15:1	8:1	5:1
+/- 0.25%	75:1	50:1	35:1	25:1	20:1	10:1

Measurement Turndown Range

Linearity	Viscosity cP					
	100:400	**20:100**	**5:20**	**2:5**	**0.8:2.0**	**0.5:0.8**
+/- 0.15%	200:1	150:1	80:1	40:1	20:1	8:1
+/- 0.25%	300:1	250:1	140:1	60:1	50:1	16:1

with electronic transmitters or direct electronic outputs, have a much lower cost of ownership.

Even though PD meters are the oldest custody transfer measurement technology, they are considered the best technology for many applications where accuracy, stability and reliability are required.

PD Meter Performance

The following is typical performance of Smith Rotary Vane type PD Meters. All types of PD meters exhibit similar performance but the manufacturer's specification must be consulted to determine the particular performance and application requirements for a given meter.

Accuracy can also be improved over a specific measurement range with tuning or over the complete range with electronic linearization.

Turbine Meters

In the mid 1960's, the petroleum industry recognized the potential of turbine meter technology for highly accurate measurement and in 1970, API published Standard 2534 - "Measurement of Liquid Hydrocarbons by Turbine Meter Systems". After publication of this standard, conventional turbine meters (Fig. 4) gained broad acceptance for custody transfer of petroleum liquids such as liquefied petroleum gases (LPG's), refined products and light crude oil. With the introduction of helical turbine meters in the 1990's, turbine meter applications were expanded to higher viscosity crude oils, waxy crude oil and other troublesome turbine meter applications.

Operating Principle

Turbine meters determine flow rate by measuring the velocity of a bladed rotor suspended in the flow stream. The volumetric flow rate is the product of the average stream velocity and the flow area at the rotor as related by the basic equation:

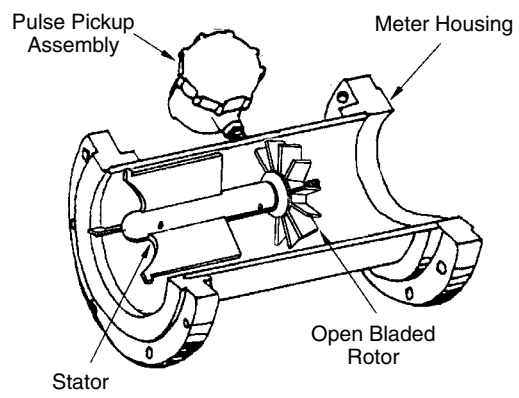
Volume Flow Rate = Area x Velocity

The accuracy of a turbine meter is based on two assumptions: (1) the flow area remains constant and; (2) the rotor velocity accurately represents the stream velocity.

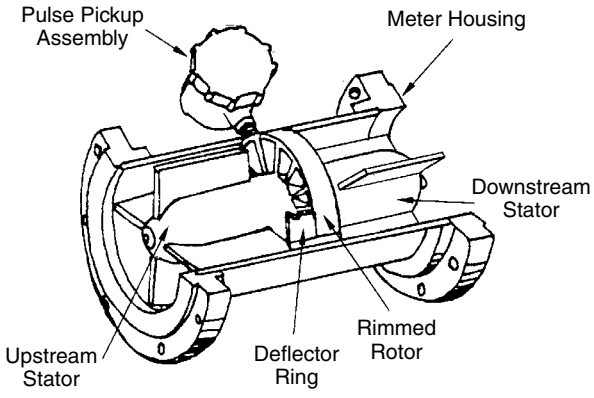
Constant Flow Area

The effective rotor flow area, and thus the meter's "K" factor (pulses / unit volume), can change for any one or a combination of the following reasons:

- **Erosion, Corrosion, Deposits –** Even a seemingly small buildup or erosion of the bladed rotor between meter provings can have a significant effect on meter performance. For example, a one mil (0.001") buildup on all surfaces of a 4" rotor will decrease the flow area through the rotor, and increase the "K" factor, by about 0.5%.
- **Boundary Layer Thickness –** Boundary layer thickness is relatively constant and insignificant when operating on products with low viscosity such as refined products or light crude oils. But as the viscosity increases, the boundary layer increases which



Turbine Meter with Open Bladed Rotor



Turbine Meter with Shrouded Rotor

Figure 4 – Conventional Turbine Meters

reduces the effective flow area. In fluid dynamics this effect is defined by the Reynolds's Number (Re No), which is the ratio of the inertia forces (the force of the flow stream) to the viscous forces (the resistance to flow). Reynolds Number can be expressed as:

$$*Re = \frac{2214 \times \text{Flow Rate (BPH)}}{\text{Diameter (Inches)} \times \text{Viscosity (cSt)}}$$

