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Compressible Fluid Calibration of Coriolis Meters

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1 INTRODUCTION

This paper presents and discusses new research results that represent an update of data and analysis as part of an ongoing program. The objective of the program is to gain a better understanding of Coriolis meter operation in compressible fluid flow measurement. Two types of data are available from a commercial calibration laboratory. First, numerous calibrations provides limited data on a relatively large number of meters. As part of the analysis the massed calibration data are classified into groups depending on the calibration curve shape. The second data category arises from more extensive testing of a smaller number of meters that allow for the variation of both mass flowrate and pressure. The results indicate dependence on one or more variables in addition to mass flowrate. The relevant secondary parameter appears to be either pressure or velocity. Test design and some results are discussed in detail in [1] and [2], this paper presents new data.

Historically Coriolis meters were restricted to liquid measurement applications, in recent years they have been widely used to measure natural gas. Some operators obtain calibration data using compressed air as a surrogate fluid; others select a water based calibration. While both fluids provide traceability, an air calibration includes compressibility that is similar to natural gas. As calibration experience has developed, compressibility effects seem to be observed with some meters but not with others.

Traditional meters exhibit a variety of second order effects which must be accounted for to maintain low uncertainty. Differential pressure meters require a gas expansion factor correction. The low flow K-factor of a gas turbine meter depends on flowing density and most liquid meters are affected by viscosity. An uncorrected compressibility effect when measuring gas with a Coriolis meter represents a potential similar measurement uncertainty source.

2 DATA SCOPE

As noted the analysis is proceeding in two parts. The first database consists of 62 calibrations distribution by line size and flowing pressure as summarized in Table 1. The data are reasonably well distributed over the 1–4.5 MPa pressure range while being slightly skewed to the higher range. Most of the data came from three meter sizes, exceptions include three smaller (quarter inch) and one larger (three inch) meter. All the meters are calibrated using compressed air except the three inch which was calibrated in natural gas. The second database consists of three meters; the current paper presents recent diagnostic data from one of the meters.

3 INVESTIGATING CALIBRATION RESULTS

This paper represents the third publication of data and analysis of Coriolis meter calibrations. The first paper [1] divided calibrations into four categories and identified potential trending with tube velocity. The second paper [2] included additional calibrations and added several additional categories. A larger percentage of meters indicated consistent trending with tube velocity.

In the current paper more calibrations have been added. A more quantitative classification methodology has been adopted and the categories have been consolidated. The trend with velocity is apparent in a larger proportion of the calibrations.

For each calibration, data are collected of the deviation (Δ_1) between the meter reading and the laboratory value of mass flowrate. The high flowrate data (above 2% full scale) are fitted to a third order polynomial, a typical graph is shown in Figure 1. The low flowrate data are fitted to a second order polynomial. The polynomials represent the average calibration values as they vary with mass flowrate. The curve shapes associated with the individual meter calibrations were observed to exhibit some consistent shapes.

The previous analyses classified the calibration curves based on visual judgement. The current analysis represents an attempt to quantify the classification. The process begins with a linear fit of meter deviation (Δ_2) against mass flowrate; the coefficients from the previous analysis are used. For each calibration, an average difference (Δ_3) and standard deviation (s) are calculated based on comparing the calibration data to fitted Δ_2 values. A figure of merit is defined as:

$$\mathrm{FOM} = |\Delta_3| + 2s \qquad (1)$$

where ±FOM represents the 95% confidence interval of how closely a calibration matches the Δ_2 values. The calibrations are ranked based on FOM and divided into four groups identified numerically as Groups 1-4. The first three contain 15 calibrations, with 17 in the last group. The current analysis redefines the grouping of data; numerical group identification is intended to avoid confusion with the previous alphabetical group identification.

