Gas Measurement with

Square Edged Orifice Meter

Primary Elements

What can be wrong, what can go wrong and how to detect or prevent it

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Elements of Gas Measurement using a *Differential Producer*

- Primary Element--sees both pressure, temperature, and flow velocity, but no electronic signals.
- Sensing Element (Secondary Element)--sees only pressure and temperature (no flow velocity); generates electronic signals (or pen movements).
- Recording Element (Tertiary Element)--sees only electronic signals (or pen movements).

Assumptions in Calculations

Calculating flow rate using a differential element is *inferential flow measurement* (the other sort of measurement is *Proportional flow measurement* which says you are measuring something that is directly affected by the flow--turbine meters, vortex meters, and coriolis meters are proportional). Inferential flow measurement means that if ALL assumptions are correct within very close tolerances, then you can *infer* a flow rate (using *Bernoulli's Equation* in this case) from some seemingly unrelated parameter (a differential pressure across a known restriction in this case). The assumptions include:

- Gas density is constant (part of the basis for derivation of *Euler's Equation* from the *Navier-Stokes Equation*).
- There is no friction between the gas and the pipe wall (this is the rest of the basis for the derivation of *Euler's Equation*)
- The flow does not change with time (part of the basis for the derivation of *Brernoulli's Equation* from *Euler's Equation*).
- There is no flow across the axis of the pipe (this is the rest of the basis for *Bernoulli's Equation*).
- Tube is straight and level (basis for removing one term from *Bernoulli's Equation*).
- The gas has no opportunity to do work (work is force applied over a distance)--this lets you convert the mass flow rate (which must be constant across the plate) to a volume flow rate (which is not constant across the plate).
- Flow Profile follows the *Power Law* (see below) with about a 1/9-power profile with no swirl, cross flow, or vortices.
- There is enough friction between the gas and the pipe wall to dampen any swirl in the flow. This is the reason that straight pipe is specified upstream of the plate.
- Single phase flow.
- Consistent and unchanging fluid makeup.
- Atmospheric pressure is known precisely.
- Gas pressure is known at a specified point in the flow.
- The temperature of the gas is well known.

- Tube is not too rough
- Tube is not too smooth
- Exact I.D. of both the tube and the plate are known with high precision.
- Leading edge of plate is sharp and free of nicks
- Trailing edge of plate will not interfere with induced flow regime

What constitutes a *Primary Element*?

- Tube--from the inlet flange of the inlet inspection tee through the outlet flange of the downstream inspection tee. Horizontal straight pipe for OFU's. Tube must be installed rigidly with adequate support to prevent it from bowing with time, and it must be precisely horizontal.
- Fitting--verified by pre-acceptance inspections to be able to hold an orifice plate square to the flow and to prevent pressure-communication between the taps in a static pressure test.
- Plate, seal ring, and plate carrier--this is the part of the primary element that is looked at the most, and has the most chances to fail in service.
- Straightening vanes/flow conditioners--located at precise distances upstream of the plate to force the flow profile to match the assumptions that went into the calculation routines.
- Tubing/valving up to sensing elements--this plumbing is intended to allow the transition from the gas flow to the sensing element with as little modification as possible. Long tubing, kinked tubing, leaking fittings, or clogged tubing can prevent this from happening.
- Thermal wells and sample ports downstream of plate--these elements have minor impact on the differential pressure as measured, but problems here can impact flow calculations.

What can be wrong?

When the primary element has passed all the pre-acceptance tests we can be assured that it is capable of accurate measurement. We cannot be as confident that it will accurately measure the gas going through it.

Flow Profile

The profile of the flow is crucial successful measurement. Since we assume that the flow is turbulent and conforms to the *Power Law* (i.e., $v_p = v_{\max}\left(1 - \frac{r}{r_p}\right)^{\frac{1}{1.66*\log(\mathrm{Re})}}$), then we assume that you can calculate the velocity (v_p) at any point (r_p) with some degree of accuracy. If the profile is skewed, contains swirl, or has velocity vectors across the pipe, then this assumption is wrong.

