Natural Gas Flow Meters - Why Calibrate? (...and how to)

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Why flow calibrate your meter?

- You suspect a problem with your meter.
- Your sales contract or tariff requires that your meter be flow calibrated.
- The applicable industry standard for your meter requires flow meter calibration.
- Your meter is part of a custody transfer dispute.
- You are conducting a lost and unaccounted for gas volume investigation that includes your meter.
- You want the meter to be as accurate as possible.
- It’s cheap (sometimes VERY cheap) insurance.
What can bias errors in an ultrasonic flow meter cost?

- AGA Report No. 9 maximum error = ±0.7% (for dia. ≥ 12”)
- Assume transmission grade gas at 850 psi flows through an ultrasonic meter at 50 ft/sec.
- Value of a 0.25% bias error corrected via flow calibration (for $4/mscf gas):

<table>
<thead>
<tr>
<th>Diameter (inches)</th>
<th>Annual Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>$320,000</td>
</tr>
<tr>
<td>12</td>
<td>$716,000</td>
</tr>
<tr>
<td>16</td>
<td>$1,273,000</td>
</tr>
<tr>
<td>20</td>
<td>$1,989,000</td>
</tr>
<tr>
<td>24</td>
<td>$2,864,000</td>
</tr>
</tbody>
</table>

Calibration cost for a 12-inch meter recouped in less than a week’s time!
Let’s begin with some terminology…

- **Accuracy (a.k.a., error)** - A qualitative concept of the closeness in agreement of a measured value and an accepted “reference” or “true” value.

- **Repeatability (a.k.a., precision)** - The variation in measurements taken by a single person or instrument on the same item (e.g., flow meter) and under the same conditions over a short period of time.

- **Reproducibility** - The variation in measurements that occurs when any of the repeatability conditions have changed (e.g., person, instrument, time, etc.).
Measurement **Uncertainty**
(a.k.a., the upper limit of the measurement error)

Magnitude of Sampled Variable, X (e.g., flow rate)

“True” Value
(Never known!)

Average Measurement

Precise, **Unbiased**

Imprecise, **Unbiased**

Precise, **Biased**

Imprecise, **Biased**

("Normal" or "Gaussian" Distribution)
What can cause metering errors?
Adverse Operational Effects
More Operational Effects...
# Reported Orifice Meter Measurement Error Sources

<table>
<thead>
<tr>
<th>Operational Characteristic</th>
<th>Approximate Flow Rate Error (% of reading)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orifice plate surface roughness</td>
<td>Up to -0.7%</td>
</tr>
<tr>
<td>Notches/grooves on orifice edge</td>
<td>-0.6% to +1.0%</td>
</tr>
<tr>
<td>Plate thickness and bevel angle</td>
<td>-3.7% to +0.4%</td>
</tr>
<tr>
<td>Plate installed backwards</td>
<td>Up to -20%</td>
</tr>
<tr>
<td>Liquid film on plate</td>
<td>Up to ±1.5%</td>
</tr>
<tr>
<td>Liquid film on meter tube</td>
<td>Up to +1%</td>
</tr>
<tr>
<td>Grease on surface of plate</td>
<td>Up to -13%</td>
</tr>
</tbody>
</table>
| Bent/warped plate | Over-measurement <+0.5%, if deflection angle < 1°  
Under-measurement beyond -1.5% for larger deflection |
| Orifice eccentricity | Within ±0.1%, if maintained at allowable limits |
| Swirl effects | Up to +5.2%, depending on swirl type |
| Location of downstream thermowells | < ±0.28% for TWs as close as 1.63 pipe diameters |
| High differential pressures (ΔP > 100 in. H₂O) | < ±0.1%, if allowable limits are followed |
| Low differential pressures (ΔP < 10 in. H₂O) | Can exceed ±4%, if ΔP < 20” H₂O column |
| Pulsation effects (SRE always over-registers) | Can exceed ±0.5%, if ΔPᵣ(avg) > 0.25 psi |
| Acoustic noise | Can exceed ±0.23%, if pulsations > 155 dBA |
The upstream piping geometry can “distort” the flow in the pipe…

