DISPLACEMENT METERS FOR LIQUID MEASUREMENT
Class Number # 2110.1

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Introduction

The petroleum measurement industry continues to demand a liquid flow meter that has a high degree of repeatability, linearity, and stability. Meter repeatability is the ability of the meter to reproduce the same meter factor, given the same conditions. Linearity is the ability of the meter to have a meter factor within a specified percentage deviation from maximum flow in comparison to minimum flow. Stability is the meter's ability to reproduce the same meter factor time after time for some given length of time, given that the operating conditions are the same.

History

PD meters have been used to measure liquid petroleum products for over a century. Many of the PD meter's designs were developed from liquid pumps or compressors. In the early thirties, PD meters were used extensively to measure liquid volume dynamically instead of static tank measurement. The meters were used widely for custody transfer measurement of petroleum liquids on tank trucks, bulk loading terminals, and small pipelines.

By the sixties, PD meters were developed that could measure in excess of 12,000 barrels per hour to accommodate the newly designed larger pipelines and marine loading terminals. Their accuracy, stability and reliability have not been surpassed, and many will agree that there is no more accurate and reliable means of liquid petroleum measurement. The PD meter had become known as the "Standard of Measurement" for the liquid petroleum industry.

Types of Meters

There are many types of fluid meters and they are divided into two classifications, Volumetric (Direct) – or – Velocity (Inference) type meters. The definition of each will be discussed below.

Volumetric (Direct) Type Meters

PD meters are direct type meters because they measure the liquid volume directly by continuously segmenting (isolating) the fluid into known parcels of volume and then counting them. Each segment utilizes a liquid or capillary type seal. Typically, a continuous series of momentary isolated segments of known volume is transmitted through an appropriate gear train to a counting mechanism. Registration is expressed in terms of volume throughput, i.e. gallons, barrels, etc. In the last several years, PD meters have been designed in a way that produces an electronic signal, eliminating the need for the mechanical gear train and meter accessories for the purpose of a visual registration.

Velocity (Inference) Type Meters

Velocity (inference) type meters infer the volumetric flow rate by measuring some dynamic property of the flow stream. There are many different types of velocity meters such as turbine meters, sonic meters, orifice plates, flow nozzles, venturis, and pitot tubes. Mass meters can also be classified as inference type meters when outputting a volumetric pulse because they infer volume from the coriolis force and density of the fluid.

Design and Construction

There are three major groups of components or subassemblies that make up the PD meter: the outer housing, measuring element, and accessory drive train. The accessory drive train includes the meter gearing, packing gland, counter, compensators (temperature and/or gravity), pulse generators and ticket printers.

External Housing

The external housing is basically a pressure vessel that contains the measuring element and houses the accessory drive train. It also consists of the inlet and outlet connections, which can vary depending on application. The connections can be ANSI or DIN flange type, NPT, RTJ, or Victaulic type, and vary in size from ¾ inch up to

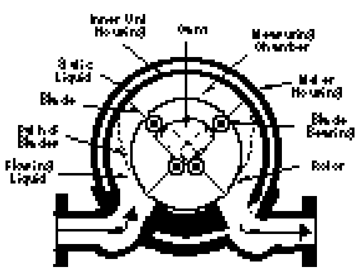
16 inches. Another consideration of the outer housing is the working pressure. Depending on construction, the working pressure can range from 150 PSI to 1,480 PSI (ANSI Class 600). Higher pressure outer housings are available but are typically supplied on special request. The outer housing orientation can be straight through, angle, or vertical configuration. The materials of construction range from carbon steel, cast iron, ductile iron, aluminum, and stainless steel. The maximum flow rate varies with meter size up to 12,500 barrels per hour.

PD meters are designed as either single or double case. The single-case design incorporates the outer housing as part of the measuring chamber and pressure vessel. The single-case design is generally used in low-pressure applications because pressure variations can affect the accuracy of the meter due to the outer housing being an integral part of the measuring chamber.