The term in the *Power Law* exponent will be 1/9 when the Reynolds Number is about 264,000 which corresponds to about 1.4 MMCF/d in a 6-inch run (470 MCF/d in a 2-inch). Flow rates substantially different from these numbers will change the profile superficially (flowing 14 MMCF/d in a 6-inch tube gives you a Reynolds Number of 2,650,000 and a *Power Law* exponent of 10.7; 140 MCF/d is 26,500 and 7.3)--the important thing is that about 25% of the flow goes through the middle 20% of the pipe and the flow is symmetrical about the pipe centerline (with velocity always decreasing toward the pipe wall).

At very low flow (i.e., Reynolds Numbers less than 3,000), the flow regime is *Laminar*. The correlation's for gas measurement work superficially in laminar flow, but the flow is much more pointed (i.e., about 30% of the flow goes through the middle 20% of the pipe) and the plates are much smaller, so it is even more critical that the highest velocity flow be in the center of the pipe. You have laminar flow up to 5 MCF/d in a 2-inch and 16 MCF/d in a 6-inch.

In the *Transition Region* between laminar flow and turbulent flow, there is no correlation between dP and flow rate and the equations do not work. The transition region ends with Reynolds Numbers above 4,000. This corresponds to 7 MCF/d in a 2-inch and 21 MCF/d in a 6-inch.

<u>How do you prevent flow profile problems?</u>

You can design your inlet piping to minimize configurations that cause problems (e.g., two close-coupled 90° elbows out of plane, reducers located near the tube, a cross-flow jet near the tube, an upstream control valve, or an upstream check valve, etc.). You can install *flow conditioners* to significantly reduce the magnitude of the problem.

<u>How do you detect flow profile problems?</u>

The only way is to make *in situ testing* part of your meter-tube installation--if you don't verify your *measurement-system* accuracy, then you can't be sure that you have an acceptable flow profile.

Backwards Plate

Backwards plates can be used to calculate a flow rate very accurately IF THE RIGHT EQUATION IS USED. A beveled plate that is installed backwards will behave much like a venturi meter so if you use the standard *square-edged orifice meter* calculation then you will get the wrong answer by about 22% low.

<u>How do you prevent backwards plates?</u>

This is the easiest problem to avoid--figure out a memory trick and use it. One example is that on a Daniels Senior® fitting, the bevel on the plate always goes on the same side of the carrier as the gears (therefore, "the bevel goes with the gears" is my memory device).

<u>How do you recover from a backwards plate?</u>

Someone will always find the backwards plate eventually. This is the error that it is the easiest to fix and to get an accounting adjustment for. Contact the measurement group for the procedure to get an accounting adjustment.

b ***Ratio***

The preponderance of the data used in developing the correlation's to infer flow rate from dP were done with the ratio of the orifice diameter to the tube diameter in the middle of the range. The current API 14.3 manual allows this ratio to be 0.15-0.75, but describes how the uncertainty below 0.30 is controlled by the sharpness of the leading edge of the plate (a fairly sensitive item that goes bad very quickly) and above about 0.62 the uncertainty gets very large very fast. If you are able to stay in the 0.3-0.62 range, then you will have better measurement.

<u>What is the "best" β ratio?</u>

Permanent pressure drop across a plate can be directly related to horsepower that has to be spent somewhere else. With charts you want to size your plate to keep the pens in the outer 2/3 of the chart. With EFM you want to size your plate to keep dP as low as reasonable (consistent with pulsation errors) while staying below 0.62 β and keeping dP consistently about 20". Onshore Order 5 calls for 0.15 to 0.70. For meter-station design we would recommend 0.3-0.62.

Plumbing and valving to sensing elements

The rest of the primary element can be perfect, but a clogged line, a gas tap off of the sensing lines, or a leaking valve can ruin measurement effectiveness.

<u>How do you ensure that the plumbing is effective?</u>

1. Don't allow ANY of the tubing or manifolds to be used for fuel gas or control gas.
2. Keep tubing as short as possible.
3. Purge lines to sensors before connecting them.
4. Check for packing and connector leaks as soon as pressure is on system.

Incorrect station parameters used in calculations

The assumptions behind the calculations include a number of *station parameters*. These parameters must be right to have any chance of inferring a proper flow rate from a dP.

<u>How do you make sure that the parameters are correct?</u>

Good practice is to have two people independently verify all the parameters for every new installation. We recently found a tube I.D. was input as 6.027 instead of 6.072--this was a very large well and we under-measured the gas by 150 MCF/d for four years to the tune of almost $650,000 (gross, including tax credits).