The following table defines the Re No of a 6" turbine meter at various viscosities:

Viscosity cSt	Reynolds Number @ Min/Max Flow (BPH) 4,000	400
1	1,474,000	147,400
5	294,800	29,480
50	29,480	2,948
100	14,740	1,474
500	2,948	295

- **Cavitation –** (the local vaporization of product) substantially reduces flow area through the rotor, dramatically increasing rotor velocity and the meter's "K" factor.
- **Obstructions –** Temporary obstructions, such as trash or "grass" immediately upstream of the bladed rotor can substantially decrease effective flow area through the rotor as well as cause a pronounced shift in fluid velocity profile.

Constant Rotor/Fluid Velocity Ratio Assumption

The second basic assumption is that rotor velocity accurately represents the stream velocity. The relationship between these factors can be affected by:

- **Rotor Blade Angle, Rotor Stability and Bearing Friction –** Changes in these areas are normally caused by damage from large foreign objects or fine grit in the fluid
- **Velocity Profile and Swirl –** Variations in velocity profile or fluid swirl are common causes of measurement errors that can be minimized by proper installation and use of flow conditioners.
- **Fluid Density –** The rotor driving torque available to overcome rotor drag forces is directly proportional to the fluid density and fluid velocity squared. Therefore, as the fluid density decreases, as with LPG products, the driving torque decreases, resulting in a decrease in performance at lower flow rates.

Helical Turbine Meters

Helical turbine meters are similar to conventional turbine meters in the fact that they have like housings, stators, bearings and pulse pickup systems and are governed by the same laws of fluid dynamics. They vary in one distinct area - the rotor has only two helical blades instead of multiple blades (Figure 5).

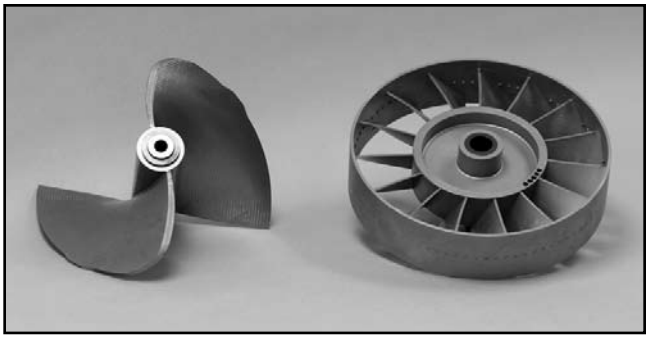


Figure 5 – Helical vs. Conventional Turbine Meter Rotors

Helical Rotor

The two-bladed helical rotor gives the meter the ability to accurately measure higher viscosity liquids because of the reduced effect of the stagnant boundary layer which builds up on rotor surfaces when higher viscosity oils are being measured. Figure 6 shows a comparison of the change in flow area with a 0.001" change in the thickness of the boundary layer between 8" conventional and helical turbine meter rotors. The change in flow area directly affects velocity through the meter and, therefore, the accuracy. The effect is over three times greater with the conventional turbine meter.

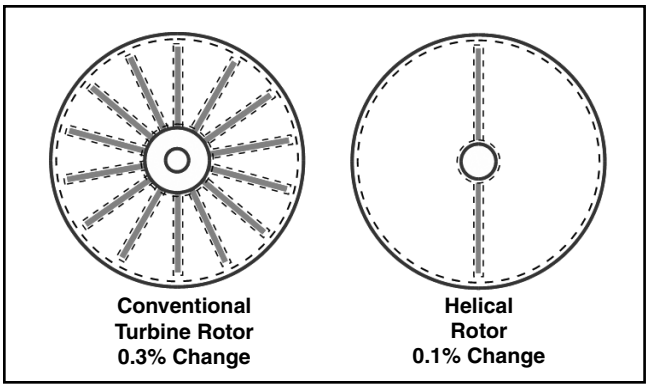


Figure 6 – Boundary Layer of a 0.001" Film on a 8" Rotor

Application Advantages of Turbine Meters

The application of turbine meters in the petroleum industry paralleled the development of electronic instrumentation. The original applications in the early 1970's were for refined products and light crude pipelines. In the 1980's, with the introduction of microprocessor based control systems, turbine meters were applied to terminal loading applications. With the introduction of helical meters, the field of application has extended to medium and even heavy crude oil applications.