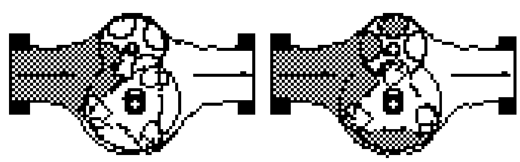
The double-case design mounts the measuring element to the outer housing and is completely surrounded by liquid. This design is used in low and high pressure applications because it offers the advantage of eliminating any pressure variations affecting the measuring element. More advantages to the double-case design are that the measuring element can be removed for hydro-test, flushing of the lines during start-up, and or during meter maintenance. During maintenance, a spare measuring element can be installed in the meter housing minimizing line down time. In many installations, the meter is subjected to line stresses through the piping end connections. The double-case design meter is less likely to be affected by line stresses because the measuring element is not directly connected to the end connections. Caution should still be taken to reduce any line stresses to optimize meter performance.

<u>Internal Measuring Element</u>

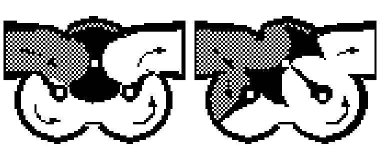
As mentioned, PD meters measure volumetric flow continuously separating the flow stream into discrete volumetric segments and counting them. Some of the most common PD meters’ measuring element principals are illustrated in Figure 1. The measuring element also servers as a hydraulic motor, absorbing energy from the flow stream to produce torque necessary to overcome internal friction and drive the counter and other accessory loads.



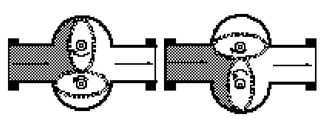
Double-Case Rotary Vane Meter



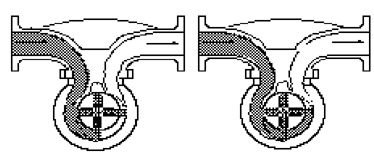
Bi-Rotor Meter



Rotating Paddle Meter



Oval Gear Meter



Sliding Vane Meter

Figure 1 — PD Meter Measuring Elements

PD Meter Flow Path

In any liquid-type seal meter, there are clearances between the moving parts. This is generally called a capillary seal because the liquid forms a seal between the moving parts. Even though a small amount of liquid can pass through the clearances, when given constant conditions of flow rate, viscosity, temperature, pressure, etc., there is little concern regarding the amount of slippage. This is because slippage is primarily a function of pressure, the greater the differential pressure across the clearance, the greater the volume of liquid that will pass through it.

The pressure loss through a PD meter can be divided into two categories: (1) hydraulic loss due to the bending of the fluid and hydraulic friction from the walls, and (2) the loss due to the energy required to turn the rotor and meter accessories.

As mentioned, the measuring element absorbs energy from the flow stream to produce the torque to overcome internal friction and to drive meter accessories. To accurately measure liquid throughput, the meter must have the following design features:

Low Pressure Drop – minimizes the slippage across clearances, minimizes pump size and operating cost, and helps the meter's accuracy.

Low Mechanical Friction – helps reduce pressure drop across the meter and improves service life while improving accuracy.

High Torque Driving Capabilities – especially important when the meter is fitted with mechanical flow output devices such as counters, compensators and transmitters.

Ability To Pass Entrained Solids – especially important if the meter is subject to foreign material such as weld slag, rouge, sand, rust, etc.

Accessory Drive Train

The accessory drive train translates flow information from the flow stream to an output device. All PD meters have some type of flow output indication in the form of devices such as mechanical counters, compensators, flow rate indicators, and transmitters. Typically, the accessory drive train is broken into three basic elements: gear train, packing gland, and calibrator (See Figure 2).

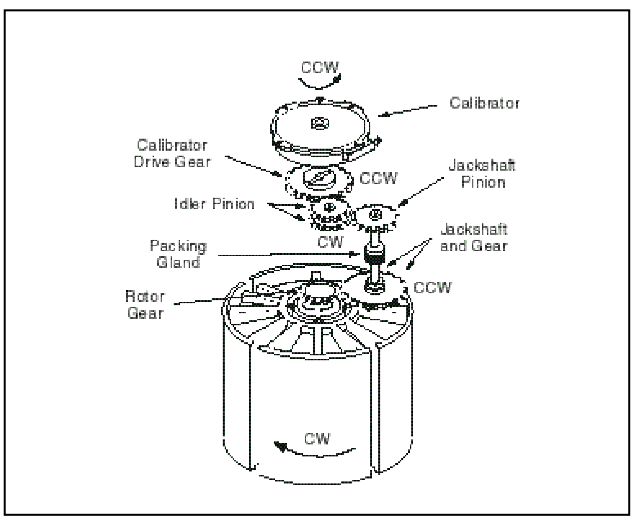


Figure 2 — Typical Counter Drive Train

1. Gear Train

The gear train begins with the rotation of the rotor inside the measuring element, which is housed inside the meter (See Figure 2). The meter gearing provides a nominal input to the meter accessories, and it also reduces the speed of the meter output shaft. For example, a Smith Meter E3-S1 PD meter has a nominal displacement of 1.400 gallons for every rotor revolution. The meter gear train converts this volume into a more convenient registration by having 5 gallons of volume pass through the meter for every one revolution of the output shaft.