Non-Rigid mounting

If a meter tube can move, then the gas will do work as it passes through the plate-- which violates one of the assumptions. Recently a test included using a test trailer to measure the output of a compressor. Since this was an equipment test and not a measurement test, little care was given to holding the tube rigid and it was allowed to swing several inches. When we began to fear that it would come apart, we anchored it and the measured volume went up 15%.

<u>How to ensure that the tube is rigid?</u>

- Make certain that supports are attached to something solid.
- Make sure that the supports can't move in unison.
- Make sure that holddown clamps are installed and tight.
- Finally, watch and listen to the tube when flow starts--if it visibly moves AT ALL, then the gas is doing work.

Blockage in the flow

After the tube has been inspected, it is prepared for shipping and shipped. There was a recent case where the inlet inspection tee was bolted on over the duct tape that was used to keep moisture out of the tube. This condition had an adverse affect on both the flow profile and the pressure drop.

How do you prevent blockages in the flow?

Attention to detail.

Backflow

There is always potential for line pressure to exceed static pressure (e.g., when a dump valve opens). When this happens liquids can flow into the tube and gas can backflow to the upstream side of the plate.

How do you prevent backflow?

Always install a check valve downstream of the meter tube.

What can go wrong?

Normal wear and tear in a piece of pipe carrying commercial quantities of gas will affect measurement accuracy over time.

Tube fouling/Surface roughness

The assumptions above want the surface roughness to be in the range of 100-250 μ inches and very uniform around the pipe circumference. Corrosion and solids-deposition change the roughness value and are generally asymmetrical. This results in friction pulling the profile out of symmetry.

How do you prevent fouling?

You can't prevent it, but installing and using blowdowns can minimize the corrosion impacts of liquid build-up.

How do you detect/repair it?

Any time a plate inspection indicates damming or buildup, visually inspect the tube. Periodically inspect the tube--a risk weighted way to calculate frequency would be:

mo-between inspections= $20{,}000/q_{mcsfd}$

(i.e. three times a year would pay off for a 5 MMCF/d station, while every 17 years or so would be often enough for a 100 MCF/d station with no other indication of a problem).

Liquids

Liquids build-up in a tube cause several additive problems: (1) the I.D. of the tube is reduced; (2) the liquid surface forces the flow profile to be off-center and/or asymmetrical; (3) downstream liquids distort the exit-profile; (4) liquids in sensor tubing can dampen sensor response; (5) liquids can freeze and burst tubing and/or fittings; and (6) the liquids that build up are often corrosive which can affect surface roughness long after they are gone.

How do you prevent liquids build-up?

Separators/dehydrators must be properly sized and properly maintained. Drain valves in fittings and piping should be installed and regularly blown down. Sensor tubing should be blown down whenever liquid is suspected (e.g., any time there is any liquid in a connection port when you are setting up to calibrate).

Seal leakage

The seal between the plate and the plate carrier is crucial to good measurement. ANY leakage around the seal will cause measurement to be low and the error will be disproportionate to the amount of gas goes through the leak (because the exit stream will be jetting into the low-pressure side of the plate which will substantially raise the downstream pressure).

<u>How do you detect seal leakage?</u>

The only way to detect it is with an *in situ* test. Every time a plate is pulled out of the seal-ring, conditions change enough that a seal that held can stop holding.

<u>How do you prevent/minimize seal leakage?</u>

Inspect the seal ring for cuts, abrasions, flatness, or swelling before reusing it. The manufacturer feels that the seal rings will last until mechanically damaged (i.e., they will not deteriorate with time in most fluids).

Damaged/Dirty plate

Plates can get nicked, bowed, scratched, dulled, and pitted. Any of these conditions will cause measurement to be low. A nick in a plate will cause a localized jet that reduces dP, a dulled leading edge prevents the flow from “tripping” (which gives a slight venturi effect), a bowed plate creates a venturi, etc.

<u>How do you detect a damaged plate?</u>

Periodic plate inspection, periodic *in situ* testing.

<u>How do you prevent a damaged plate?</u>

You can’t.

Fouled or plugged sensing ports/lines

See *Plumbing and valving to sensing elements* above.

Flexure of tube

It is very common for the supports near the fitting to be rigid while settling in the inlet and/or outlet piping lowers the end(s) of the tube. This action will create a “rainbow effect” that will shift the centerline of the flow away from the centerline of the pipe. An extreme case of the rainbow is the use of 45° elbows to come into the meter tube--even with straightening vanes this will cause the flow profile to be very asymmetrical.