Conventional Turbine Meters

Refined Products and Light Crude Oil for High Volume Applications

Turbine meters used in pipelines and ship loading / unloading facilities are operated at higher flow ranges for optimum accuracy. With only one running part, the rotor, no packing glands and direct pulse output turbine meter service life can exceed 20 years. In general, turbine meters:

- Can handle higher through-put than PD meters or Coriolis mass meters of equal size.
- Are especially well suited for LPG applications. Their tungsten carbide bearing system and compact tubular design make them more economical to manufacture and operate for higher operating pressures.
- Are easily and accurately calibrated on-site with conventional or small volume provers.

Refined Product Truck Loading Terminals

Turbine meters used for loading terminals utilize the same features that make them popular for pipeline service:

- They are specifically utilized for terminal blending of different octane ratings and / or oxygenated motor fuels.
- With many of the microprocessor based terminal controllers, turbine meter signals can be linearized to achieve an even higher level of accuracy.

Helical Turbine Meters

Production and Transportation of Crude Oils

Helical turbine meters extend the measurement range of conventional turbine meters. They can handle a wider range of crude oils over a wider flow range within limitations. Initially, some helical turbine meters were used to replace PD meters on medium to heavy crude oil applications with disappointing results. Manufacturer flow testing has determined that as the measurement range (previously defined as flow turndown range x viscosity turndown range) increases, the helical turbine meter must be "tuned" to specific operating conditions.

In many measurement applications, microprocessors have been used to enhance meter performance. Each helical meter has a unique footprint that is highly stable over a wide measurement range. By testing a meter not only over the flow range but also over the viscosity range, the meter's footprint can be accurately characterized and programmed into a microprocessor. To utilize the enhanced measurement accuracy only requires viscosity input from either an RTD for a single product with a known temperature viscosity relationship or a viscometer for a wide range of products. The meter should then be proven on-site over the complete measurement range to validate performance.

Turbine Meter Performance

The following is typical turbine meter performance. For actual performance and application requirements, consult the manufacturer's specifications.

Accuracy can also be improved over a specific measurement range with tuning or over the complete range with electronic linearization.

Conventional Turbine Meter Performance

- Flow Turndown Range: Any flow range from 10% to 100% of maximum flow rate
- Viscosity Turndown Range: Any viscosity (cSt) up to 2 times the meter's diameter (inches)
- Reynolds Number: Greater than 50,000
- Measurement Turndown Range (MTR) vs. Linearity:

MTR	Linearity
10:1	+/- 0.15%
15:1	+/- 0.25%

Helical Turbine Meter Performance

- Flow Turndown Range: Any flow range from 10% to 100% of maximum flow rate
- Viscosity Turndown Range: Any viscosity (cSt) up to 10 times the meter's diameter (inches)
- Reynolds Number: Greater than 20,000
- Measurement Turndown Range (MTR) vs. Linearity:

MTR	Linearity
40:1	+/- 0.15%
60:1	+/- 0.25%

Coriolis Mass Meters

Coriolis mass meters were introduced to industry in the early 1980's and have gained acceptance as accurate and reliable flow measuring devices. A major factor contributing to their popularity is that Coriolis meters measure mass flow rate directly thus eliminating the need for pressure and temperature compensation. Direct mass flow measurement led to the rapid adoption of Coriolis meters by the Chemical and Petrochemical industries. Petroleum applications most often require a volumetric flow rate output. To accomplish a volume measurement a Coriolis meter transmitter calculates volume flow rate (Q) from measured mass flow rate (m) and measured density (ρ):

$$Q = m/\rho$$

The Coriolis meter volume measurement accuracy reflects the combined uncertainty of the mass flow rate and density measurement.

Operating Principle

Two phenomena are required to generate a Coriolis force - a rotation and a mass moving toward and away from the axis of rotation. In Coriolis meters, the rotation is created through vibration of a flow conduit or multiple conduits. Figure 7 illustrates an element of fluid moving through a tube that rotates about a fixed axis perpendicular to the centerline of the tube.

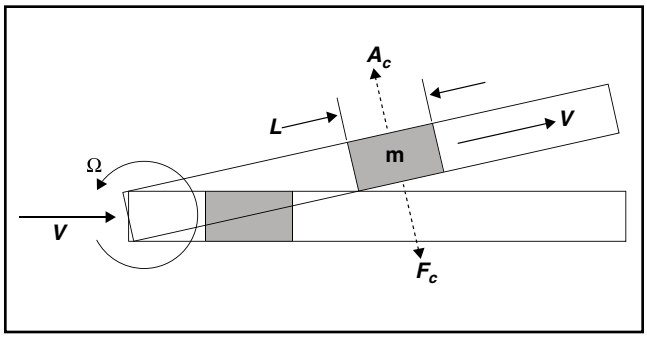


Figure 7 – Fluid Moving Through the Meter Tube

The inlet and outlet of the flow tube(s) are anchored while the tube is vibrated at a midway point. The tube vibration is produced by means of an electromagnetic drive system consisting of a coil and magnet. Located upstream and downstream of the drive system are sensors used to measure the Coriolis response.