The calibration curve fits are shown in Figures 2–5. The ordinate in each represents Δ_1, the abscissa represents tube velocity. The distributions of meter diameter and calibration pressure values are given in Tables 2 and 3. Qualitatively, Groups 1 and 2 both fit the clear trend, Group 1 better than Group 2. Quantitatively the 95% confidence intervals widths are ±0.121% and ±0.175%. The confidence interval contains 95% of the data, the interval width is an indicator of how well data fit a curve.

The 95% confidence interval width for Group 3 is ±0.260%, the data don’t fit as well as the first two groups. While most of the data fit the general curve shapes of Groups 1 and 2, two calibrations are observed to follow different trends. The first, indicated in green, is well centered about $\Delta_1=0$. The second curve, in red, is concave down while most of the rest are concave up. It is noted that a few of the Group 1 and 2 curves are also concave down.

The 95% confidence interval width for Group 4 is ±0.559% indicating a rather poor fit. Group 4 contains ten calibrations that are well centered about zero which indicate no velocity effects. These have been classified visually and identified in green; the distribution of diameters is given in the final column of Table 2. Qualitatively, the mean value is -0.110% and the 95% confidence interval width is ±0.230%. The curves in green do not indicate the presence of a velocity effects, in fact they represent meters that work quite well.

Referring to Table 2 it seems as if the diameters become distributed towards larger values when moving from Group 1 to Group 4. That trend plus the observations regarding the green Group 4 data tend to indicate that the velocity effect becomes weaker as the meter size increases.

Prior work included extensive analysis of a one inch meter that was calibrated over a broad range of pressures. For the present discussion it will be identified as COR01. The data correlated well with volume flowrate and therefore would be expected to also correlate well with velocity. The results are shown in Figure 6. The yellow symbols represent most of the pressure values, these data collapse quite well into a single line. Interestingly, the lowest pressure data, in blue, don’t fit the same trend.

The solid lines represent a 95% confidence interval with width of ±0.175% about the curve fit of Groups 1 and 2. On average the solid lines agree with the COR01 data reasonably well. The slopes do not match as well; the COR01 data indicate a larger magnitude velocity effect. Also, the lower velocity data do not follow the same trend. Finally, the data at 7.5 m/s indicate a local “hump” in the curve. Comparable velocity data from multiple calibrations velocities have not been included in the current analysis. No explanation of the COR01 curve shape is currently proposed, it is hoped that additional data will help in understanding these behaviors.

4 INVESTIGATING DIAGNOSTIC PARAMETERS

The application of ultrasonic meter diagnostics has progressed over the past 10 years. A typical scenario has been described in numerous publications; an example is contained in [3]. In the typical case one or more diagnostic parameters indicates a potential measurement problem. The problem is identified during a field visit, often a foreign object or damaged component is found. The problem is resolved and the diagnostics return to normal. Laboratory testing identifies the potential range of measurement errors as a result. The industry is thus prepared for future occurrences if similar problems.

Coriolis diagnostics are in an earlier stage of development, few published examples are available. The discussion in [4] is used as a model for the current work. That example related changes in drive gain and pickoff amplitudes to a gradual increase in free liquids within flowing gas. The present analysis begins with the COR01 meter. The drive gain is plotted against pressure in Figure 7; it is expressed as a percentage of the maximum gain. Constant volume flowrates are identified by the different symbol colors. Two observed trends are easily understood: First, as the pressure increases the stiffness of the vibrating structure increases and more power (higher gain) is required to maintain resonance. Second, as the volume flowrate increases with constant pressure, the mass flowrate also increases. Once again more power is required.

Figure 8 shows the variation in drive gain expressed as a standard deviation of values obtained during one data point. The 3.5 MPa data represent the minimum variation with volume flowrate, clearly this pressure has significance. The lower flowrate curves indicate a sharp peak at 3.5 MPa, the peak diminishes with increasing flowrate. No current explanation is proposed, it is hoped that additional data will help to gain a better understanding.

