Orifice Meters for Liquid Measurement

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"To Accomplish Great Things, We Must Not Only Act But Also Dream, Not Only Plan But Also Believe." - Anatole France

INTRODUCTION

Measurement is the basis of commerce between oil producers, royalty owners, oil transporters, refiners, marketers, governmental authorities and the general public. In fact, accurate measurement of hydrocarbon fluids has a high impact on the Gross National Product of exporting and importing countries, the financial performance and asset base of global companies, and the perceived efficiency of operating facilities. The need for accurate hydrocarbon measurement is obvious. As a result, accurate unbiased hydrocarbon measurement is an essential goal of any responsible organization. Fiscal measurement involves the use of standard proven equipment and procedures.

The most commonly used method at present for the accurate flow measurement of highly compressible hydrocarbon fluids (LPG mixes) and dense phase fluids is by orifice meter, using appropriate secondary instrumentation. Specifically, concentric, square-edged, flange-tapped orifice meter is used for fiscal measurement in North America.

An understanding of the process (operating and fluid) conditions, as well as, the physical properties of the hydrocarbon fluids are fundamentally important before designing or analyzing these measurement facilities. Several methods and types of equipment are utilized to achieve accurate measurement. The basic measurement process remains the same ---- the act of comparing a known mass quantity to an unknown mass quantity. However, the Law of Similarity is too often violated resulting in inaccurate measurement and under performing facilities.

APPLICABLE FLUIDS

Measurement of hydrocarbon fluids applies to steady-state mass flow conditions for fluids that, for all practical purposes, are considered to be clean, single phase, homogeneous and Newtonian under the operating conditions of the facility. All gases, most liquids and most dense phase fluids associated with the petroleum, petrochemical and natural gas industries are usually considered to be Newtonian fluids.

For simplicity, we will limit our treatise to dynamic measurement applications using orifice metering for high compressible or dense phase fluids. These fluids are assumed to be clean and homogeneous - predominately hydrocarbon mixtures of ethane, propane or butane.

FLUID PHYSICAL PROPERTIES

Fluid physical properties are of fundamental importance and must be ascertained before any serious measurement design or analysis. The important physical properties for the measurement of these fluids are -

- Fluid Composition (ρ_b, MW)
- Flowing Density
- Absolute Viscosity
- Vapor Pressure
- Isentropic Exponent
- Water Content

PROCESS (OR OPERATING) CONDITIONS

The operating or process conditions for the metering application are also critical design parameters. In certain situations, the metering facility may be relocated due to the process conditions and the dynamics of the physical properties. In other situations, the meter facility may require special elastomeric materials, operating procedures, or meter calibration frequencies to control the impact of the process conditions on the uncertainty of the measurements.

To design and operate an accurate flowmetering application, an ***envelop*** of the following process conditions should be assembled and validated after startup.

- Flowrate - max, min, normal
- Pressure - max, min, normal
- Temperature - max, min, normal
- Fluid Density - max, min, normal
- Absolute Viscosity - max, min, normal

Other process or operating conditions and preventive maintenance programs to consider in the design and operation are -

- Pseudo Fully Developed Flow
- Cleanliness of Stream
- Polymerization and/or Dimerization
- Elastomer Compatibility

ORIFICE FLOWMETER

The choice of primary device is likely to be the most important design decision. In the case of fiscal measurement it will be influenced more by the established in-service performance of the type of meter under consideration rather than cost or other factors. At this time, the concentric, square-edged, flange-tapped orifice meter is the most widely used meter type for LPG mixtures and dense phase fluid measurement for three reasons:

- *in situ* calibration is not required as long as the Law of Similarity is not violated
- the orifice meter's linearity is better than most turbine meters
- unlike turbine meters, for orifice meters the density term is under the square root, thereby minimizing the sensitivity to determining the flowing density

Other meters, such as turbine and displacement meters, are in use for fiscal measurement but to
a lesser extent then the orifice meter. This is mainly due to the difficulty and expense of providing calibration facilities that truly reflect the conditions met in service. The multipath ultrasonic meter and the Coriolis effect meter are also potential primary devices for fiscal measurement.