The operation of a Coriolis mass flowmeter is explained by the application of Newton's second law, F = M x A (Force = Mass x Acceleration). The vibrating tube exerts a force on the flowing fluid, and in response, the flowing fluid exerts a Coriolis force (Fc) on the tube. The fluid flowing toward the middle of the flow tube opposes the motion of the tube, while the fluid flowing away from the middle assists in the motion of the tube. Because the flow tube is elastic, the tube walls bend in response to this Coriolis force.

Under no-flow conditions, the flow signals generated upstream and downstream of the drive system are in phase, as shown in Figure 8.

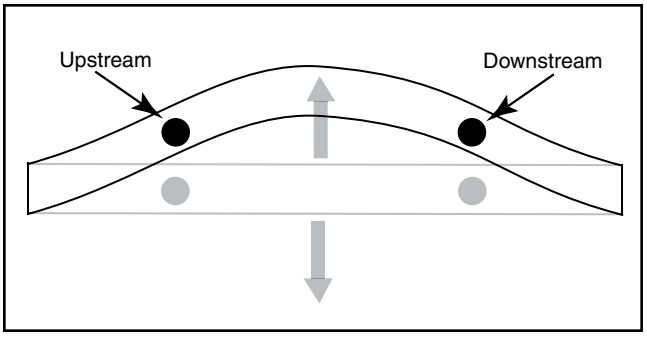


Figure 8 – The Meter Tube Under No Flow Conditions

As flow rate increases, the deflection magnitude increases, and as flow rate decreases the deflection magnitude decreases. This tube deflection is evidenced by a phase difference or shift between the upstream and downstream pick-off signals.

Several methods are used to measure the Coriolis deflection. The most commonly applied technique is the measurement of the phase difference between upstream and downstream pick-off coils. Since phase difference occurs in time, measures of the time difference between the two signals produce a "delta time" value that is proportional to mass flow rate. An alternative method involves the direct measurement of Coriolis deflection. This direct measurement of the tube deflection resulting from Fc is accomplished by continuous measurement of the upstream and downstream signals and subtracting the outlet from the inlet signal. The result is a continuous sinusoidal signal of Coriolis deflection magnitude. Digital signal processing techniques, such as synchronous demodulation, calculate and provide a continuous positive signal of mass flow. Figure 10 illustrates Coriolis response signals.

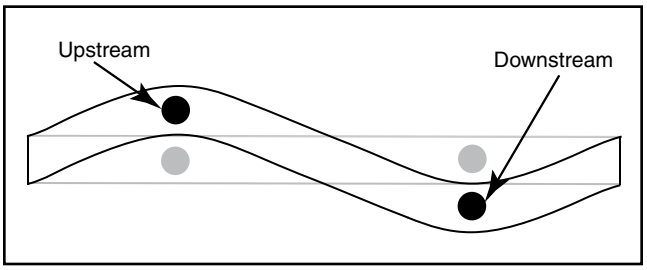


Figure 9 – The Meter Tube Under Flow Conditions

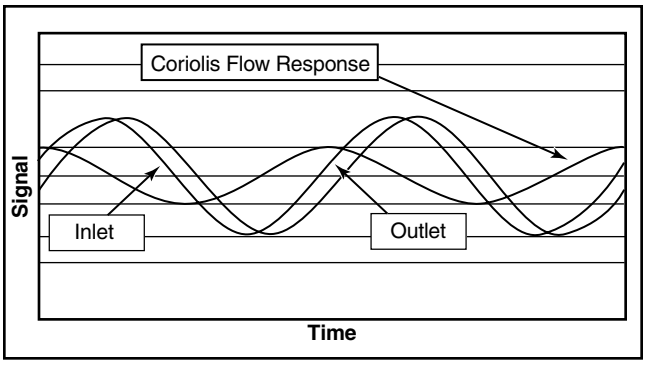


Figure 10 – Coriolis Response Signal

Performance

Coriolis meter specifications typically state probable error, or accuracy, as a percentage of flow rate plus the zero stability value:

% Error = ± [base error, %
± (zero stability/flow rate) x 100]

The zero stability value establishes the limits within which the meter zero may vary during operation and is constant over the operating range – assuming all other parameters, e.g. temperature, pressure, pipeline stress, are fixed. Zero stability can be expressed as value in flow rate units or as a percentage of upper range limit. Specified zero stability performance is achieved when the Coriolis meter is installed and "zeroed" at operating conditions. Process temperature, pressure and/or environmental temperature changes will affect Coriolis meter zero stability. Limits for changes in these installed conditions may be given which, when exceeded, will require re-zeroing of the meter. Zero stability has the greatest effect on flow measurement accuracy at the lowest flow rate.