- Changes in direction or pipe bends
  - Elbows
  - Ys, tees, headers, etc.
- Blockages/obstructions
  - Valves
  - Pressure regulators
  - Filters/separators
  - Orifice plates
  - Flow conditioners
Meter Sensitivity to Flow Field Distortion

- Flow meters sensitive to flow field distortions...
  - Orifice
  - Ultrasonic
  - Straight tube (radial mode) Coriolis
  - Pitot-probe type
  - Turbine (sometimes)

- Flow meters **not** sensitive to flow field distortions...
  - Positive displacement (e.g., rotary & diaphragm)
  - Bent tube Coriolis
  - Turbine (sometimes)
Flow Meter Calibration Options

- **Field (in-situ) proving**
  - American Gas Association Report No. 6
    “Field Proving of Gas Meters Using Transfer Methods,” March 2013
    - Proving meters using critical flow devices
    - Proving field meters with “master” meters

- **Flow lab calibration**
  - “Open” system, i.e., side branch on a pipeline
  - Closed-loop (recirculating) system
Field Meter Proving...
In-situ Sonic Nozzle Meter Proving Field Test
(Example data provided by Dr. Frank Ting - Chevron)

- Objective: Optimize orifice meter beta ratios & operating conditions
- Orifice meter sizes: 2, 4, 6, 8, & 16 inch dia.
- Flow range: Up to 200 MMSCFD
- Pressure: Up to 1,000 psig
- Flow reference: Flow calibrated sonic nozzles (±0.25% of reading uncertainty)

Sonic Nozzle
8" Pipe, Custom Flange
In-situ Sonic Nozzle Proving - Example Flow Performance

~83% of the flow is under-registered by at least 1.25%!
Field Meter Station with an Ultrasonic Flow Meter Plumbed in Series for Performing In-situ Meter Calibration Checks
The Basis of All Flow Meter Calibrations

Conservation of **MASS** (simplified)

\[ Q_m = (\rho A V)_1 = (\rho A V)_2 \]

Flow Direction

**Steady Flow**
(The desired test condition!)

**Unsteady Flow**
(An undesirable test condition)

Control Boundary

**Meter No. 1**
(Field meter being checked @ \(P_1, T_1, \rho_1, A_1, \& V_1\))

**Meter No. 2**
(Prover @ \(P_2, T_2, \rho_2, A_2, \& V_2\))
Flow Meter Calibration Facilities

- Two basic types of calibration facilities…
  - Open design – uses existing pipeline flow (side branch).
  - Closed-loop – purpose-built flow meter calibration facility.

- Secondary measurement (lab “working” standard):
  - Turbine meter(s)
  - Sonic nozzle(s) (a.k.a., critical flow Venturi)
  - Rotary meter(s)

- Primary measurement
  - Sliding piston/swept volume
  - Pressure, (fixed) volume, temperature, time (PVTt) system
  - Weigh tank

- Inter-lab comparison testing provides information on equivalence of different lab facilities.
Primary Gas Calibration System
Total Measurement Uncertainty

- Primary systems are those that determine flow rate from fundamental measurements of mass, length, & time.
- Lowest measurement uncertainty - typically in the range of ±0.02 to ±0.05% of reading.
Secondary ("Working") Gas Calibration System Total Measurement Uncertainty

- Secondary systems are those calibrated using a primary system.
- Typically include empirical calibration coefficients.
- Measurement uncertainty is typically in the range of ±0.05 to ±0.15% of reading.

MRF Critical Flow Venturis (i.e., sonic nozzles)
Meter Calibration Considerations

- Meter only vs. meter with upstream/downstream piping included.
- Digital vs. analog flow meter/lab interface.
- “As-found” testing allows assessment of potential measurement biases from meter/adjacent piping/flow conditioner fouling for meters removed from service.
- Scheduling: Lab backlog times vary (1-3 months is typical), so plan ahead as much as possible.
- Flow meter owner/operator/manufacturer test witnessing varies.
Flow Meter Installation

- Flow meter is shipped pre-assembled or is assembled at the flow calibration facility.
  - On-site assembly of piping components typically proceeds from upstream to downstream to allow internal inspection of flange alignment.
- Meter power, data communication, and secondary instrumentation installation.
  - Lab instrumentation is typically used for pressure and temperature measurements.
  - Initial meter checkout typically is done prior to the flow calibration.
- Example piping configurations follow.
Example Single Flow Meter Installation
Ultrasonic Meters Flow Calibrated in a Skid
Meter Calibration Details
(Example: Ultrasonic flow meter)

