White Paper
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Fundamentals of Orifice Meter Measurement

Summary

This white paper provides an overview of orifice meter technology, its advantages and general installation recommendations, as well as describes basic gas flow laws and the variables of orifice meter flow equations.

1.0 Overview

Fluid meters are divided into two functional groups: one measures quantity (positive displacement) and the other measures rate of flow (inferential). All fluid meters consist of two distinct parts, each of which has a different function to perform. The first part is the primary element which is in contact with the fluid, resulting in some form of interaction. This interaction may be that of imparting motion to the primary element (i.e. the fluid may be accelerated, etc.). The second part is the secondary element that translates the interaction between the fluid and primary element into a signal that can be converted into volume, weight or rate of flow. The device then indicates or records the results.

With an orifice meter, the orifice together with the adjacent part of the pipe and the pressure connections constitute the primary element. The secondary element consists of a differential pressure device together with a mechanism that translates the pressure difference into a rate of flow and indicates the result. In some cases, the device also records the result graphically and integrates the data with respect to time. This combination of primary and secondary elements is typical in most types of fluid meters, including:

1.1 Positive Displacement (quantity meters)

Common types of positive displacement meters include reciprocating piston, rotating piston, nutating disk, sliding and rotating vanes, and gear and lobed impeller. The meter most commonly used to sell small quantities of natural gas at relatively low flow rates is known as the bellows meter.

1.2 Inferential (rate meters)

There are many types of inferential meters available, including:

1.2.1 Orifice Plates

The most commonly used inferential or rate meter is the thin-plate, concentric orifice meter which is the primary device discussed in this paper.

1.2.2 Flow Nozzles and Venturi Tubes

Flow nozzles and Venturi tubes are primary rate devices which will handle about 60% more flow than an orifice plate for the same size bore under the same conditions, enabling these devices to handle higher velocity flows. If a differential pressure limit is chosen, a smaller bore nozzle or Venturi may be used to measure flow under the same conditions. These devices are more expensive to install and, due to their size, are not as easy to change or inspect as orifice plates.

1.2.3 Pitot Tubes

A pitot or impact tube accounts for the difference between static and kinetic pressures at a single point. A similar device, the averaging pitot tube is, in effect, a multi-point pitot tube that averages the flow profile.

1.2.4 Turbine Meters

A turbine meter has a primary element that is kept in rotation by the linear velocity of the flow in which it is immersed. The number of revolutions the device makes is proportional to the actual volume of flow.

1.2.5 Vortex Shedding Meters

Vortex meters use a bluff body to create vortices with the frequency of the vortices directly proportional to flow velocity.

1.2.6 Magnetic Resonance Meters

Magnetic resonance meters, also known as mag meters, operate on the principal of induction. By surrounding a conductive liquid with a magnetic field, movement of the liquid creates a measurable signal proportional with flow velocity.

1.3 Permanent Pressure Loss

The amount of unrecovered loss due to a flow element is known as permanent pressure loss. For differential pressure elements, the calculation of pressure loss is straightforward. The total system pressure loss should be based on the amount of differential created at a given beta ratio for a given flow. Devices with a higher coefficient of discharge may not necessarily have a lower permanent loss for the same flow.

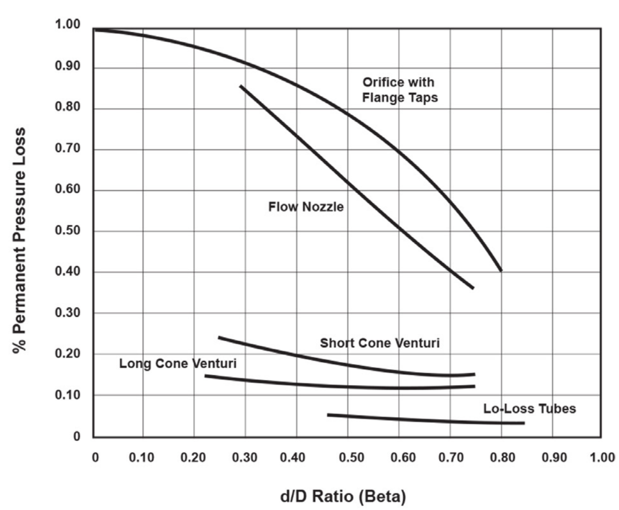

Figure 1 – Pressure Loss Characteristics of Primary Devices

2. Overview of Orifice Meter Technology

A differential pressure meter creates a pressure drop by combining a conduit and a restriction. A nozzle, Venturi or thin, sharp-edged orifice can be used as the flow restriction. Prior to using any of these devices for measurement, it is necessary to empirically calibrate them by passing a known volume through the meter and noting the reading to provide a measurement standard for other quantities.