Coriolis Meter Application Advantages

Coriolis meters are widely used in the Petroleum industry in applications that could not be effectively addressed with conventional flow meter technology. Most of these applications are non-custody transfer but with API's issuing the standards for Measuring Liquid Hydrocarbons by Coriolis Meters the use of this technology for custody transfer applications is expected to increase.

Some of the common custody transfer applications for Coriolis Meters in the petroleum industry today are:

Crude Oil Measurement in Lease Automatic Custody Transfer (LACT) Systems – Coriolis meters are generally of non-intrusive design and have no moving parts to wear or foul and are thus ideally suited for LACT applications where contaminants such as sand may be present.

Coriolis meters also have an added feature that has been utilized in this application. Most LACT applications handle crude oil with up to 5% water content. Part of a LACT system is a water analyzer to determine the percent water in the crude oil, which is then subtracted from the total measurement to determine marketable crude. Since a Coriolis meter also can determine product density, there are methods where if the oil and water density can be accurately established, the percent water can be determined from the Coriolis density output.

Transportation and Marketing Terminals for LPG, LNG and NGL – Coriolis meters have two advantages over turbine meters which are traditionally used in these applications:

- The volume of these products is highly affected by both temperature and pressure. As such, the output must be pressure and temperature compensated to provide accurate measurement. Coriolis mass meters are relatively insensitive to these parameters so they can provide an accurate measurement over a wider measurement range. If the custody transfer is in mass units, which is which is common for these fluids the measurement accuracy may be further increased because the density does not have to be determined to convert the output to volume units.
- Because the Coriolis meters contain no internal wear parts, they have a highly favorable service life when applied to dry, low lubricity fluids. Dry products are ones that have a very low lubricating quality which cause accelerated wear on bearing systems.

Transport or Loading of any Product with Entrained Particulates – Since Coriolis mass flow meters do not contain any internal wear parts, they are far less susceptible to fine contaminates such as sand, which can significantly decrease the life of PD or turbine meters. Coriolis flow meters are successfully applied to harsh crude oil applications and asphalt loading terminals where the high operating temperatures and particulates make it a difficult application for alternative meter types.

Proving Coriolis Mass Flow Meters

Field proving of Coriolis mass flow meters can be accomplished using established methods and equipment. There are marked differences in proving Coriolis meters as compared to proving PD and Turbine meters. Two of the major differences are:

- Proper meter installation and the facility for establishing an initial zero point adjustment under stable process conditions are critical factors for successful "in-situ" calibration. If the meter is re-zeroed a Coriolis meter must be re-proven.
- Coriolis meter output pulse are not instantaneous, i.e. Coriolis meter output is not "real time". Rather a time delay exists between the measurement and the transmitted pulse/frequency output. An API task group has been formed to investigate the effect of microprocessor generated pulse delay on field proving using a Small Volume Prover (SVP).

Coriolis Meter Performance

The following is typical Coriolis Meter performance for mass accuracy. Conversion to volume would add an additional uncertainty because the product's density would also have to be determined. For specific performance and application requirements consult the manufacture's specifications.

Flow Turndown Range

+/- 0.15% linearity:
20% to 100% of maximum flow rate

(5:1)+/- 0.25% linearity:
10% to 100% of maximum flow rate (10:1)

Viscosity Turndown Range

Limited by pressure drop at maximum flow rate. Typically under 20 psig pressure drop for products with a viscosity under 100 cSt.

Measurement Turndown Range

Linearity	Viscosity cP					
	100:400	20:100	5:20	2:5	0.8:2.0	0.5:0.8
+/- 0.15%	Viscosity Over 20 psig	25:1	20:1	12:1	12:1	8:1
+/- 0.25%		50:1	40:1	24:1	24:1	16:1

Liquid Ultrasonic Flow Meters

Transit Time Ultrasonic Meters have been used in the petroleum industry for many years in non-custody transfer applications such as leak detection, allocation measurement and check meter measurement. With advancements in multiprocessors, transducers and electronic technology, ultrasonic flow meters are now available with custody transfer accuracy. Liquid Ultrasonic Meters were initially recognized in Europe for custody transfer service and recently in North America with publication of the API Standard – "*Measurement of Liquid Hydrocarbons by Ultrasonic Flowmeters Using Transit Time Technology"*. Because of their non-intrusive design features, there is much excitement about the possibilities of ultrasonic meters for custody transfer measurement but more application experience is needed to verify the meter's performance under various operating conditions.