There are many variations in unit output, gear ratios, and gearing percentage. The units of output registration such as gallons, barrels, and even pounds are established by the meter gearing.

2. Packing Gland

In most PD meters, a packing gland is used to retain the liquid and pressure inside the meter while allowing rotor rotation to be transferred outside. Since the packing gland is subject to wear, most PD meters have a low shaft speed to improve the packing gland seal life. The packing gland is generally a higher friction point, so the gear reduction of the meter's gear train reduces the amount of torque required by the meter to drive the accessories.

Some PD meters use a magnetic drive coupling. This eliminates the packing gland or also known as the rotary shaft seal. The advantage of this is it eliminates the need to service a dynamic seal.

3. Calibrator

The meter calibrator is a device that adjusts the meter's mechanical counter to register the true volume that passes through the meter. It is used to compensate for manufacturing variations. Without a calibrator, meter error would be between 0.5–1.0%. This is due to manufacturing variations and relatively coarse gear ratio increments in the meter gear train. Thus, whenever a mechanical counter must register accurate volume, a calibrator must be installed. The calibrator utilizes a double overriding clutch mechanism that can only add counts to the mechanical register; thus the meter gearing is always less than 100 percent.

The desired drive ratio is accomplished by increasing the speed of the output shaft in relation to the input shaft. This is accomplished during approximately one-half of a revolution. During the second half revolution, both shafts rotate at the same speed. Because of the speed variation between the two shafts during rotation, a cyclic rotation is produced through the output shaft. The amount of variation is proportional to the amount of correction being applied. Cyclic speed variation between the input/output shafts does not cause mechanical registration errors because the meter gearing and register are typically in whole units. When proving a PD meter, the cyclic speed variation can cause problems depending on the type of prover. The volume of a tank or can-type prover is typically in whole units which are multiple of the meter volume so the meter calibration is unaffected by the cyclic speed variation of the calibrator.

However, when proving with a pipe (displacement-type) prover, the volume between detector switches is not normally in whole units or multiples of the meter volume. Thus, the cyclic speed variations of the calibrator can cause repeatability problems. This is especially true when using a Small Volume Prover. If repeatability problems occur due to the cyclic output of the calibrator when proving the meter then group proving or statistical averaging of consecutive runs may be done to achieve accurate meter calibration.

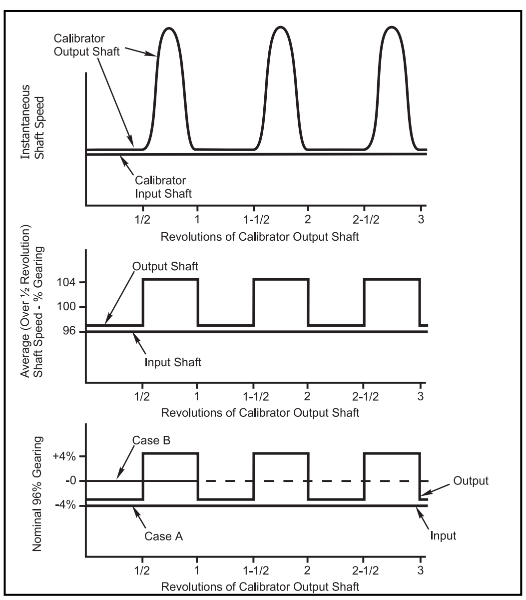


Figure 3 — Revolutions of Calibrator Output Shaft

Cyclic speed variation from the calibrator, and how it can cause non-repeatability when calibrating a PD meter, are illustrated in Figure 3. The graphs demonstrate the calibrator input/output shaft relationships to each other. As you can see, the input shaft speed is 96% of unity (specific registration, Gallons, Liters, Barrels, etc.) during one-half revolution but then rotates at 104% of unity during the second half of rotation.