An orifice meter is a fluid flow measuring device that produces a differential pressure to infer flowrate. The meter consists of the following elements:

- A thin, concentric, square-edged orifice plate.
- An orifice plate holder consisting of a set of orifice flanges (or an orifice fitting) equipped with the appropriate differential pressure sensing taps.
- A meter tube consisting of adjacent piping sections with *isolating flow conditioner.*

The auxiliary (secondary) devices necessary for the precise determination of flowrate sense differential and static pressure, fluid temperature, a user selected technique for determining flowing and reference density, and a flow computing device. Additional instrumentation to ensure the quality of the fluid are normally included in the facility design.

The designer should be aware of the requirements for maintenance and calibration while the meter is in service, since these recurring costs may affect the design decisions.

Where meter calibration is required it should be done over the flowrate range that will be met in service and on a fluid of similar composition and pressure, or if necessary on a range of compositions and pressures that cover those likely to be met in service.

The calibration of a meter at regular intervals can be done using on of two methods --- a central calibration or an *in situ* calibration technique.

Procedures for the operation, calibration and maintenance of the primary and secondary instrumentation should be provided for the metering system.

Law of Similarity

For orifice meters, the empirical discharge coefficients determined from the experiments are valid if dynamic and geometric similarity exists between the metering installation and the experimental data base. For turbine and PD meters, the meter factor determined at the time of proving is valid if dynamic and geometric similarity exists between the meter calibration and the entire custody transfer period. Both approaches are termed the Law of Similarity – that is geometric and dynamic similarity exists between the calibration or prediction and the operating meter.

Geometric similarity requires that the experimental flow system be a scale model of the field installations. The experimental pattern's design locates sensitive dimensional regions to explore, measure and empirically fit. A proper experimental pattern for orifice meters allows the user to extrapolate to larger meter tube diameters without increasing the uncertainty.

Dynamic similarity is the underlying principle for present day theoretical and experimental fluid mechanics. The principle states that two geometrically similar meters, with fully developed flow conditions shall display geometrically similar streamlines.

Dynamic similarity implies a correspondence of fluid forces between the two metering systems. For the orifice meter, the inertial and viscous forces are the ones considered significant within the application limitations of this standard. As a result, the Reynolds number, which measures of the ratio of the inertial to viscous forces, is the term which correlates dynamic similarity in all empirical coefficient of discharge and flow coefficient equations. In fact, the Reynolds number correlation provides a rational basis for extrapolation provided the physics of the fluid does not change. The physics changes, for instance, between subsonic and sonic flow.

The mechanical specifications for the flowmetering technology must be adhered to as stated in the standard to assure dynamic similarity.

Many factors influence the overall measurement uncertainty associated with a metering facility. Major contributors include construction tolerances of the meter components, tolerances of the empirical discharge coefficient or *in situ* calibration, predictability of and the variations in the fluid's physical properties, and uncertainties associated with the auxiliary devices.

Under certain conditions, it is normal practice to calibrate an orifice meter independently since its accuracy is controlled by compliance with the tight geometrical tolerances laid down for the orifice plate itself, the orifice plate holder, and the pipework immediately upstream and downstream of the meter.

Basic Design Criteria

The primary element of the orifice meter is a plate of uniform thickness with a centrally located circular hole. This is square-edged on the upstream side, and is beveled with a 45° chamfer on the downstream side if the thickness of the plate is greater than the limit defined by ANSI/API MPMS Chapter 14 Section 3. The plate has to be accurately located in a concentric position relative to the centerline of the upstream and downstream piping.

For fiscal measurement the plate shall be manufactured according to the geometrical tolerances of ANSI/API MPMS Chapter 14 Section 3, and any additional requirements of the fiscal authorities.

The flow of gas to the orifice meter should be subsonic and have a fully developed velocity profile and turbulence structure. The flow should also be substantially free of pressure or flow pulsations, and be free of liquid. Where there is a likelihood of liquid entrainment or condensation occurring in the piping it may be permissible to provide a drain hole at the bottom of the orifice plate to prevent accumulation of liquid upstream of the plate.