Many of the calibrations in the current analysis included a record of diagnostic parameters. In some cases "as found" and "as left" values were recorded; only the as found data are currently considered. The investigation begins by calculating mean and standard deviation for constant flowrate values of each diagnostic. Data were obtained approximately once every 1.5 seconds; multiple readings were made per data point and multiple data points were obtained at a fixed flowrate. Typically 200-500 readings were used to determine mean and standard deviation.

The first step to investigate recent calibrations of one inch meters, as the analysis proceeds additional meter sizes as well as older data will be added. The more recent data is more likely to include diagnostic data; it also represents the newest meters which are more likely to benefit from any technical developments.

The drive gains from the massed calibrations are plotted against mass flowrate in Figure 9. Each line represents a second order polynomial fit to data from a single calibration. Recalling the discussion of Figure 2-5, the calibration data are obtained over a nominally consistent velocity range. The variability in the calibration mass flowrate range Figure 9 is the result of the consistent velocity range subjected to variable pressure. In general the data are quite consistent, the magnitude of drive gain agrees with the COR01 results. Slight variation between the curve fits do not appear to correlate with pressure. It is concluded that the observed variation represents random variations between similar meters.

The drive gain standard deviation (s_G) from the massed calibrations plotted against mass flowrate in Figure 10. Each line represents a second order polynomial fit to data from a single calibration. The black lines correspond to 13 calibrations of one inch meters; the red and green lines represent data from half inch and two inch size meters. Clearly there are differences between the multiple one inch meter calibrations; the s_G values vary by as much as 25%. The plot of Figure 11 shows a strong relationship between s_G and calibration pressure at a single value of mass flowrate [1.54 kg/s]. With the exception of one data point the s_G values are seen to increase with increasing pressure. It is concluded that the observed variation in Figure 10 is a result of pressure.

The drive gain values vary with nominal meter size. A half inch meter drive gain is approximately 8-12% while a two inch drive gain is approximately 1.5–2.0%. Data from multiple calibrations have not yet been collected; this step is planned for the future.

As previously noted, comparison with COR01 data provides a valuable link between the two data sets. Clear differences are noted in the magnitude of standard deviation values; values a bit larger than 1% compared to other values approaching 50%. The differences are due to sample rates and averaging because the values arise through to different routes. The larger standard deviation values are based on 200-500 readings produced directly by the meter; these are considered to be raw data. The smaller standard deviation values are based on gain values recorded by the calibration data acquisition system which calculates standard deviations based on averages rather than raw data. An averaging process will always reduce the standard deviation. Unfortunately the raw data were not saved so that comparable s_G values cannot be re-calculated.

While absolute s_G values are not comparable, general trends can be compared. Inspection of Figure 8 reveals that s_G values increase with volume flowrate at constant pressure and therefore also increase with mass flowrate. In general the trending agrees with the data of Figure 10. Further, the it is likely that the shape of the curve will change with pressure. Re-arranging the data will reveal the specific curve shape; this step has not yet been completed.

5 SUMMARY

An ongoing Coriolis meter investigation has the objective of providing better understanding by CEESI as well as industry in general. This is the third paper to be published. It documents the steady increase in quantity of meters and parameters under investigation. The massed calibration database now contains 62 meters, clearly the meter output often depends on velocity. Also presented is the first investigation of diagnostic parameter. It appears as if the drive gain variations (standard deviation) are dependent on pressure for one inch meter.

6 REFERENCES

[1] Kegel, T. and Baldwin, S., "Compressible Flow Effects in Coriolis Meters," North Sea Flow Measurement Workshop, 21-24 October 2014.

[2] Kegel, T., "Compressible Flow Effects in Coriolis Meters: A Continuing Study," Gas Mexico Congress, 2015.

[3] Lansing, J. "Ultrasonic Meter Condition Based Monitoring – A New And Simplified Solution," AGA Operations Conference, American Gas Association, 2007.

[4] Stobie, G. et al, "Blind Testing of a Micro Motion® Gas Coriolis Meter in Wet Gas Flows at the CEESI Wet Gas Facility." Americas Flow Measurement Conference, 2012.