If a "meter factor" (ratio of actual volume/indicated volume) is required then nominal 100 percent meter gearing and a "dummy" calibrator is necessary. A dummy calibrator is a calibrator housing with a straight through shaft. If a pulse generator is required, a dummy calibrator must be used. This prevents cyclic speed variation, which would affect pulse output.

Cyclic speed variation can come from other sources, such as inconsistent flow rates, eccentricity in meter gears, drive couplings, and rotor eccentricity between center and O.D. These secondary sources of cyclic speed variation are peculiar to each individual meter and cannot be predicted.

4. Meter Accessories

a) Mechanical Counters

Mechanical counters provide a means of indicating volume throughput. The readout can be adjusted via the calibrator to register the actual volume throughput of the meter. Mechanical counters can register in many different units (gallons, barrels, liters, pounds etc.).

b) Ticket Printer

Ticket printers are used in conjunction with mechanical counters to provide a paper document of the volume throughput.

c) Transmitters

Transmitters provide an electronic signal to another electronic device for volume throughput indication. The volume throughput information coming from the measuring element is converted into a precise ratio of pulses per unit volume. When transmitters are used, no mechanical adjuster or calibrator is needed since the electronic instrument is programmed with a meter factor or calibration factor to adjust the meter throughput volume to actual volume.

Several new designs of PD meters have been introduced in the last several years that have no mechanical output. Figure 4 illustrates the Smith Meter Prime 4, which is designed with only an electronic pulse output. These newly designed PD meters have been specifically designed to provide electronic pulses directly from the meter rotor. The advantage of these meters is that no packing gland, gear train or calibrator is required. The exclusion of these components eliminates speed variations of the meter output shaft as well as mechanical friction, wear, maintenance and reduces environmental hazards.

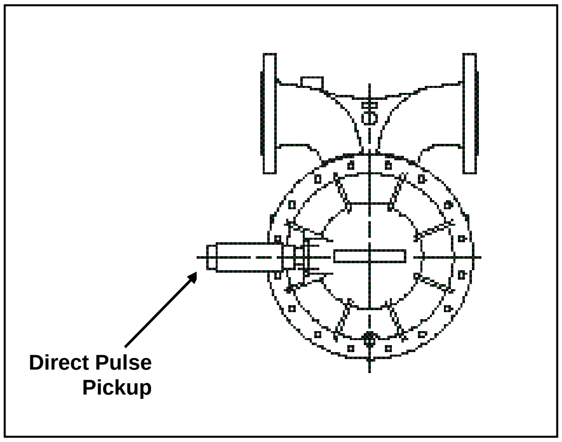


Figure 4 – Direct Pulse Output Meter

d) Compensators

Volume indication can be compensated for temperature and/or gravity of the liquid being metered. A characteristic of all liquids is that a change in volume occurs with a change in temperature. The measurement and legal sale of most liquids is based on a net volume at a reference base temperature (60°F). By installing compensators in the meter stack-up, the registration will be compensated for any changes in fluid temperature.

Accuracy Theory

Meter accuracy is very important during the custody transfer of product. The meter now becomes a cash register and provides information to calculate the total value of the transaction. There are two factors that affect the accuracy of a PD meter: measuring chamber displacement volume and slippage through the capillary seals (clearances). The accuracy considerations of any meter can be divided into three classifications:

1. Stability (Reproducibility)

   Stability is the ability of the meter to reproduce the same meter factor over time (Figure 5).

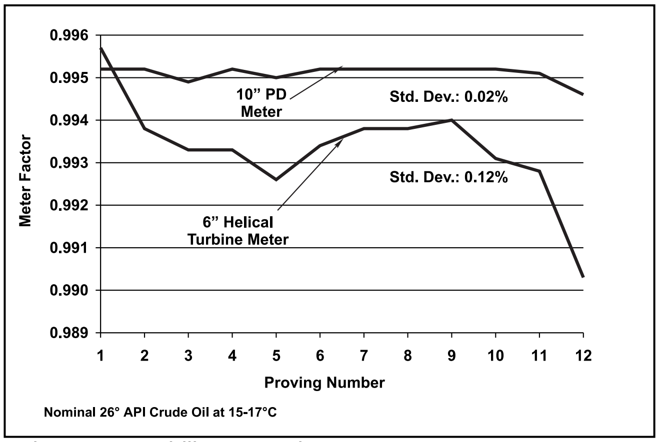


Figure 5 – Stability Example

2. Linearity

   Linearity is a relationship between the high flow rate and the low flow rate. Generally this relationship referred to as the meter's turndown. The difference between the two-meter factors or volume indication should not exceed +/- 0.15% (Figure 6).

