MEASUREMENT BEST PRACTICES
FOR BETTER POWERPLANT/POWERHOUSE
SAFETY, AVAILABILITY & EFFICIENCY

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ABSTRACT
Accurate, repeatable and reliable measurements are vital to safe and efficient powerplant operation. Modern measurement technologies typically boast excellent accuracy and repeatability under “reference” or “laboratory” conditions. Unfortunately, measurements are rarely made under laboratory conditions – as a result, performance is always worse in the “real world”. Using DP-flowmeter examples, this paper presents the key reasons for this deviation between laboratory and real world performance. It also presents tools that allow the user to quantify expected deviations prior to installation – in real applications, with real products. Finally, the tools allow the user to calculate the impact of different maintenance and installation practices on measurement accuracy and repeatability, and ultimately to determine the “best practice” for any given application.

How Can Better Measurement Improve Power Plant Safety, Availability & Efficiency?

In many control or interlocking applications, the user needs to balance competing safety and efficiency motivations. For example, for fuel-air cross-limiting control, the user needs to maintain the ratio between fuel and air flowrates. Excessive fuel can cause “smoking” – an environmental hazard - and unburned fuel in the stack can cause a safety hazard. Excessive air, while safe and non-polluting, is expensive – instead of being used to make steam, combustion energy is used to heat air.

With an “ideal” measurement and control system, the user would maintain fuel and air at the exact stoichiometric ratio. In practice, there is no such “ideal” system. Since the environmental and safety consequences of excess fuel greatly outweigh the purely economic consequences of excess air, most users operate with an excess air “safety buffer”. Although many factors contribute to make a system non-ideal, it should be apparent that a system with a 5% flow measurement uncertainty will require a minimum 5% safety buffer.

A reduction in flow measurement uncertainty does not directly reduce operating costs. Instead, it improves consistency, and provides the user with the opportunity – at no increased environmental or safety risk – to reduce excess air and hence fuel costs. Therefore, one dollar of reduced gas flow uncertainty yields one dollar of opportunity to reduce fuel usage.
Why is Accuracy and Repeatability Worse in the Real-World than in the Laboratory?

Even with a well-installed and well-maintained transmitter, real-world accuracy can be significantly worse than laboratory accuracy, for any measurement technology. The reason for this is that real-world transmitters are not installed and operated under “laboratory conditions”. Using the example of a differential-pressure flowmeter, “real-world” effects may include:

- Ambient temperature variation
- High static line pressures
- Device drift

**Ambient Temperature Variation:** In the vast majority of “real-world” flow measurements, the transmitter can operate at a very different ambient temperature than the temperature at which it was calibrated. In some outdoor applications, ambient temperatures can vary more than 50 degF from calibration temperature. These variations can have a significant effect, which is easily simulated on the bench – blow warm air over a transmitter, and watch its output change.

**High Static Line Pressures:** The differential pressure transmitter used to infer flow can be significantly affected by a high line pressure. To simulate this effect on the bench, the user should apply a small differential pressure across a transmitter. Then, add several hundred pounds of additional static pressure to both sides of the transmitter. In theory, the measured differential pressure should not change. In reality, it does.

**Drift/Stability:** The output of any analog component will vary over time. As with the ambient temperature effect described above, this can affect all flow technologies. Better, smart transmitters are more stable than older, analog transmitters or transducers. Within regulatory or contractual restrictions, a more stable transmitter will allow the user to obtain equivalent accuracy and repeatability when calibrated less frequently. An inferior device will need to be calibrated more frequently to maintain acceptable performance.

How Can the User Quantify the Impact of “Real-World” Sources of Error?

Reputable suppliers publish specifications which allow the user to calculate and predict the impact of these and other “real-world” effects on installed flow accuracy and repeatability. For the purposes of this paper, a spreadsheet was designed (Appendix 1) which uses published specifications to calculate flow error caused by a DP transmitter in an orifice meter installation. The results at 100% flow, under “typical” installed conditions, are shown in Figure 2.
Note that:

- Reference (laboratory) accuracy is a trivial component of total transmitter installed error.
- Two DP transmitters with identical 0.075% “reference accuracies” can provide dramatically different installed accuracies.
- If a supplier does not publish specifications for “real-world” effects, this does not mean that their products are immune to these effects – usually, the reverse is true.
- Although the example of an orifice meter is used below for illustration, installed accuracy is worse than laboratory accuracy for all flow technologies, including but not limited to ultrasonic, vortex, PD, turbine, thermal and Coriolis.