Table 1 – Summary of Calibration Data

Pressure Range [MPa]	Quantity
1.0 – 1.5	7
1.5 – 2.0	7
2.0 – 2.5	3
2.5 – 3.0	7
3.0 – 3.5	9
3.5 – 4.0	6
4.0 – 4.5	19
4.5 – 5.0	1
5.0 – 5.5	3

Nominal Size [in]	Quantity
0.25	3
0.5	20
1.0	26
2.0	12
3.0	1

Table 2 – Distribution of Meters Based on Nominal Diameter

Nominal Size [inch]	Quantity Group 1	Quantity Group 2	Quantity Group 3	Quantity Group 4	Quantity Group 4 (green)
0.25	0	1	0	2	0
0.50	7	7	4	2	0
1.0	8	6	10	2	2
2.0	0	1	1	10	7
3.0	0	0	0	1	1

Table 3 – Distribution of Meters Based on Calibration Pressure

Pressure Range [MPa]	Quantity Group 1	Quantity Group 2	Quantity Group 3	Quantity Group 4
1.0 – 1.5	1	1	3	2
1.5 – 2.0	2	3	1	1
2.0 – 2.5	0	2	0	1
2.5 – 3.0	2	0	1	4
3.0 – 3.5	1	2	4	2
3.5 – 4.0	3	1	2	0
4.0 – 4.5	5	5	2	6
4.5 – 5.0	1	0	0	1
5.0 – 5.5	0	1	2	0