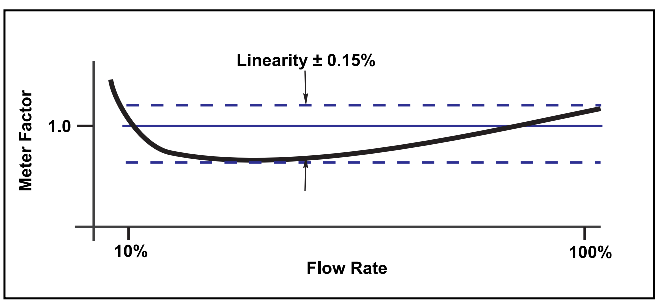


Figure 6 – Linearity Example

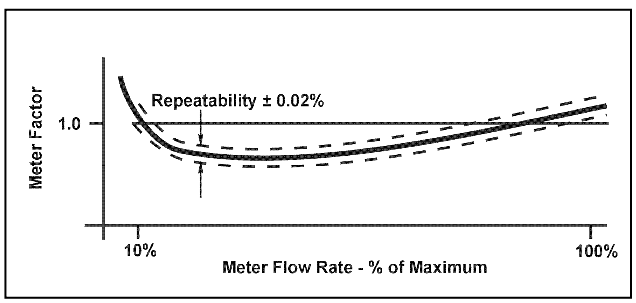


Figure 7 – Repeatability Example

3. Repeatability

   Repeatability is the ability of the meter to reproduce the same meter factor at one given flow rate with the same operating conditions (Figure 7).

Volume Displacement

The volume displaced by the measuring element is affected by: temperature, pressure, viscosity, wear, and deposits.

1. Temperature

   Changes in temperature will affect the displacement of the meter because of the thermal expansion or contraction of the materials specified by the design. This is directly related to the cubical thermal expansion coefficient of the material. In a standard Smith Meter rotary vane PD meter, the blades are manufactured from aluminum, which have a higher cubical thermal expansion coefficient than cast iron rotor and measuring chamber material. When the blades expand, the volumetric segment displaces more volume because the blades “sweep” a greater volume. Typically, for every 10°F change in fluid temperature, about a 0.02% change in accuracy will be observed.

2. Pressure

   Substantial pressure changes during operation will affect the accuracy of single case meters. Double case meters are not affected by these pressure changes. Therefore a general guideline is to use double case meters when there will be variations of 20 psi or more during meter operation. Single case meters can be used in these conditions but there should be a meter factor for different pressures that can be applied to achieve the required accuracy.

3. Viscosity

   As the fluid viscosity increases it will produce a film on the surfaces of the measuring chamber and other internal parts. This film will continue to increase until the wiping action of the measuring elements parts stops the build up. This can be an accuracy issue if the meter is not proved for different products. For example if a heavy crude oil is run through the meter then a load of condensate follows in another batch the meter should be proved for each product. The crude oil will produce a film in the measuring element whereas the condensate will wash this film away.

4. Wear

   Wear has several effects on the volumetric displacement of a PD meter. In the case of a Smith Meter rotary vane PD, wear on the cam and blade bearings allows the blade to travel closer to the measuring chamber wall, displacing more volume. This wear is slow but can be predicted by plotting meter factors on a curve. Another form of wear results in increased mechanical friction which can be in the areas of the rotor thrust bearing, gear train, and meter accessories. It is recommended that a low flow calibration be performed periodically to detect and adjust for mechanical friction. As friction increases the meter factor will also increase. This is why meter proving and proving records are important to retain, record, and compare.

5. Deposits

   Deposits can be similar to the effects of viscosity. An example of deposits is paraffin wax that is found in some crude oil. The wax can build to the point that it closes the clearances and reduces the slippage to almost nil. This is generally not a problem as long as the operating conditions stay consistent. A variation in temperature can affect the accuracy in this type of condition because of the possibility of the wax melting therefore changing the measuring element’s displacement. This may cause significant shifts in meter factor.

Slippage

All PD meters have moving and stationary parts. These parts require clearances between them. As mentioned this clearance is referred to as a capillary seal. Because there is no contact between the parts to form the seal, the liquid forms the seal. A differential pressure through the measuring chamber can cause flow that may not be accounted for in the displacement. This flow is referred to as “slippage.”