<u>How do you detect tube flexure?</u>

Very small amounts of flexure can cause problems, so it should be a normal practice to check the tube for level at the farthest extent of the tube on both ends every time the sensing elements are calibrated.

Shift of plate centering

The latest version of API 14.3 part 2 significantly tightened the requirements for positioning the center of the plate bore coincident with the meter-tube centerline. While the standard refers to this as “eccentricity” it is really “concentricity” (or coincident centers). For a 2-inch tube (at a 0.5 β-ratio), the maximum shift of centerline is 0.021 inches. For a 6-inch tube (still at a 0.5), the maximum shift is 0.062. A swelled seal ring in a Senior® fitting, a thick gasket in a Simplex®, or debris in any fitting can shift the concentrictiy out of tolerance.

<u>How do you prevent center shift?</u>

- Make sure that the carrier on a Senior® fitting is all the way down. On an old style fitting, the plate could move up to 0.125 inches on a 6-inch which is twice the tollerance. The new style (Daniels calls them “14.3 fittings”) has a pin to help with the concentricity and the travel is 0.015-0.025 so the difference between “right” and “wrong” is much less.
- Use the right gaskets in a Simplex® fitting.
- Inspect the bottom of any fitting for debris while the carrier is out.

Summary

Accuracy of measurement is a financial necessity. Your company's profits can be directly reduced by inaccurate measurement. Installation, calibration, and inspection of measurement equipment in the field must be done with high quality workmanship and attention to small details.

Installation best practices

For every meter tube installation we should:

- Size the measurement equipment to provide effective measurement.
- Design the inlet piping to the station to avoid creating difficult flow profiles.
- Purge sensor tubing to make certain that ports are open and free-flowing.
- Verify that the tube is rigid and can't move under dynamic flow forces.
- Check and double check station parameters are reported properly to the recording element.
- Run an *in situ* test to verify that the measurement system works together.
- Install liquid blowdown valves.
- Install downstream check valves.

Operations best practices

To ensure that the station continues to be effective, we should:

- Blow any liquids out of the tubes frequently.
- Inspect the plates at least each calibration.
- Inspect the seal ring every time you remove a plate and change it at the first sign of wear, abrasion, swelling, blistering, or cuts.
- Inspect the tubes when the plate-inspection indicates a problem.
- Verify that there is no flexure in the tube each calibration.

Way more than anyone wanted to know about the arithmetic of fluid dynamics

The *Navier-Stokes equation* is a second order, non-linear, partial differential equation with seven unknowns:

$$r\left[\frac{\P u_i}{\P t} + u_j\frac{\P u_i}{\P x_j}\right] = -\frac{\P P}{\P x_i} + m\left[\frac{\P u_i}{\P x_j} - \frac{2}{3}d_{ij}\left(\frac{\P u_k}{\P x_k}\right)\right] + r g_i$$

No one has ever been able to develop a generalized solution to that equation. If you assume that the viscosity (m) is zero and density is constant, then the second order term falls out and you have *Euler's Equation* (pronounced *Oiler's Equation*):

$$r\left[\frac{\P u_i}{\P t} + u_j\frac{\P u_i}{\P x_j}\right] = -\frac{\P P}{\P x_i} + r g_i$$

If the flow is steady with respect to time and there is no cross flow, then *Euler's Equation* can have a generalized solution (called *Bernoulli's Equation*):

$$\frac{\vec{v}_1^2}{2} + \frac{P_1}{r} + gZ_1 = \frac{\vec{v}_2^2}{2} + \frac{P_2}{r} + gZ_2$$

or

$$\frac{1}{2}\left(\vec{v}_1^2 - \vec{v}_2^2\right) = \frac{1}{r}\left(P_2 - P_1\right) + g\left(Z_2 - Z_1\right)$$

or

$$\frac{\Delta\vec{v}^2}{2} = \frac{\Delta P}{r} + g\Delta Z$$

Through some manipulations and many assumptions, this can be "rewritten" as:

$$q = k\frac{C_d E_v Y d^2\sqrt{r\Delta P}}{r} = C'\sqrt{\frac{P\Delta P}{T}}$$

where the new terms were developed through empirical measurements assuming VERY specific conditions.

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