Operating Principle

Ultrasonic meters, like turbine meters, are inferential meters that derive flow rate by measuring stream velocity. Volume through-put is then calculated by multiplying the velocity by the flow area as shown by the following equation:

Volume Through put (Q) = Velocity (V) x Area (A)

$$Q = V \times A$$

The flow area can be accurately determined from measuring the average internal pipe diameter in the measurement area.

The velocity is determined by measuring the difference in transit time of high frequency sound pulses that are transmitted along and against the flow stream (Figure 11). The pulses are generated by piezoelectric transducers that are positioned at an angle to the flow stream.

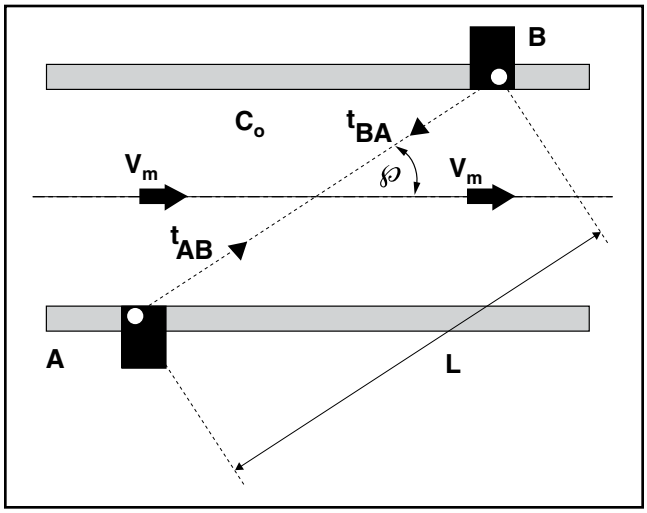


Figure 11 – Single Path of a Liquid Ultrasonic Meter

The principle of measurement is simple but determining the true average velocity is difficult, especially to obtain custody transfer measurement accuracy. The difference in time between the two transducers is in the order of 30 – 120 picoseconds for typical liquid ultrasonic flow meters. Detecting and precisely measuring this small difference in time is extremely important to measurement accuracy and each manufacturer has proprietary techniques to achieve this measurement. Velocity profiles are highly complex and one set of traducers only measures the velocity along a very thin path. To determine the velocity profile more accurately, custody transfer ultrasonic meters use multiple sets of transducers (Fig. 12) The number of paths, their location and the algorithms that integrate the path velocities into an average velocity all contribute to the meter's accuracy.

Besides the stream velocity there is swirl (transverse velocity) caused by elbows and other piping configurations and local velocities at the transducer ports that are included in the path velocity. The local velocities are normally symmetrical and can be statistically cancelled. The transverse velocity must either be eliminated by flow conditioning or accounted for by the meter. Some ultrasonic designs measure the transverse velocity and account for it in the velocity algorithms.