Due to the ease of duplication and the simple construction, the thin, sharp-edged orifice has been adopted as a measurement standard. Extensive calibration work has also been performed on the device, making it widely accepted as a standard means for measuring fluids. Provided the standard mechanics of construction are followed, no calibration is required. An orifice installed in a pipeline along with a manometer for measuring the drop in pressure (differential) as the fluid passes through the orifice is shown in Figure 2. The minimum cross-sectional area of the jet immediately after the orifice is known as the "vena contracta."

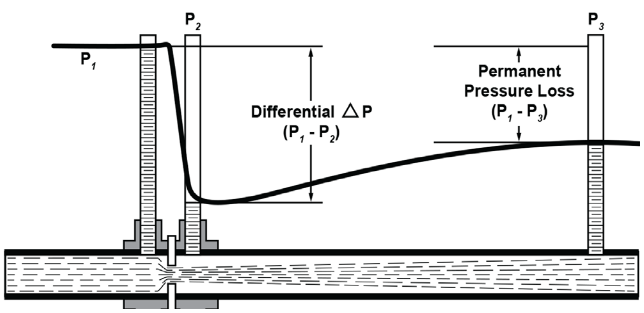

Figure 2 – Typical Orifice Flow Pattern Flange Tap Diagram

3. How An Orifice Meter Works

As fluid approaches the orifice, the pressure increases slightly and then drops suddenly as the fluid passes through the orifice. The pressure continues to drop until it reaches the "vena contracta" and then it gradually increases until it is approximately 5D to 8D. At this point, it reaches maximum downstream pressure which is lower than the pressure upstream of the orifice.

The pressure decrease as fluid passes through the orifice is due to the increased velocity of the natural gas passing through the reduced area of the orifice. When the velocity decreases as the fluid leaves the orifice, the pressure increases and tends to return to its original level. The pressure loss is not fully recovered due to loss of friction and turbulence in the stream. The pressure drop across the orifice (Figure 2) increases when the rate of flow increases.

When there is no flow, there is no differential pressure. The differential pressure is proportional to the square root of the velocity. Therefore, it follows that if all other factors remain constant the differential is proportional to the square root of the flow rate.

4. History of Orifice Flow Measurement

The first recorded use of an orifice device for fluid measurement was in 1797 by Giovanni B. Venturi, an Italian physicist whose work led to the development of the modern Venturi meter in 1886 by Clemons Herschel. In 1890, it has been reported that an orifice meter designed by Professor S.W. Robinson of Ohio State University was used to measure gas near Columbus, Ohio. In 1903, T.B. Weymouth began a series of tests in Pennsylvania leading to the publication of coefficients for orifice meters with flange taps. At the same time, E.O. Hickstein conducted a similar series of tests at Joplin, Missouri from which he developed data for orifice meters with integrated pipe taps.

From 1924 to 1935, a significant amount of research and experimental work was conducted by the American Gas Association (AGA) and the American Society of Mechanical Engineers (ASME) that resulted in the development of orifice meter coefficients and standards of construction for orifice meters. In 1935, a joint AGA-ASME report was issued, "History of Orifice Meters and The Calibration, Construction, and Operation of Orifices for Metering" that remains as the basis for most present day orifice meter measurement installations. In early 1991, the American Petroleum Institute (API) issued an updated version of this standard based on new data titled, "Manual of Petroleum Measurement Standards, Chapter 14, Section 3, Parts 1-4." Several additional publications are available to simplify measurement by orifice meters, including "ASME Fluid Meters 6th Edition, ASME Power Test Code, Chapter 4 on Flow Measurement" and The Flow Measurement Engineering Handbook by R.W. Miller.

5. Gas Law Measurement

All matter is composed of exceedingly tiny particles called molecules. A molecule is defined as the smallest particle that can exist in the free and undecomposed state (i.e., natural gas is composed of molecules of methane, ethane, etc.). These molecules are in constant motion and it is the impact of these molecules on the sides of a container that is measured as pressure. Temperature regulates the speed of the molecules. Therefore, an increase in temperature increases the motion of the molecules which increases the pressure in a constant volume vessel.