- Establish stable flow/pressure and ensure thermal stability.
- Test over a range of flow rates: For ultrasonic flow meters, AGA-9 recommends 100, 75, 50, 25, 10, 5, 2.5% of full scale, but other points can be used, depending on the application.
- At the MRF, we acquire multiple samples at each flow rate (3 to 6 measurement points, each of 90 to 300 seconds in duration).
- Record path-by-path and other diagnostic information and examine for consistency (run log files).
- Compare speed of sound measurement to those values produced using AGA-10.
AGA-9 recommends 15 items that should be included in the meter calibration report. Examples include:

- Flow lab calibration procedure
- Meter manufacturer, model, & serial number
- Description of mechanical installation
- Raw data, adjustment factor(s), and test method used (should include measurement uncertainty estimate)
- Final meter configuration, including firmware revision number
Some things to consider, depending on your type of flow meter...
Ultrasonic Flow Meters

(Image courtesy of Sick, Inc.)
Ultrasonic Meter ‘A’ with Flow Conditioning
(97 diameters of straight pipe upstream)

![Graph showing percent error vs. velocity for different flow conditioning methods including Bare Tube, 19-tube Bundle, VORTAB™, CPA 50E, and GFC™. The graph includes data points for various velocities ranging from 0 to 35 ft/sec.]
Ultrasonic Meter Adjustments

- AGA-9 references three common methods of correcting the meter output:
  - Flow Weighted Mean Error (FWME) correction
  - Polynomial error correction
  - Multi-point (point-by-point) linearization

- Depending on the characteristics of the meter error curve, one of the above methods may be preferred over the others.
This method applies a single meter calibration factor to all of the calibration points. The method does allow for greater importance to be placed on a particular flow rate to ensure that the error at that flow rate is minimized. The calculation method is explained in detail in AGA Report No. 9.
Polynomial Correction

\[ Y = -2.00258 \times 10^{-4}x^2 + 3.26980 \times 10^{-2}x - 1.49299 \]
Point-by-Point Linearization

[Graph showing velocity (ft/sec) on the x-axis and percent error on the y-axis. The graph includes points marked with triangles, circles, and squares, each representing different data sets or conditions. Arrows indicate changes or comparisons between these data points.]
Orifice Flow Meters
(Built to specifications of American Gas Association Report No. 3)
Orifice Flow Meter Calibration

8-inch diameter
$\beta = 0.600$

Reynolds Number
$= \frac{\rho \times V \times D}{\mu} = \frac{\text{Inertial Forces}}{\text{Viscous Forces}}$

$q_m = N_1 C_d E_v Y d^2 \sqrt{\rho_{t,p}} \Delta P$

Reader-Harris
Gallagher
$C_d$ Equation

~0.15% difference
Turbine Flow Meters

Good integral flow conditioning (i.e., conical nose, straightening vanes, contracting inlet cross section, and tapered exit).

Poorer integral flow conditioning (i.e., fewer straightening vanes, no contracting inlet section, and more open cross section).

- Rounded nose cone with many straightening vanes
- Narrow flow annulus
- Tapered tail

- A rounded nose cone, but few straightening vanes
- Wide flow annulus
- No tapered tail
Turbine Flow Meter Calibration

8-inch diameter meter
Error relative to single K-factor
Test conditions: 750 psia, 70°F

Percent Error

Volumetric Flow Rate (acfm)
Example Calibration Factor vs. Flow Rate
(4-inch diameter meter)

- Atmospheric air
- 150 psia natural gas
- 400 psia natural gas
- 700 psia natural gas

1.9 %
Turbine meters should be characterized as a function of Reynolds number (per AGA-7).

Calibration at operating pressure can further reduce the measurement uncertainty.

Characterizing a turbine meter by a single K-factor can lead to error.

Multi-point linearization can be built into the flow computer to minimize the error.
Coriolis Flow Meters
(Bent tube and straight tube designs)
Coriolis Flow Meter Calibration

- Without meter zeroed
- With meter zeroed

- Mass Flow Rate (lb/s) vs. Percent Error

- Data points for different mass flow rates with and without meter zeroing.
Zeroing the meter provides the reference condition upon which Coriolis meters are highly dependent.