**Figure 2 - Flow Error from DP Transmitter**

![Chart showing flow error from DP transmitter](image)

Figures 3 & 4 show the impact of this error at lower flowrates. Note that:

- these errors apply to accuracy and repeatability, and are usually **fixed** over the DP range
- DP $\alpha$ flow$^2$ – since DP declines twice as fast as flow, small errors at 100% - and small differences in transmitter accuracy - are **magnified** at lower flowrates

**Figure 3 – Flow Error from DP Transmitter**

<table>
<thead>
<tr>
<th>Flowrate (scfm)</th>
<th>DP</th>
<th>“Better”.075%</th>
<th>“Worse”.075%</th>
<th>Analog</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>100</td>
<td>0.09%</td>
<td>0.21%</td>
<td>0.65%</td>
</tr>
<tr>
<td>750</td>
<td>50</td>
<td>0.16%</td>
<td>0.38%</td>
<td>1.16%</td>
</tr>
<tr>
<td>500</td>
<td>25</td>
<td>0.37%</td>
<td>0.85%</td>
<td>2.60%</td>
</tr>
<tr>
<td>250</td>
<td>6.25</td>
<td>1.48%</td>
<td>3.40%</td>
<td>10.40%</td>
</tr>
</tbody>
</table>

**Seemingly trivial** improvements in transmitter accuracy yield significantly better flow accuracy and repeatability at normal flows – the effect is dramatic at lower flows.
Although a comparison of technologies is beyond the scope of this paper, the user should note that this deviation between “reference” and “installed” accuracy can be observed for all measurement technologies – flow, pressure, level, temperature, etc. “Reference accuracy” for any of these technologies may be stated in the form of a “nominal” specification – “1% over 20:1 turndown” – or may be the output of the supplier’s sizing program. As with a DP flowmeter, convert reference to installed accuracy by adding “real-world” effects, which may include the effects listed above and/or additional effects such as “D/A error”, “zero stability”, etc.

Special Considerations for Gas and Steam Flow Applications

The main source of flow error in most gas or steam application is error due to changes in fluid density, caused by fluid pressure and/or temperature variation. This assumes, of course, that the application requires mass flow. The need for mass – rather than volumetric - flow can be inferred when a flowrate is expressed in mass (lb/hr) or “standard volumetric” units, such as standard cubic feet per minute (scfm). In very rare cases, the user is actually concerned with volumetric flowrate, represented in volumetric units such as actual cubic feet per minute (acfm). In these cases, a velocity-based technology such as Vortex is often the best solution.

Figure 5 is a schematic of a system in which minimal pressure or temperature variation is expected – steam flow out of a new, pilot-operated regulator followed by two elbows and a short length of clean, straight pipe.

**Fig. 5 - Piping Schematic**
Figure 6 plots pressure variation against flowrate, and is obtained by using the P&T.xls spreadsheet (see Appendix II). Major sources of pressure variation:

- “typical” regulator droop – increases with increasing flow (1% assumed - note that an older direct-acting regulator will typically suffer from 5-10% droop)
- barometric variation – typical week-to-week variation of 0.3 psi – independent of flowrate

Zero temperature variation was assumed for this saturated steam application. However, temperature variation can be as significant as pressure variation for superheated steam or gases:

- variation in “source” temperature (for example, ambient air)
- heat conduction from un-insulated pipes

Total pressure variation is not repeatable, and varies with flowrate. Also, applications with longer, rougher pipe or more fittings - particularly strainers or check valves - can suffer from much larger pressure variations. Online pressure and temperature compensation using the steam tables (or compressibility calculations for gases) can virtually eliminate these errors, and even for this minimal piping arrangement will yield a reduction in flow measurement error of >2%.

Although the focus of this paper thus far has been the DP flowmeter, note that linear and volumetric flow technologies such as Vortex, Ultrasonic and Turbine are twice as sensitive to pressure and temperature variation. This means that pressure and temperature compensation is doubly important for these other flow technologies.

What are the “Best Practices?”

For any process measurement, the first step is to determine required measurement performance for each application. “Performance” in a flow context includes accuracy and repeatability over the required flow range. It is important to understand that accuracy and repeatability requirements will usually be different at different flowrates. For example, in some applications high accuracy may be important at higher flowrates, because that is where the process is operating the vast majority of the time. In other
applications, performance is more important at lower flowrates, because that is where safety constraints operate. This determination of required measurement performance should be made by individuals who understand the economic, environmental and safety impact of measurement uncertainty.

The second step is to quantify the operating conditions which are not controllable. For a flow measurement, these can include:

- expected ambient temperature variation
- maximum static line pressure
- static line pressure and temperature variation (for gas or steam)
- line temperature variation (for liquids)
- maximum allowable permanent pressure loss
- flow turndown

The third and final step is to select hardware and installation and maintenance procedures which will ensure that the measurement provides the required installed performance under the expected (uncontrollable) operating conditions. For example, the user can:

- select a transmitter which has better or worse performance under a given set of “real-world” operating conditions
- use or not use pressure and temperature compensation in a gas or steam application
- calibrate the transmitter frequently or infrequently
- in the case of a DP flowmeter, size the primary element for a higher or lower differential pressure (higher DP’s provide higher accuracy, at the expense of higher pressure loss)

While the first and second steps involve gathering data, the third step requires calculations, which may be facilitated by the spreadsheets shown in the Appendix.