As decreased temperature and pressure causes decreased motion of the molecules, there must be a point where there is no molecular activity. The points where there is no molecular activity are absolute zero temperature [approximately -273°C (-460°F)] and absolute zero pressure (approximately 14.7 psi below atmospheric pressure). Absolute pressure is equal to gauge pressure plus atmospheric pressure (14.7 psi at sea level). Absolute temperature is equal to degrees Fahrenheit plus +459.67°F and is called degrees Rankine (°R).

Boyle's Law states that in an ideal gas the volume is inversely proportional to the absolute pressure. If a cylinder has a volume of gas at an absolute pressure of 14.7 psi and a piston was to displace the volume in the cylinder until the pressure doubled, the cylinder would contain half of its original volume.

Charles' Law states that the volume of an ideal gas is directly proportional to the absolute temperature. If a cylinder has a volume of gas at +16°C (+60°F) or +514.67°R and a piston was used to displace the volume in order to maintain a constant pressure while the absolute temperature was doubled to +304°C (+580°F) or +1039.67°R, the cylinder would then contain twice its original volume.

The combined ideal Boyle's and Charles' Law is commonly written in the form of the equation:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Where:

P = Pressure at condition 1 or 2

V = Volume at condition 1 or 2

T = Temperature at condition 1 or 2

1 = Flowing conditions

2 = Base conditions

6. Orifice Gas Flow Equation

To determine gas flow with an orifice, many variables are required. Each variable is included in this equation followed by a definition of each variable.

$$Q_v = C_d E Y_2 d^2 \left(\frac{T_b}{P_b}\right) \sqrt{\left(\frac{P_{f1} * Z_b * h_w}{G_r * Z_{f1} * T_f}\right)}$$

Where

C_d = Orifice plate coefficient of discharge

d = Orifice plate bore diameter calculated at flowing temperature (T_f) (mm or inches)

G_r = Real gas relative density (specify gravity)

h_w = Differential pressure (kPa or inches of water at +60°F)

E = Velocity of approach factor

P_b = Base pressure (bara or psia)

P_{f1} = Flowing pressure (upstream tap) (bara or psia)

Q_v = Standard volume flow rate (Nm^3/hr or SCF/hr)

T_b = Base temperature (°R)

T_f = Flowing temperature (°R)

Y_2 = Expansion factor (downstream tap)

Z_b = Compressibility at base conditions (P_b, T_b)

Z_{f1} = Compressibility (upstream flowing conditions - P_{f1}, T_f)

6.1 Orifice Plate Coefficient of Discharge (C_d)

This coefficient has been determined empirically for flange-tapped orifice meters. To accurately use this coefficient, the orifice meter must be manufactured to the specifications of AGA 3/API 14.3. Basically, the coefficient of discharge depends on the Reynolds number, sensing tap location, meter tube diameter and orifice diameter with a few other minor influences. Each coefficient of discharge applies to the Reynolds number at which it is calculated.

6.2 Orifice Plate Bore Diameter (*d*)

This diameter must represent the bore diameter at flowing conditions. Corrections must be made if the temperature at which the plate was measured is different from the flowing temperature to account for the effects of thermal expansion.

6.3 Real Gas Relative Density or Specific Gravity (G_r)

This is the normal specific gravity obtained from a specific gravity test or recording instrument. It represents the ratio of the density of the gas divided by the density of air at the same conditions. A larger quantity of gas with specific gravity = 0.25 can be passed through an orifice than a gas with specific gravity = 1.0. Since flow varies as the square root of one over the specific gravity, twice as much gas will flow with the lighter gas.

6.4 Differential Pressure (h_w)

This measure of the pressure drop across the orifice is measured in kPa or inches of water at +60°F. Approximately 27.7 inches of water is equal to one psi.

6.5 Velocity of Approach Factor (E)

This factor corrects for the change in velocity between the upstream meter tube and the velocity in the orifice bore. This factor varies with the beta ratio.

$$E = \sqrt{\frac{1}{1 - \beta^4}}$$

6.6 Beta Ratio (β)

The ratio of the orifice plate bore divided by the inside pipe diameter.

$$\beta = \frac{d}{D}$$

Where

d is the plate bore (mm or inches)

D is the pipe I.D. (mm or inches)

6.7 Base Pressure (P_b)

To define the quantity of gas measured, the base pressure must be defined. This pressure is set by contract, by governmental law or as an agreement of the measurement by the two parties. AGA 3 uses 14.73 psia as the base pressure.