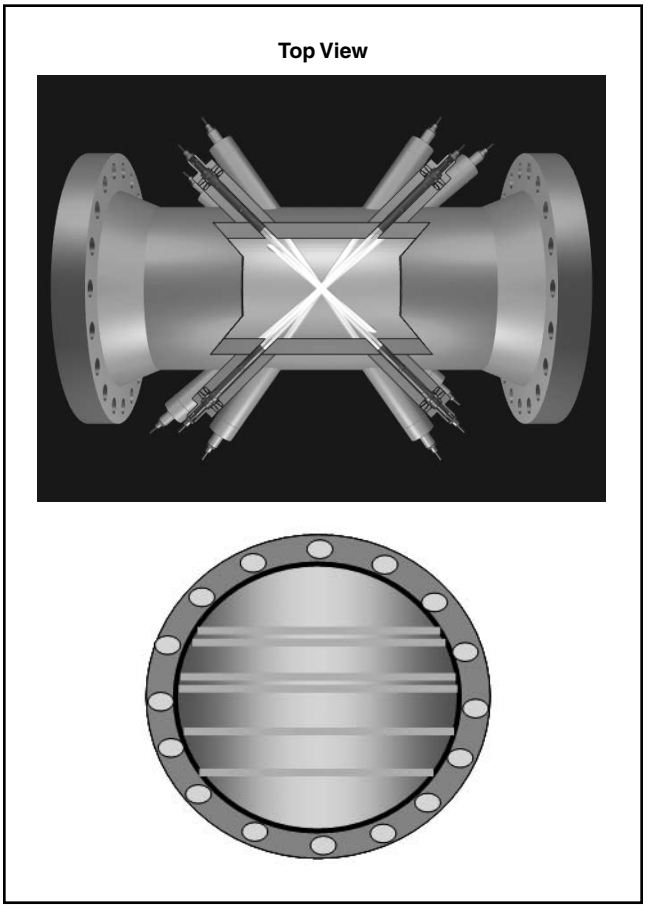


Figure 12 – Multipath Ultrasonic Meter

To determine the true average velocity, ultrasonic meters measure the path and transverse velocities many times a second. Each meter has a unique method but a number of samples must be taken before the microprocessor outputs the volume that passed through the meter as pulses per unit volume.

A key difference between ultrasonic meters and other meters is inertia. In PD meters, turbine meters and

Coriolis mass meters there is an inertia transfer from the flow stream and to the measuring element. The ultrasonic meter measures the flow stream directly without imposing any constraints. Without inertia an Ultrasonic Meter detects any small change in stream velocity, transverse velocity or instantaneous changes in local velocity. For this reason ultrasonic meters are far more sensitive to systematic error then conventional meters. Measurement accuracy is improved by taking more samples. The inertia free measuring principle and the pulse output delay due to sampling are key reasons why it is more difficult to prove ultrasonic meters with conventional provers and methods.

Application Advantages of Ultrasonic Meters

The advantages of an ultrasonic meter include:

- Non-intrusive measurement (no obstruction to flow)
- No moving parts
- No pressure loss
- Bi-directional
- Possibility of self-diagnostics
- Provide information on other fluid properties
- Potential for remote operation

The advantages of an Ultrasonic Meter make it a compelling choice for many applications but cost, proving and application experience should also be considered.

Refined Products and Light Crude Oil High Volume Through-Put Applications – The advantages of Ultrasonic Meters make them well suited choice for high volume applications such as pipelines and ship loading / unloading facilities. Like turbine meters they are best operated at the higher flow ranges for optimum accuracy. No pressure loss reduces operating cost. No moving parts increases service life and may reduce the frequency of proving because usage wear is a key reason why meters are recalibrated. Like turbine meters ultrasonic meters:

- Can handle higher through-put than PD meters or Coriolis mass meters of equal size.
- Are practically well suited for LPG applications because of no moving parts and their compact tubular design make them economical to manufacture for higher operating pressures.

Transportation of Crude Oils – the advantages of Ultrasonic Meters make them an ideal choice for the transportation of crude oil especially for the harsh applications where the crude oil has entrained particulates which can significantly reduce the service life of PD meters. There are limitations to using Ultrasonic Meters in these applications, which include:

- Products with entrained solids or gas can attenuate or fully block the signals. Typically, solids and entrained gas is limited to 5% and 1%, respectively, but even less amounts can significantly affect the meters performance.
- High viscosity products can affect the meter in two ways.
  - Highly viscous products can attenuate or block the signal. Since the acoustical path lengths vary with meter size, each size has a maximum viscosity which is stated by the manufacturer.
  - Like Turbine Meters, Ultrasonic Meters are affected by boundary layer thickness. With medium to high viscosity products this effect must be compensated to achieve accurate measurement. . Multi-path Ultrasonic Meters have methods to minimize this effect but some methods may be more robust then others. Even with these compensation methods there is a transitional region where the velocity profile can change significantly under the same dynamic conditions.

The prospects for the application of ultrasonic meters for medium to heavy crude oils are promising but there are application limitations that must be defined to obtain acceptable results.

Proving Liquid Ultrasonic Flow Meters

Field proving of liquid ultrasonic flow meters is difficult for two reasons:

- Like Coriolis Meters, Ultrasonic Meters' output pulses are not related in "real time" to the meter through-put. There is a time delay exists between what is being measured and the pulse output. Reducing the meter's response time and / or increasing the prove volume are recommended.
- The inertia free measuring principle makes the ultrasonic meters far more sensitive to systematic error then conventional meters. Measurement accuracy is improved by taking more samples.

In the new API Ultrasonic Flow Meter Measurement standard, the following prover volumes are recommended to achieve acceptable results. Also included are prover sizes for similar size turbine meters.