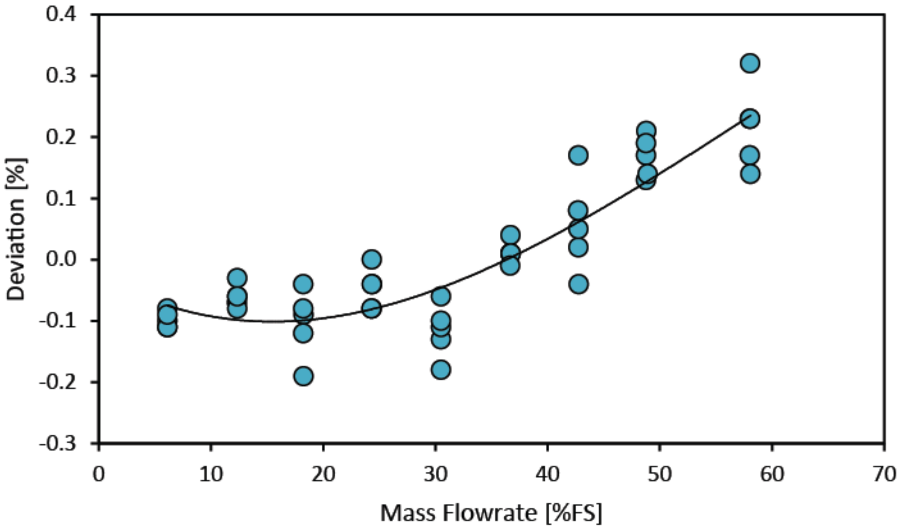

Fig. 1 – Typical Calibration Data With Polynomial Curve Fit

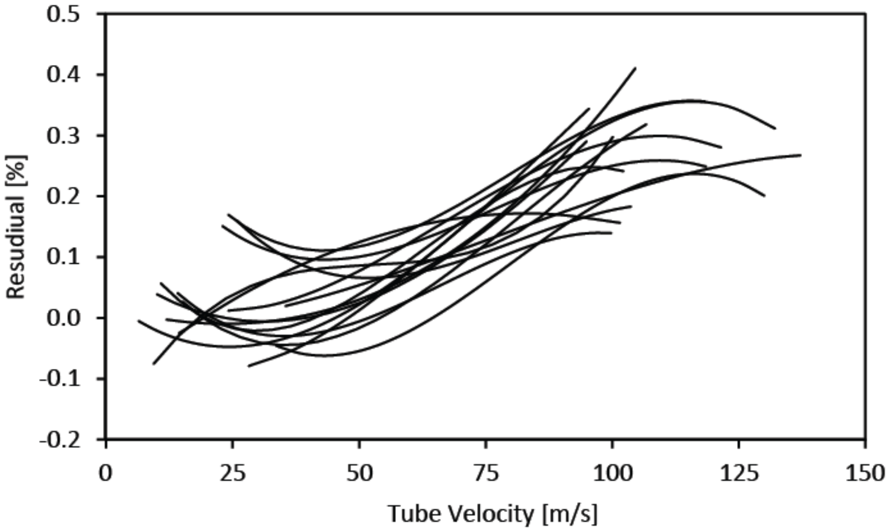

Fig. 2 – Group 1, Fifteen Calibrations

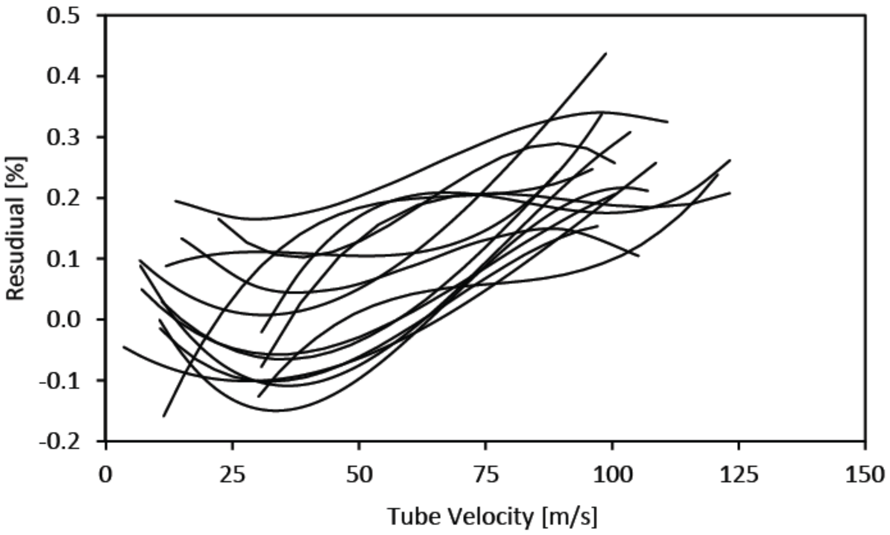

Fig. 3 – Group 2, 15 Calibrations