6.8 Flowing Pressure (P_{f1})

The pressure is measured at either the upstream or downstream pressure tap locations (Figure 8). It is common in the natural gas industry to measure at the downstream tap. Pressure has two effects on volume: gas is denser at higher pressure, resulting in less volume flowing through the meter. However, when the volume is expanded to base pressure, the volume is increased.

6.9 Base Volume Flow Rate (Q_v)

This diameter must represent the bore diameter at flowing conditions. Corrections must be made if the temperature at which the plate was measured is different from the flowing temperature to account for the effects of thermal expansion.

6.10 Base Temperature (T_b)

The base temperature is defined by contract, by governmental law or as an agreement of the measurement by the two parties. To correct degrees Fahrenheit to degrees Rankine, +459.67°F is added. Most natural gas is at a base temperature of +519.67°R. For instance, +60°F plus +459.67°F.

6.11 Flowing Temperature (T_f)

The flowing temperature is normally measured downstream from the orifice and must represent the average temperature of the flowing stream in degrees Rankine. Temperature has two effects on volume: a higher temperature means a less dense gas and higher flows but, when this higher flow is corrected to the base temperature, the base flow is less.

6.12 Expansion Factor (Y_1 or Y_2)

The expansion factor corrects for the density change between the measured tap density and the density at the plane of the orifice face. Since the common static pressure tap used in natural gas measurement is the downstream factor Y2; this factor is smaller than the Y1 correction.

6.13 Compressibility at Base Conditions [(P_b T_b) - Z_b]

Since 1985, it has been a requirement to correct for the gas compressibility from the base pressure to absolute zero pressure at +16°C (+60°F).

6.14 Compressibility at Flowing Conditions [(P_f, T_f) - Z_f1]

Real gases compress more than the ideal gas law predicts and this compression must be corrected for when gas is measured at high pressure and at temperatures other than +16°C (+60°F) that are mathematically reduced to base conditions. This correction, when applied outside of the square root radical, is called supercompressibility. In round numbers at ambient temperature, the compressibility affects volume by 0.5% per bar (14.5 psi) of pressure change.

7. Critical Flow

The gas flow equation applies to subsonic flow only. Sonic or critical flow occurs when the velocity of the gas or vapor reaches the speed of sound (approximately 1200 kph, or 700 mph in air). A gas cannot travel any faster and remain in the same state. A guideline to approximate when critical gas flow is reached is when the downstream pipe tap registers an absolute pressure of approximately 50% or less than the upstream pipe tap.

8. Major Advantages of Orifice Meter Measurement

Flow can be accurately determined without the need for actual fluid flow calibration. Well established procedures convert the differential pressure into a flow rate using empirically derived coefficients. These coefficients are based on the ability to accurately measure orifice plate dimensions and pipe diameters as defined in standards combined with easily measurable characteristics of the fluid rather than on fluid flow calibrations.

With the exception of the orifice meter, almost all flow meters require fluid flow calibration at flow and temperature conditions closely approximating of those when the meter will be in service in order to establish accuracy. Orifice meters do not require direct fluid flow calibration and offer the advantages of being simple to operate, rugged, widely accepted, reliable and relatively inexpensive with no moving parts.

9. The Three “R’s”

9.1 Reliability (uncertainty/accuracy)

The coefficients calculated for flange taps by the equations in AGA 3/API 14.3 are subject to an uncertainty of approximately ±0.5% when the beta ratio is between 0.2 and 0.7. When the beta ratio is between 0.1 and 0.2 or 0.7 and 0.75, the uncertainty may be greater. Minimum uncertainty occurs between 0.2 and 0.6 beta ratios. Below a Reynolds number of 1,000,000, there will be a minimal increase in uncertainty with the minimum Reynolds number of 4,000 being the limit of the standard.

9.2 Rangeability

Rangeability, also referred to as turndown, is the ratio of maximum flow to minimum flow throughout which a stated accuracy is maintained. For example, if an orifice meter installation is said to be accurate to ±1% from 16,990 to 5,663 m^3/hour (600,000 to 200,000 SCFH), the rangeability would be 3:1.