Prover Volume vs Meter Size				
	5 Runs 0.05%		8 Runs 0.09%	10 Runs 0.12%
	Prover Size (barrels)			
Meter Size	TM	Ultrasonic Meters		
4"	5	33	15	10
6"	12	73	34	22
8"	20	130	60	40
10"	24	203	94	62
12"	48	293	135	89
16"	100	521	241	158

Ultrasonic Meter Performance

The following is typical ultrasonic meter performance. For specific performance and application requirements, consult the manufacturer's specifications.

- Flow Turndown Range: Any flow range from 10% to 100% of maximum flow rate
- Viscosity Turndown Range: Any viscosity (cSt) up to 10 times the meter's diameter (inches)
- Reynolds Number: Greater than 20,000
- Measurement Turndown Range (MTR) vs. Linearity:

MTR	Linearity
40:1	+/- 0.15%
60:1	+/- 0.25%

Summary

There is a choice in custody transfer meters for nearly all applications. Proper selection is based on several factors but the primary criteria for selecting a custody transfer meter should be accuracy. The ramifications of measurement error and uncertainty can outweigh the purchase and operating cost of the meters. The below table is a summary of standard operating specifications for the various types of custody transfer meters. The proper meter for the application may be outside these parameters in which case a meter would be customized for the operating conditions.

There are choices and selecting the right meter for the job can optimize measurement accuracy while minimizing operating cost.

Summary of Typical Custody Transfer Meters

Category	Units	PD Meter	Coriolis Mass Meter	Conventional Turbine Meter	Helical Turbine Meter	Ultrasonic Meters
Sizes		< 1" - 16"	< 1/2" - 6"	< 1" - 20"	< 1" - 16"	4" - 20"
Max. Flow Rates	BPH	12,500	4,500	42,000	28,000	50,000
	m^3h	2,000	715	6,650	4,450	7,930
Max. Working Pressure	psi	1,440				
	bar	100				
Measurement Turndown at +/- 0.15%		8:1 to 200:1	8:1 to 25:1	10:1	40:1	40:1
Proving Types		VTP, SVP, CPP	CPP	SVP, CPP	SVP, CPP with pulse interpolation	CPP sized to meet sample rate

** **Prover Types –** Volumetric Tank Prover (VTP); Small Volume Prover (SVP) and Conventional Pipe Prover (CPP).*

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B.T. Arnberg, *"Practice and Procedures of Error Calculations"*, Flow "Its Measurement and Control" Volume 1, ISA 1974

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This paper was first presented by R. J. Kalivoda on March 9-11, 2005 at the NEL 4th South East Asia Hydrocarbon Flow Measurement Workshop in Kuala Lampur, Malaysia.

Appendix A

*Typical Viscosity and Specific Gravity of Petroleum Products**

	Typical Viscosity in cP** @ Degrees F (Degrees C)						S.G. @ Degrees F (Degrees C)	
Product	**30 (-1)**	**60 (15)**	**100 (38)**	**150 (66)**	**300 (150)**	**400 (205)**	**60 (15)**	**150 (66)**
Ethane -LPG	0.07	0.05	0.03				0.38	0
Propane –LPG	0.14	0.12	0.09	0.07			0.51	0.41
Butane – LPG	0.20	0.18	0.15	0.13			0.56	0.49
Gasoline	0.83	0.63	0.49	0.38			0.75	0.70
Water	1.8	1.2	0.7	0.4	0.2	0.1	1.00	0.95
Kerosene	3.5	2.2	1.7	0.9	0.4	0.2	0.82	0.77
Jet Fuel	3.5	2.2	1.7	0.9	0.4	0.2	0.82	0.77
48 API Crude	3.5	2.7	1.7	1.1			0.79	0.74
40 API Crude	10	7	4	2			0.82	0.77
35.6 API Crude	25	16	6	3			0.85	0.80
32.6 API Crude	42	21	9	5			0.86	0.81
Fuel 3 (Max.)		10	5	3	1	0.5	0.90	0.85
Fuel 5 (Min.)		16	7	4	1	0.6	0.97	0.92
Fuel 6 (Min.)		820	150	43	5	2	0.99	0.94
SAE 10 Lub		68	29	11	2	1	0.88	0.83
SAE 30 Lub		450	105	31	4	2	0.90	0.85
SAE 70 Lub			460	95	8	3	0.92	0.87
Bunker C			1500	290	16	5	1.01	0.96
Asphalt				>3000	80	19	0	0

**Data made available from the Crane Co.*
***Centipoise (cP) = Specific Gravity (S.G.) x Centistokes (cSt).*

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