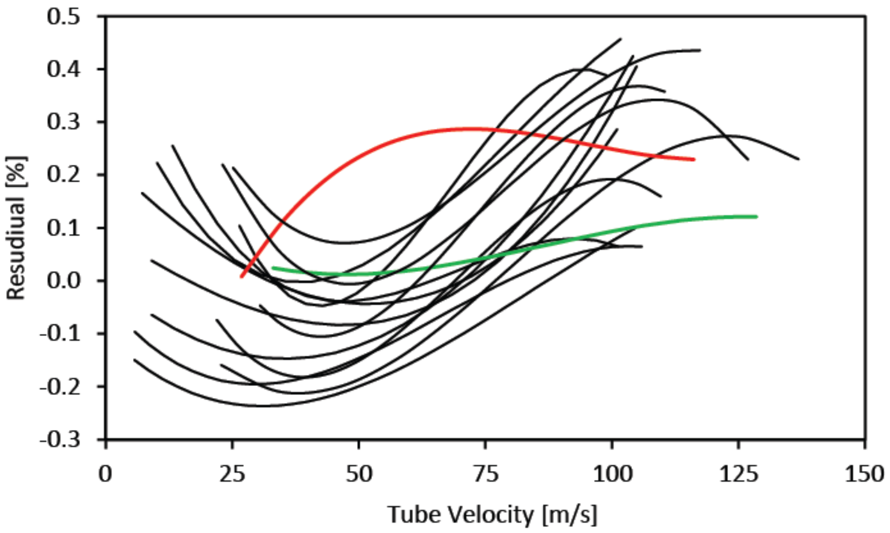

Fig. 4 – Group 3, Fifteen Calibrations

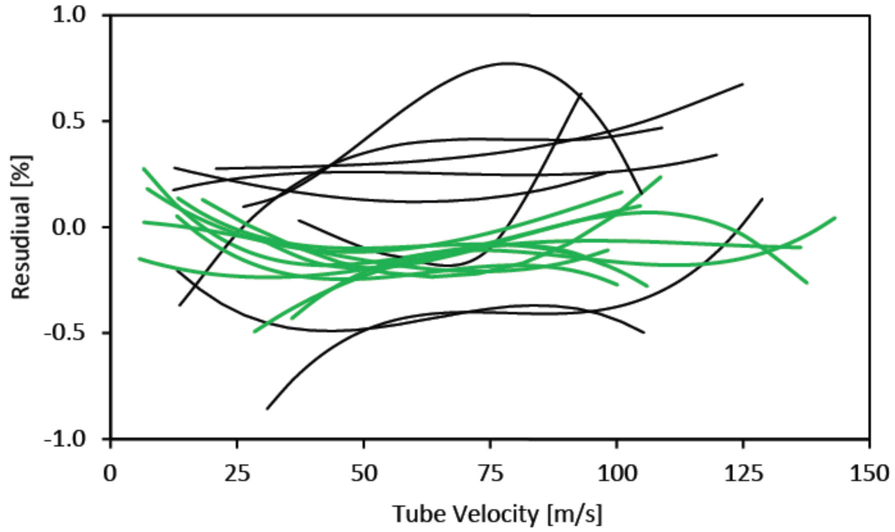

Fig. 5 – Group 4, Seventeen Calibrations

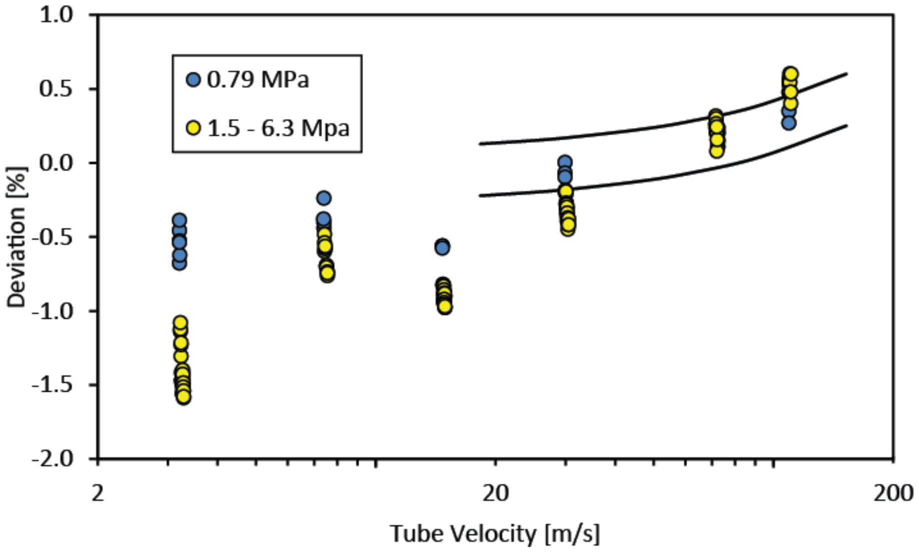

Fig. 6 – COR01 Meter Calibration Data