9.3 Repeatability

Repeatability is the ability of a flow meter to indicate the same readings each time the same flow conditions exist. These readings may or may not be accurate but will repeat. This capability is important when a flow meter is used for flow control.

10. The Orifice Plate

Orifice plate bores can be configured to handle various flow measurement applications. The flowing conditions should be checked to determine the appropriate bore configuration for each application.

10.1 Thin Plate, Concentric Orifice

The thin plate, concentric orifice is the most commonly used orifice plate. In the design and use of orifice plates, several basic factors must be followed to assure accurate, reliable measurement. The upstream edge of the orifice must be sharp and square. In addition, the minimum plate thickness is standardized based on pipe I.D., orifice bore, etc. The plate should not depart from flatness along any diameter by more than 0.25mm per mm or 0.01 inch per inch of the dam height (D-d)/2. To ensure conformance with recommended practices, the beta ratio must not exceed recommended limits.

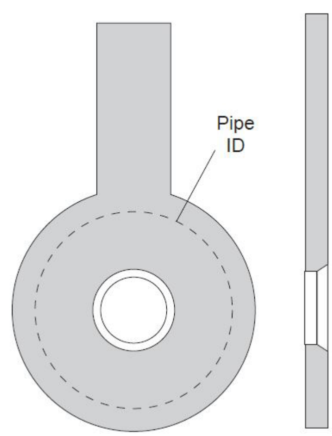

Figure 3 – Thin Plate. Concentric Orifice

10.2 Eccentric Orifice Plate

The eccentric orifice plate has a round opening (bore) tangent to the inside wall of the pipe. This type of plate is most commonly used to measure fluids which carry a small amount of non-abrasive solids or gases with small amounts of liquid. With the opening at the bottom of the plate, the solids and liquids will carry through rather than collect at the orifice plate.

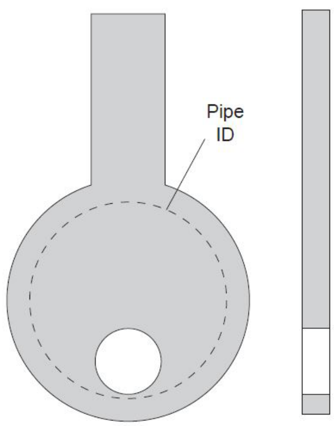

Figure 4 – Eccentric Orifice Plate

10.3 Segmental Orifice Plate

The opening in a segmental orifice plate is comparable to a partially opened gate valve. This plate is generally used for measuring liquids or gases which carry non-abrasive impurities, including light slurries or exceptionally dirty gases. The predictable accuracy of both eccentric and segmental plates is not as high or reliable as the concentric plate.

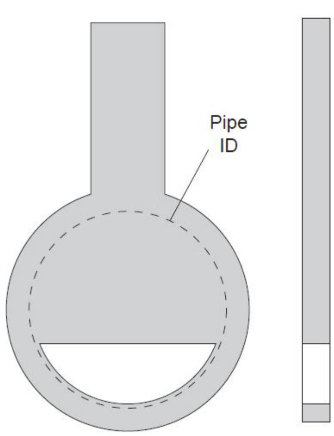

Figure 5 – Segmental Orifice Plate

10.4 Quadrant Edge Plate

The quarter-circle or quadrant edge orifice is used for high viscosity fluids with low Reynolds numbers. The orifice incorporates a rounded edge of definite radius which is a particular function of the orifice diameter.

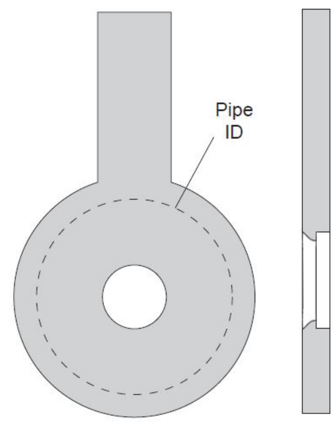

Figure 6 – Quadrant Orifice Plate

10.5 Conic Edge Plate

The conic edge plate has a 45° bevel facing upstream into the flowing stream. It is useful for measuring fluids that have even lower Reynolds numbers than the quadrant edge.