The piping installation and orifice fitting are characterized by the type and location of the pressure tappings used for measuring the pressure differential across the plate. The position of the tappings affects the discharge coefficient. These tappings may be within the orifice fitting itself or a set of orifice flanges.

Performance

The accuracy of the primary device, that is the orifice plate itself, is such that an uncertainty in discharge coefficient of 0.45% can be attained by conforming to the Reynolds Law of Similarity. To achieve this the overall design must conform to the requirements for maximum accuracy laid down in ANSI/API MPMS Chapter 14 Section 3. The overall uncertainty of the orifice meter, including the effects of the secondary instrumentation, can thus be as low as 0.6% based on the Law of Similarity.

With *in situ* calibration, the orifice meter can achieve an uncertainty of 0.25%.

The above levels of accuracy is typical of the best fiscal applications, and can only be attained if the piping geometry requirements in the standards, particularly for upstream and downstream straight pipe lengths, are strictly observed in combination with *isolating flow conditioners*. Certain flow limitations must be followed:

- The flow shall approach steady-state mass flow conditions on fluids that for all practical purposes are considered to be clean, single phase, homogeneous and Newtonian .
- The flow shall not undergo any change of phase as it passes through the orifice plate.
- The fluid shall be subsonic, that is the flowing velocity shall be below the fluid's sonic velocity.
- The Reynolds number shall be within the specified limitations of the empirical discharge coefficient.
- No bypass of flow around the orifice hall occur at any time.
- As with all flowmeters, the orifice meter relies on the Law of Similarity, even when calibrated *in situ*.

Current Research and Other Standards

In the industrial environment, multiple piping configurations are assembled in series generating complex problems for standard writing organizations and flow metering engineers. The challenge is to minimize the difference between the actual or "real" flow conditions and the "fully developed" flow conditions in a pipe to maintain a minimum error associated with the selected metering device's performance. One of the standard error minimization methods is to install a flow conditioner in combination with straight lengths of pipe to "isolate" the meter from upstream piping disturbances.

At the time of preparation of this guide, a considerable amount of research is being carried out in the USA and Europe into installation effects. The results of the American work have been reported in several Gas Research Institute publications. It is anticipated that a revision of the ANSI/API MPMS Chapter 14 Section 3 standard is scheduled to occur by the end of 1998 covering new installation requirements for orifice meters.

The results of this effort is to highlight the use of *isolating flow conditioners* over the traditional tube bundle flow conditioners. Significant bias error has been exhibited by the tube bundle devices in recent research programs.

Attention is also drawn to the ISO 5167. This standard differs in many respects, though the calculation results from the basic discharge coefficients are similar. This standard is widely used in Europe and the North Sea for fiscal measurement purposes. A revision of ISO 5167 is expected in the near future, and international agreement on:

- calculation of discharge coefficients
- installation lengths with/without tube bundle conditioners
- isolating flow conditioners will be incorporated in this revision.

FLOW EQUATIONS

Basic Orifice Flow Equation

The flowrate through the orifice plate is primarily dependent on the size of the orifice and the pressure drop across it. The contraction of the fluid streamlines downstream of the plate, the *vena contracta* effect, causes the actual flowrate to be about one third less than the theoretical, ideal value. To allow for this, a discharge coefficient has to be included in the theoretical flow equation to adjust for multidimensional viscous fluid dynamic effects. In addition, an empirical expansion factor is applied to the theoretical equation to adjust for the reduction in density that a compressible fluid experiences when it passes through an orifice plate.

The accepted one-dimensional equation for mass flow through an orifice is as follows -

$$q_m = C_d\ E_v Y\ (\pi/4)\ d^2 \sqrt{}\ (2 g_c \rho_{tp} dP)$$

or, stated using the practical equation which combines the numerical constant and the unit conversion constants,

$$q_m = N_1\ C_d\ E_v Y\ d^2 \sqrt{}\ (\rho_{tp} dP)$$

Note that in the above equation the fluid density, ρ_{tp}, is at line pressure, measured at the plane of the upstream tapping, and the flowing temperature measured in the downstream meter run. Note also that the equation assumes an isentropic expansion through the orifice plate. In practice the value of the expansion factor, Y, will lie between the isothermal and isentropic values.