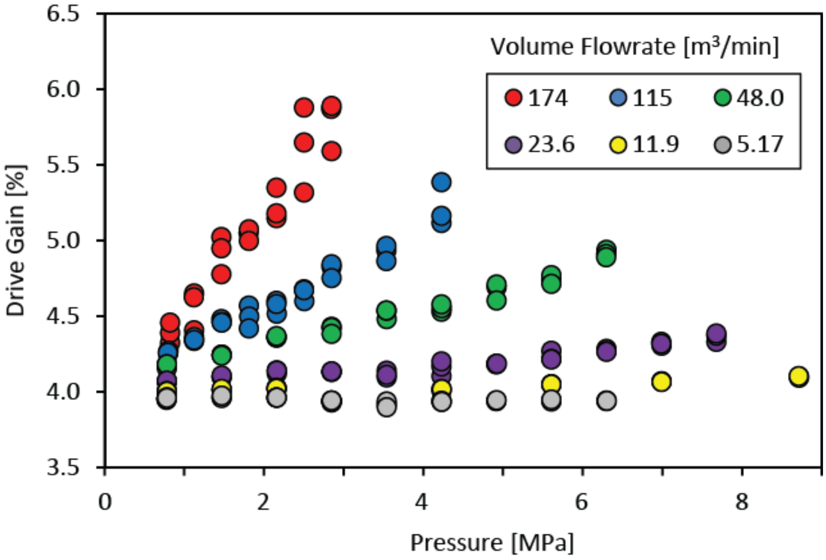

Fig. 7 – COR01 Meter Drive Gain

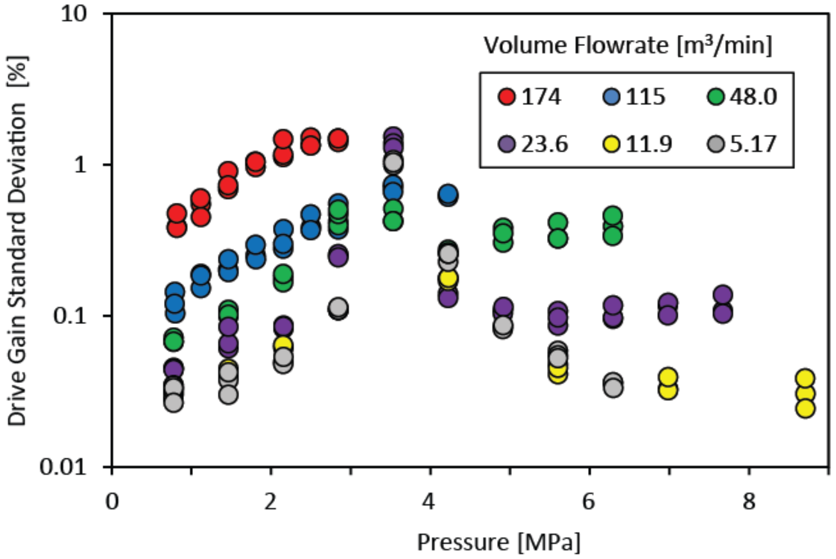

Fig. 8 – COR01 Meter Drive Gain Variation

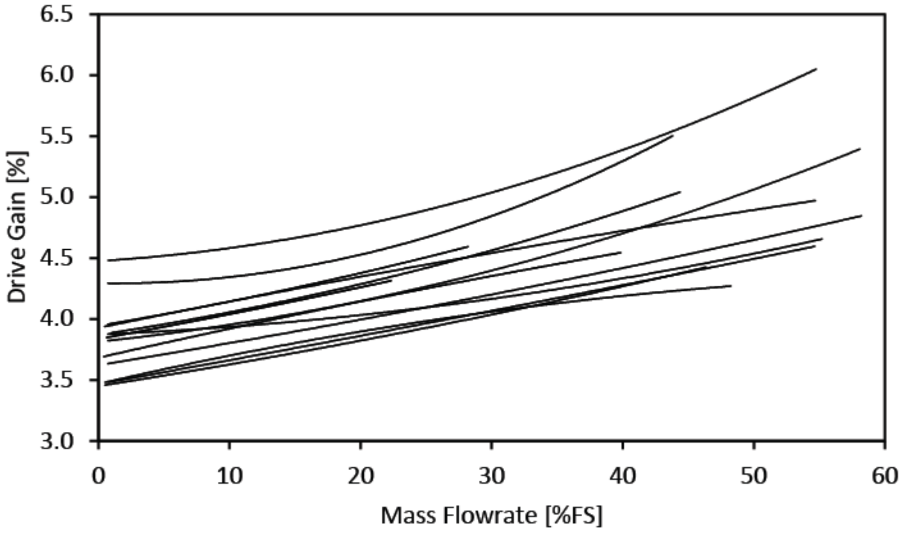

Fig. 9 – Drive Gains From Multiple Calibrations