There are two typical causes of differential pressure, mechanical and hydraulic. Mechanical ΔP is induced because of internal friction, packing gland, gear train, and accessory drive train. Hydraulic ΔP is induced by the fluid properties.

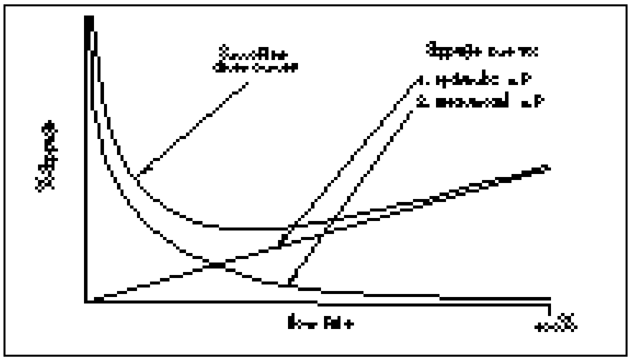


Figure 8 — Accuracy Curve

The graph in Figure 8 depicts the net results of mechanical and hydraulic differential pressures and the corresponding slippage.

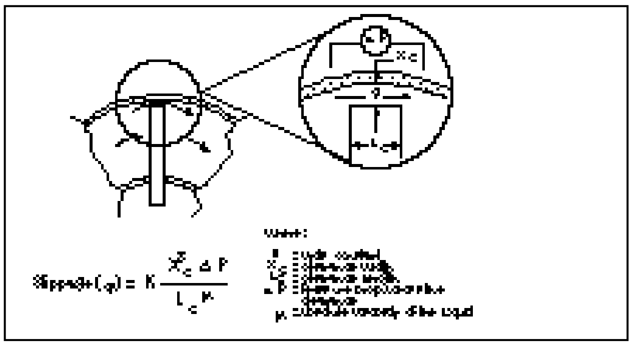


Figure 9 — Slippage Through PD Meter Clearances

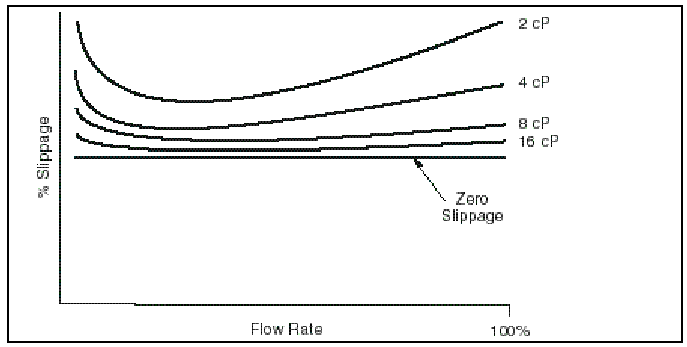


Figure 10 — Effect of Viscosity on the Accuracy Curve

Slippage through the clearances of a PD Meter can be characterized by the equation in Figure 9. Slippage through clearances is affected by the following factors:

1. Flow Rate

   The percentage of slippage change is directly related to the differential pressure produced by hydraulic and mechanical friction. Generally high flow rates have a hydraulic friction and the lower flow rates is where the mechanical friction takes over.

2. Viscosity

   If the fluid viscosity is increased, it becomes more difficult for it to pass through the clearances of the measuring element. Figure 10 depicts how various viscosities affect the accuracy curve of a PD. Note: when the viscosity is doubled, the slippage percentage amount is halved. At viscosities greater than 16cP, the amount of slippage is almost nil and the percentage changes in slippage at various flow rates are negligible.

3. Friction

   As mechanical friction is increased, more pressure differential is required to produce the torque to drive the meter and accessories, thereby allowing more product to flow past the clearances without being metered. Meters with relatively high mechanical friction can have good accuracy at a given flow rate, but the linearity of the meter across the whole flow range is reduced (See Figure 11).