Conclusion

Many measurement technologies provide excellent accuracy and repeatability under laboratory conditions. Unfortunately, these same technologies will typically provide significantly worse performance under “real-world” conditions, which in the case of the DP-flowmeter may include:

- changing ambient temperature
- high static line pressures
- drift between calibrations

and, for gas and steam applications: density error due to fluid pressure and temperature variation

Using published specifications and expected conditions, it is possible to calculate prior to installation the impact of these real-world effects on installed measurement repeatability. This will allow the user to both predict installed repeatability for any given application and flow technology, but also to select transmitters and maintenance procedures which will meet the needs of each specific application.
Appendix 1: TPFE.XLS

The Total Probable Flow Error (TPFE) spreadsheet calculates flow error due to the DP transmitter, using:
- user-entered application conditions
- manufacturers’ published specifications
and clearly shows all calculations.

The TPFE.xls spreadsheet runs in Microsoft Excel, and is available at www.Rosemount.com.

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### Total Probable Flow Error Due to DP Transmitter

**Fluid / Service:** Natural Gas to Boiler #1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter Calibrated Span</td>
<td>0 - 100 in H2O</td>
</tr>
<tr>
<td>Ambient Temp. Variation</td>
<td>25 deg F</td>
</tr>
<tr>
<td>Static Line Pressure</td>
<td>300 psig</td>
</tr>
<tr>
<td>Calibration Frequency</td>
<td>18 months</td>
</tr>
<tr>
<td>Maximum Flow</td>
<td>1000 scf/min</td>
</tr>
<tr>
<td>Normal Flow</td>
<td>500 scf/min</td>
</tr>
<tr>
<td>Value of Fluid</td>
<td>.002 $ / scf</td>
</tr>
</tbody>
</table>

**Fluid / Service:** Natural Gas to Boiler #1

**Transmitter Calibrated Span:** 0 - 100 in H2O
**Ambient Temp. Variation:** 25 deg F
**Static Line Pressure:** 300 psig
**Calibration Frequency:** 18 months

**Maximum Flow:** 1000 scf/min
**Normal Flow:** 500 scf/min
**Value of Fluid:** .002 $ / scf

**DP Transmitter flow error at normal flow (500 scf/min):**

<table>
<thead>
<tr>
<th>DP Transmitter</th>
<th>Flow Error</th>
<th>Annual Value of Flow Error</th>
<th>&quot;Best&quot; Improvement*</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Better&quot; .075% Transmitter</td>
<td>0.37%</td>
<td>$ 1920</td>
<td>-</td>
</tr>
<tr>
<td>&quot;Worse&quot; .075% Transmitter</td>
<td>0.85%</td>
<td>$ 4457</td>
<td>$ 2537</td>
</tr>
<tr>
<td>Analog (.2%)</td>
<td>2.60%</td>
<td>$ 13682</td>
<td>$ 11762</td>
</tr>
</tbody>
</table>

*Annual Reduced flow uncertainty (accuracy/repeatability)

**Flow Error at normal flow (500 scf/min):**

**"Better" .075% Transmitter:** -
**"Worse" .075% Transmitter:** $ 2537
**Analog (.2%)** $ 11762
APPENDIX II: P&T.XLS

The Pressure & Temperature (P&T) spreadsheet calculates:
- pressure variation given user-entered flow conditions and piping schematic (including fittings) using Crane (1991)
- flow error for DP and velocity/volumetric flowmeters due to this calculated pressure variation, plus any user-entered temperature variation


### Flow Rate Error Due to Pressure and Temperature (Density) Variation

**Process Data:**
- Static Pressure @ Flowing Conditions: 50 psi
- Temperature @ Flowing Conditions: 290°F
- Flowrate: 7500 lb/hr
- Fluid: Steam
- Density (lb/ft³): 0.145
- Pipe ID: 4 inches
- Velocity (ft/sec): 164.79

**Sources of Pressure Variation:**
- Barometric (+/-): 0.3 psi (typical weekly variation)
- Regulator / Header: 0.65 psi
- Friction:
  - Length of Pipe: 40 feet
  - Number of 90 Degree Elbows: 2
  - Number of Flow Thru "T"s: 0
  - Number of "T"s: 1
  - Number of Open Ball Valves: 0
  - Number of Open Gate Valves: 0
  - Number of Open Globe Valves: 0
  - Number of Swing Check Valves: 0
  - Number of Strainers: 0

**Total Possible Pressure Variation:** 2.63 psi

**Calculated Flow Error from P/T Variation and Annual Value of Mis-Measured Fluid**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Error</th>
<th>Fluid Value/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncompensated Velocity Meter*</td>
<td>4.06%</td>
<td>$16,006</td>
</tr>
<tr>
<td>Uncompensated DP Meter</td>
<td>2.03%</td>
<td>$8,003</td>
</tr>
</tbody>
</table>

**Annual Value of Flow Measurement Error From P&T Variation**

**Worst-Case Pressure Variation over Flow Range**