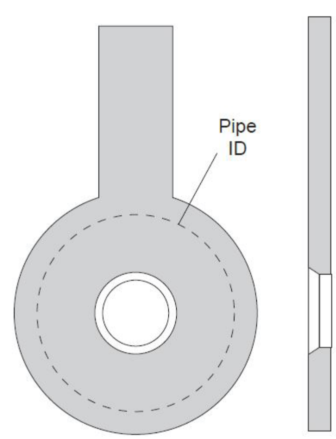

Figure 7 – Conic Orifice Plate

11. Meter Tap Location

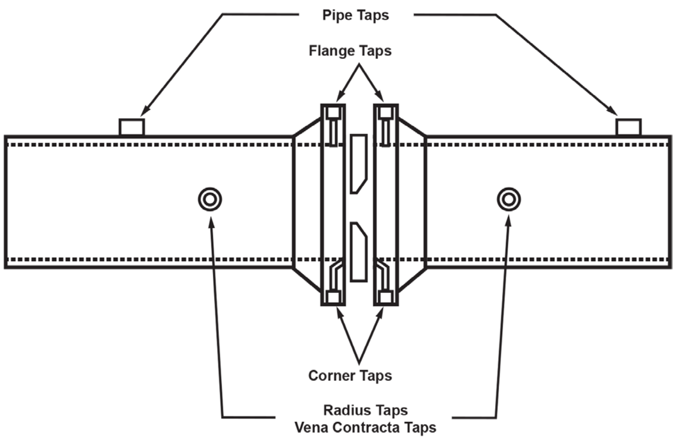

Figure 8 – Pressure Tap Locations

11.1 Flange Taps

These taps are located 25.4mm or one inch from the upstream face of the orifice plate and 25.4mm or one inch from the downstream face with a tolerance of ±0.4mm (±1/64 of an inch) to ±0.8mm (±1/32 of an inch). Flange taps are most commonly used in the U.S. Older meter stations may still use pipe taps.

11.2 Pipe Taps

These taps are located 2.5D upstream and 8D downstream (i.e. point of maximum pressure recovery).

11.3 Vena Contracta Taps

These taps are located 1D upstream and at the point of minimum pressure downstream (i.e. the vena contracta). This point varies with the beta ratio and is generally only used in plant measurement where flows are relatively constant and plates are not changed.

11.4 Corner Taps

These taps are located immediately adjacent to the plate faces, upstream and downstream. Corner taps are most widely used in Europe. In line sizes less than 50mm (2-inch), these taps are used in conjunction with specially honed flow meter tubes to improve low flow rate measurement.

12. Orifice Flange Unions

The most elementary device used to hold an orifice plate in place is the orifice flange union. While orifice flanges have been used for many years, these devices gained importance during the 1920s when the petroleum industry began extensive orifice measurement. However, it was quickly discovered that the orifice flange, in spite of its simplicity, fell short in certain applications. For instance, it could not be conveniently used for wide variations of flow, for dirty fluids requiring frequent plate cleanings, or in services where flow interruptions are expensive. Therefore, it was often necessary to bypass the flow, allowing the orifice plate to be inspected or changed as conditions warranted.

13. Dual-Chamber Orifice Fitting

Changing plates in orifice flanges is time consuming and expensive. Operators benefit from a device that ensures plate changes and/or inspection is less tedious and safer. The original type of orifice fitting that reigns today as the most widely used device is known as the dual-chamber type. Its design permits the change or the removal of a plate under flowing conditions.

The lower chamber of the dual-chamber fitting holds the orifice plate in the fluid flow. The lower chamber is bolted to an upper chamber. Separating the two chambers is a slide valve that is operated (i.e. opened and closed) with a gear shaft. By opening the slide valve, the plate carrier and orifice plate are elevated into the top chamber. Once the slide valve is closed again and pressure bled from the top chamber, the plate carrier and plate can be removed.

14. Single-Chamber Orifice Fitting

While the dual-chamber fitting was designed to offer many advantages, it does not address the challenges associated with changing orifice plates when a bypass is in existence or where two or more meter tubes are joined by common headers. In addition, orifice flanges are not convenient in all cases and are time consuming to operate, creating the need for a simple single-chamber type fitting. While similar to the dual-chamber fitting, the single-chamber fitting does not have a slide valve or top chamber. Typically, larger, single-chamber fittings have gears for easy plate removal, whereas smaller, single-chamber fittings 50mm to 200mm (2-inch to 8-inch) do not have gears and the plates are removed by hand.