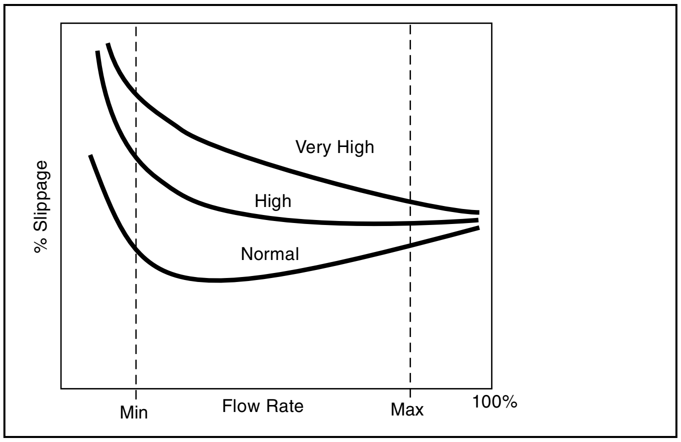


Figure 11 — Effects of Mechanical Friction

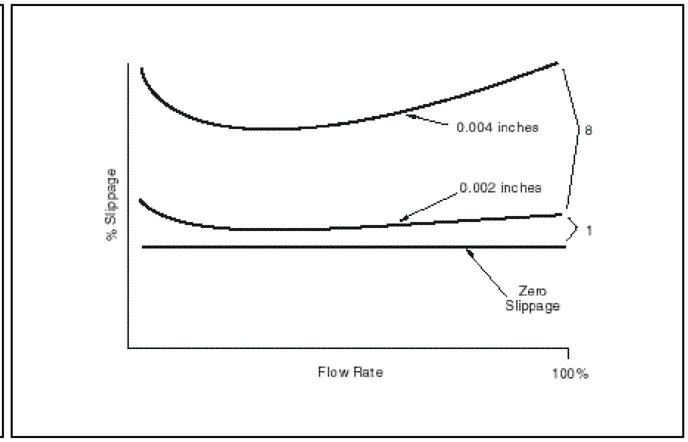


Figure 12 — Effects of Clearances

4. Wear

   As the components inside the meter wear and the type of wear will determine the meter slippage change. As shown in Figure 12, as parts wear, the clearances inside the measuring element will change. Any changes to the clearances will cause significant change to the amount of slippage. As the slippage changes the meter factor will also change.

Maintaining PD Meter Accuracy

Generally, if operating conditions such as viscosity, flow rate and temperature remain stable, there are only two factors that can cause substantial shift in meter factor: excessive mechanical friction (measuring element, gear train, meter accessories), or excessive meter clearances. Figure 12 shows a typical PD meter accuracy curve shift with clearance changes. Figure 11 shows a typical PD meter accuracy curve shift with mechanical friction. These two accuracy curves demonstrate that mechanical friction provides a greater shift at lower flow rates, while an increase in clearances would have a greater shift in the accuracy curve at high flow rates. Looking at these curves and historical proving data of the meter can be a very useful tool on setting up a maintenance program to ensure the PD will produce the best accuracy that is possible.

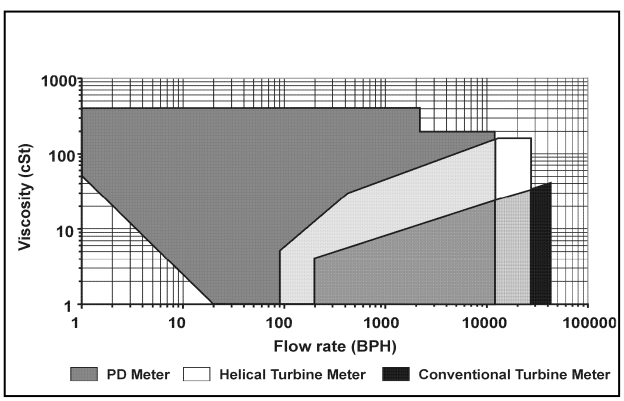


Figure 13 — Meter Application Ranges

Conclusion

For optimum meter performance and longevity, it is critical that the PD meter user have a basic understanding of how various designs and operating conditions can affect the accuracy of metering. PD meters have an advantage over other meters because they have the capability of measuring products with varying viscosity without appreciable shift in the meter factor. The meter factor of the PD meter is constant over wide variations in viscosity, pressure, temperature, line conditions, and flow profile.

Since petroleum is valuable, the petroleum industry demands high accuracy in meters for custody transfer measurement in pipelines, marine loading terminals, tank trucks, and marketing terminals. Figure 13 illustrates the viscosity and flow ranges where PD meters excel. There are many metering technologies including new technologies available today, but PD meters still continue to be the industry leader for accuracy and dependability.

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