For discussion at a later point, the accepted one-dimensional equation for mass flow for a turbine meter is as follows -

$$q_m = \rho_{tp} * MF * (N/K)$$

where,
MF - Meter Factor for the meter
N - number of totalized pulses
K - K Factor assigned to the meter

The volume flowrate, for both orifice and turbine meters, at reference conditions can be calculated from the mass flow equation -

$$q_v = q_m /\ \rho_r$$

where the reference density, ρ_b, is at the reference temperature and pressure.

Empirical coefficients of discharge for orifice meters have been determined by comparing the measured and theoretical flowrates. A major factor in the definition of the experimental patterns for this research was dynamic similarity. Using Reynolds's Law of Similarity, experimental correlations can be applied to dynamically and geometrically similar meters.

To accurately predict the coefficient of discharge, C_d, for an orifice meter manufactured to the specifications of the ANSI standard, certain parameters concerning the orifice meter and the fluid must be known. The relationships between these functions can be simplified for application to commercial use. In fact, the concentric, square-edged, flange-tapped orifice meter coefficient of discharge, C_d (FT), developed by Reader-Harris/Gallagher (RG), is structured into distinct linkage terms and is considered to best represent the worldwide regression data base. The discharge coefficient, C_d, is a function of the pipe Reynolds number (Re_D), the sensing tap location, the meter tube diameter, D, and the orifice diameter ratio, β ---

$$C_d = f(\ Re_D,\ \text{Sensing Tap Location},\ D,\ \beta\ )$$

The velocity of approach factor, E_v, corrects the flow equation for the effect of the upstream kinetic energy on the differential pressure across the orifice. The latter is proportional to the square of the velocity, which is inversely proportional to the square of the diameter, and thus E_v and β are related as follows:

$$E_v = 1/\ [\sqrt{}\ (1 - \beta^4)]$$

Expansion Factor

Compressible fluids expand as they flow through a square-edged orifice. For practical applications, it is assumed that the expansion factor, Y, follows a polytropic, ideal one-dimensional path. Within practical operating ranges of differential pressure, flowing pressure, and temperature, the expansion factor is insensitive to the value of the isentropic exponent. As a result, the assumption of a perfect or ideal isentropic exponent is reasonable for field applications. This approach was adopted by Buckingham and Bean in their empirical correlation. They developed the empirical expansion factor, Y, using the downstream temperature and upstream pressure ---

$$Y = f(\beta, k, x)$$

Within the limits of the ANSI/API MPMS Chapter 14 Section 3 standard, it is assumed that the temperatures of the fluid at the upstream and downstream differential sensing taps are identical for the expansion factor calculation.

If the absolute static pressure is taken at the upstream differential pressure tap, then the value of the upstream expansion factor, Y_1, shall be calculated as follows ---

$$Y_1 = 1 - [\,(0.41 + 0.35\beta^4)\, x_1/k\,]$$

where,

$$x_1 = (dP)/(N_3 P_f)$$

Calculation of Orifice Diameter

The designer is usually required to calculate the size of meter for a given flowrate and gas condition. This is an iterative calculation, since the discharge coefficient is a function of the orifice diameter ratio, β, meter tube diameter, and pipe Reynolds number.

ORIFICE METER DESIGN

Meter Rangeability

Meter rangeability is an important design factor. The flowrate range that an orifice plate can handle is normally limited by the performance of the differential pressure (dP) instrumentation. Owing to the square root relationship of the flow equation, and the fact that differential pressure is usually an analog signal, the accuracy of the flow measurement degrades rapidly at low flows. As a result, it is common practice in fiscal measurement to use stacked dP transmitters with overlapping high and low ranges.

Long term variations in flowrate can be accommodated by changing the size of the orifice plate bore.