15. Meter Tubes

Many companies have joined the industry to study the effects of the upstream and downstream pipe immediately adjacent to the orifice plate. These lengths of pipe are known as meter tubes, meter runs, flow sections and/or meter sections. However, the most generally accepted terminology is meter tubes. Tests have proven that the length and condition of the pipe used in meter tubes has a significant impact on the overall accuracy of the measurement. The proper manufacture of orifice meters and orifice fittings is critical.

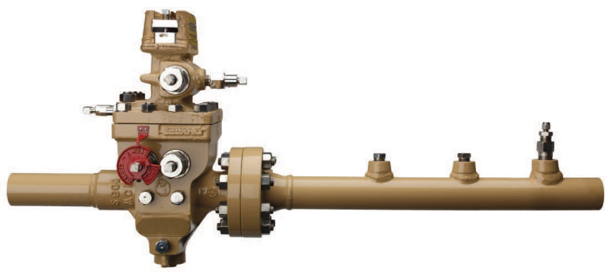

Figure 9 – Typical Meter Tube with an Installed Orifice Fitting

16. Visual Manometers

A manometer in its simplest form is a glass tube bent in the form of the letter "U" and partially filled with some liquid. If both ends of the "U" are open to atmosphere, the pressure on each side will be similar and the column of liquid on the one side of the "U" tube will exactly balance the column of liquid on the other side (i.e. the surface on both sides will be at the same level). If one leg of the "U" is connected to a supply pipe in which the pressure is a little greater than the other leg, the column of liquid will be down on the high pressure side and up on the low pressure side. This difference in height is a true measure of the difference in pressure in the two legs of the manometer. If the manometer liquid is water, the height difference is measured in inches of water column at room temperature. The basic visual manometer is rarely used in the field today but gives an elementary understanding of differential pressure measurement.

17. Differential Pressure (DP) Cell

The DP transducer measures the differential pressure and converts the reading to an electrical signal for input into a flow computer. The latest models are smart transducers that correct for the effects of temperature and pressure and offer measurement stability for up to 15 years.

Multivariable transmitters have the ability to measure three variables in one device, including DP, pressure and temperature. This capability helps reduce the number of pipe penetrations, instrument connections and configurations. Most multivariable transmitters can also complete fully compensated mass flow calculations.

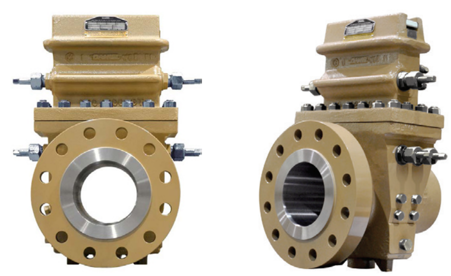

Figure 10 – Daniel Senior Orifice Fitting

18. Daniel Senior Orifice Fitting

The Daniel Senior™ Orifice Fitting is engineered to provide the best possible conditions for metering accuracy and ease-of-use. It meets all AGA 3/API 14.3 recommendations for sizes and tolerances, pressure ratings and tap locations. The dual-chamber design permits the orifice plate to be removed from pressurized lines safely and quickly, resulting in considerable savings. Regular inspection and replacement of orifice plates results in higher accuracy. The Senior fitting is available from 50mm to 600mm (2-inch to 24-inch) line sizes and pressure ratings up to ANSI Class 2500.

19. Daniel Simplex Orifice Plate Holder

The Daniel Simplex™ Orifice Plate Holder is a single-chamber orifice fitting. It was developed to provide an economical, accurate solution for conventional orifice flanges where plate changes are infrequent and orifice flange unions are too cumbersome. Featuring the same basic design as the Junior fitting, it is not necessary to elevate the orifice plate using a shaft and pinion gear. The Simplex fitting is only offered in 50mm to 100mm (2-inch to 4-inch) line sizes, making the plate and plate carrier easily removable by hand. In addition, the line does not have to be jacked apart nor liquid product spilled.

Two types of end connections (i.e. body styles) are available and all Simplex holders are made to AGA 3/API 14.3 recommendations. Pressure ratings are available up to ANSI Class 2500.

Figure 12 – Daniel Simplex Orifice Plate Holder

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