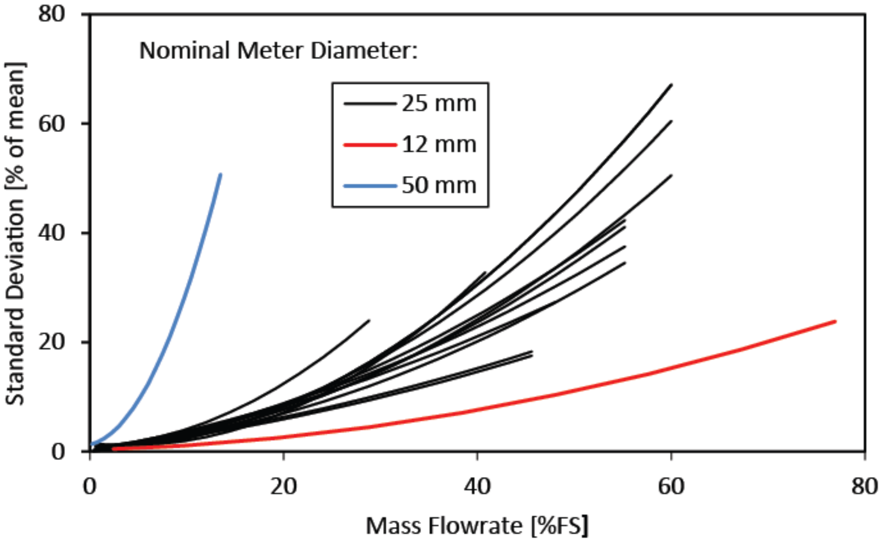

Fig. 10 - Drive Gain Variations From Multiple Calibrations

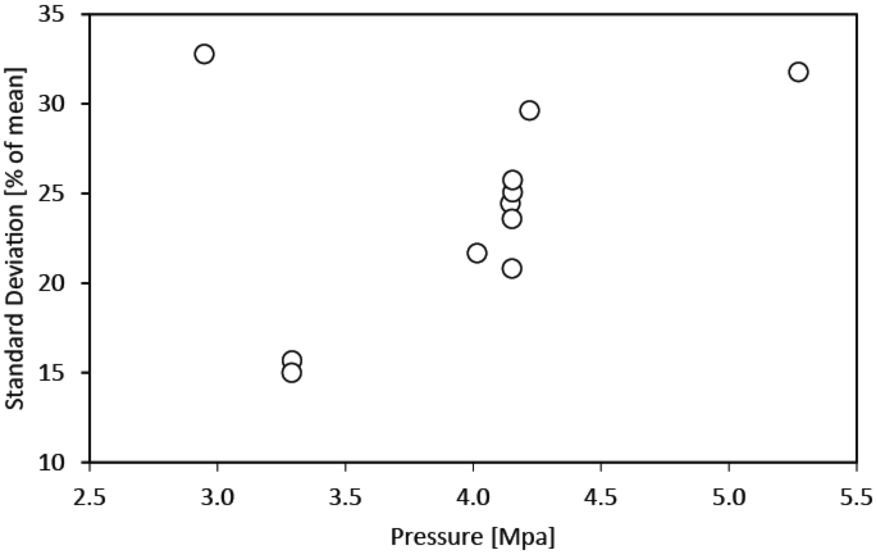

Fig. 11 - Drive Gain Variations From Multiple Calibrations, Data at Constant Mass Flowrate = 1.54 kg/s