Gas calibrations at elevated pressure should consider the pressure sensitivity of the meter.
Conclusions

- Informed users can make good choices for calibration requirements. For instance, decide how accurate your meter needs to be!
- Calibration facilities can offer advice to help with your decisions and planning.
- Properly calibrated flow meters provide an accurate means of measurement that will reduce system measurement biases - and associated operating costs.
- An initial meter calibration prior to field installation provides both verification of meter performance and removal of any measurement bias error - and provides baseline (reference) diagnostic information for monitoring of meter health in the future.
Thank you. Any questions?
Example FWME Calculation & Correction

\[ FWE = \frac{\text{Flow Rate}}{100 \text{ ft/s}} \cdot \text{Error} \]

<table>
<thead>
<tr>
<th>Point</th>
<th>Velocity (ft/s)</th>
<th>Error (%)</th>
<th>Full Scale Fraction</th>
<th>Flow Weighted Error</th>
<th>FWME Corrected Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>94.558</td>
<td>-0.169</td>
<td>0.946</td>
<td>-0.160</td>
<td>0.212</td>
</tr>
<tr>
<td>2</td>
<td>70.983</td>
<td>-0.190</td>
<td>0.710</td>
<td>-0.135</td>
<td>0.191</td>
</tr>
<tr>
<td>3</td>
<td>52.117</td>
<td>-0.414</td>
<td>0.521</td>
<td>-0.216</td>
<td>-0.034</td>
</tr>
<tr>
<td>4</td>
<td>37.820</td>
<td>-0.570</td>
<td>0.378</td>
<td>-0.216</td>
<td>-0.191</td>
</tr>
<tr>
<td>5</td>
<td>23.628</td>
<td>-0.648</td>
<td>0.236</td>
<td>-0.153</td>
<td>-0.269</td>
</tr>
<tr>
<td>6</td>
<td>14.217</td>
<td>-1.023</td>
<td>0.142</td>
<td>-0.145</td>
<td>-0.646</td>
</tr>
<tr>
<td>7</td>
<td>9.443</td>
<td>-1.338</td>
<td>0.094</td>
<td>-0.126</td>
<td>-0.961</td>
</tr>
<tr>
<td></td>
<td>Sum =</td>
<td></td>
<td>3.028</td>
<td>-1.151</td>
<td></td>
</tr>
</tbody>
</table>

\[
\text{FWME Corrected Error} = \sum \left( \frac{\text{FWME}}{\text{Full Scale Flow Rate} + 100} \right) \cdot \left( \frac{-1.151}{3.028} + 1 \right) = -0.380\% 
\]
Example Flow Distortion (Swirl) Caused by Two 90° Elbows, 90° Out of Plane

"Type 2" Swirl (Counter-rotating vortices)

Swirl can persist for 200 to 300 nominal pipe diameters!
Wake Downstream of a Cylindrical Body
(e.g., thermowell or gas sample probe)
Side Branches or Splits in the Flow Stream

First-order or Fundamental Mode

Second-order Mode
Flow Separation Downstream of an Obstruction
(e.g., partially closed valve, protruding gasket, orifice...)

Flow Direction

Separation Zone

Flow Obstruction

Recirculation Zone

Flow Obstruction
Partially Closed Valves
(Ball valve example)
Example Flow Distortion (Swirl) Caused by Two 90° Elbows, 90° Out of Plane
(Numerical simulation courtesy of E-on Ruhrgas)
Is a flow “conditioner” necessary?

Example Flow Conditioners
(They do not all perform the same!)
Flow “conditioners” also disturb the flow!

Figure 1: Smoke visualization of uniform laminar stream owing through a perforated plate, showing laminar, transitional, and turbulent flow, photograph by Thomas Corke and Hassan Nagib.
Installation Guidelines Are Included in the Applicable Standards

Orifice Meters

Ultrasonic Meters

Turbine Meters

Coriolis Meters
Installation with Inlet Elbows and Cleanout Tees
Integral Elbow-Tee-Cleanout Combination
Z-pattern - Two Meters in Series in a Header