Specific Design Criteria

For fiscal gas measurement, the design shall comply with API MPMS Chapter 14 Section 3 and the following additional specifications:

- The maximum orifice diameter ratio β shall be within the range of 0.20 to 0.65.
- The maximum Reynolds number to be 5.0×10^7.
- A maximum differential pressure of 200 inches of H2O@60 (~0.5 bar) is preferred. Higher differential pressures are allowed provided that the plate deformation and expansion factor limitations are satisfied.
- The minimum differential pressure of 10 inches of H2O@60 (0.025 bar) is required to distinguish flow from turbulence noise in the stream.
- The uncertainty in flow measurement caused by elastic deformation of the orifice plate shall be less than 0.10%.
- Special considerations may be applicable where pulsating flow is unavoidable, but normally the uncertainty due to any such effects should be kept below 0.10%.
- The meter should be designed and constructed as specified in ANSI/API MPMS Chapter 14 Section 3.

Calculation of Uncertainty

For fiscal measurement the designer should estimate the overall uncertainty of the metering system as an aid to optimizing the selection of equipment. It is recommended to include this calculation in the design dossier. Calculations of the overall uncertainty of an orifice plate metering system, for both single and multiple meter operation, should be performed by Measurement Experts.

Selection of Method of Density Determination

Head class meters require the density at line conditions to be determined at all times. The density can be determined in one of the following ways:

- Using the fluid's composition, calculating the flowing density using pressure, temperature and an equation of state.
- By measurement of density at line conditions using an online density meter.

The first technique use the *pTZ* or corresponding equation of state method for the calculations. The use of either of these methods have operational advantages over the use of online density measurement. Note however, that significant changes in fluid pressure, temperature or composition will require the recalculation of the fluid densities on a continuous basis when using the first technique.

METER CALIBRATION CONCEPTS

When a liquid metering system is designed in Europe, two calibration concepts are considered — in situ and central calibration.

The in situ calibration concept, the traditional solution for North America, uses a permanent or portable prover at every metering facility.

The central calibration concept, applied at times on the European continent, uses a central calibration facility for a pipeline system. This facility is usually located at an originating station for logistical reasons -- access to the variety of transport properties. The facility is usually a stand alone design which does not interfere with daily operations of the pipeline movements. The meter runs in their entirety are transported to the central facility for calibration.

For both types of calibration, compliance with the Law of Similarity is critical to ensure proper measurement.

UNCERTAINTY OF MEASUREMENT

The designer and/or user needs to consider the custody transfer facility from a holistic view point or stated another way — the big picture. The user must define the desired uncertainty to the designer in order to build, operate and maintain the facility properly.

At a single metering facility, there are two types of uncertainty. The average of the many readings may be offset from the true value (bias error) and/or the readings may be randomly scattered about the offset (random error).

Many factors influence the overall measurement uncertainty associated with a metering application. The uncertainty of the metered quantities is dependent on a combination of the following:

- the traceability chain associated with the field standards.
- the calculation procedure and means of computation (flow computer, mainframe, personal computer, etc.).
- the uncertainty associated with the fluid density predictions.
- the sensitivity of the fluid prediction correlation to errors in pressure, temperature and base density determinations.
- the design, installation, and operation of the metering facility.
- the choice of measurement equipment (transmitters, A/D converters, data loggers, etc.)

- the data transmission means (analog, pneumatic, digital, manual).

- the operating/calibration equipment's effects due to ambient temperature, fluid temperature, fluid pressure, response time, local gravitational forces, atmospheric pressure, etc.

- construction tolerances of the meter components

- tolerances associated with the coefficient of discharge, or central calibration technique, or Meter Factor (in-situ calibration technique)

- predictability of and variations in the fluid's physical properties

- overall compliance with the Law of Similarity.

The uncertainty is dependent not just on the hardware or equipment, but also on the hardware's performance, the software's performance, the method of calculation, the method of calibration, the calibration equipment, the calibration procedures and the human factor.

CONCLUSION

Designing and operating an accurate orifice flowmeter application require understanding the fluid's physical properties. An envelop must be drawn around the process (or operating) conditions, and identifying any special conditions. Understanding the physical principles upon which the orifice meter is based and comprehending it's sensitivities to physical and process conditions is critical. The benefits of orifice meters over turbine meters in compressible and dense phase fluids are:

- low sensitivity to flowing density determination

- *in situ* calibration costs are not required

- low cost of meter maintenance

- excellent linearity versus turbine meter

Typical pipeline balances with orifice meters on compressible and dense phase fluids are +/- 0.25% over a year's time.