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Compressible Flow Effects in Coriolis Meters

Thomas Kegel, CEESI
Steve Baldwin, Chevron

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1 Introduction

Historically Coriolis meters were restricted to liquid measurement applications, but 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 is a potential similar measurement uncertainty source.

2 Organization

This paper discusses a three part project on Coriolis meter gas flow compressibility effects. The first part is a review of the literature for both theoretical models and test data. Some of the test data indicate second order compressibility effects, some do not. Several theoretical models predict compressibility effects and allow for understanding the underlying physics. The published literature is reviewed in Section 3.

The second part of the project provides calibration data of two meters tested over a range of flow rates and pressures, thereby allowing analysis of compressibility effects. During the past 15 years CEESI has calibrated over 350 Coriolis meters using compressed air. The third part of the project shows massed Coriolis meter air flow calibration data from this extensive history. Collected variables include meter size, zero setting, inlet and exit pressures, and mass flow rate. The data and analyses are discussed in Sections 4 and 5.

3 Review of Published Literature

In the present discussion the published literature is divided classified based on whether the treatment is based on data or a mathematical model.

Several publications present data directly comparing calibration results based on compressible and incompressible fluids and conclude that calibration with an incompressible fluid is acceptable for compressible fluid service. Data from three different laboratories are presented in [1], [2] presents data from three meters at one laboratory, and [3] describes data obtained for the AGA 11 report [4]. Based in part on the third reference, AGA 11 allows for water calibration for use with natural gas provided the manufacturer presents supporting data from an independent laboratory.

Data from two studies indicate meter shifts in compressible flow. In [5] extensive data are presented from testing two meters. The two meters had unique curve shapes, one meter had more pronounced pressure effects. In [6] a 0.5% shift is noted between natural gas and water calibrations, the same shift was noted when the meter was re-calibrated [7].

Reports from operational data indicate a critical velocity above which a Coriolis meter becomes unstable. The first test program [8] evaluated coriolis meters for vehicle fueling while the second [6] supported compressed gas measurement in general.

The remaining published literature are more theoretical. A mathematical model of compressible flow [9] includes effects of speed of sound, velocity squared and a density. Experimental data are claimed to support the theory, but the data are not published. Similar results are noted from a model reported in [10].

A model based on a straight tube design [11] is said to be applicable to bent tube designs. The model includes compressibility, velocity and density effects. Compressibility and density effects act in opposite directions, sometimes cancelling each other out. The velocity effect results in non-linear meter behavior.

Difficulties in modelling gas flow is because of the turbulence are discussed in [12]. Stability criteria are proposed [13, 14] including a critical velocity that depends primarily on meter geometry.

In summary, mathematical models predict several compressible flow effects. It is difficult to judge the significance of the various effects without digging deep into the mathematics. Some published data show effects while other data do not. The data that show effects tend to be older, newer meters based on improved technology might be less sensitive.

4 Meter 1

This section discusses the first of two meters that have been calibrated over a range of pressures and flowrates. Meter 1 is a one inch, ANSI 600 class, double bent tube design meter that has been in use at CEESI for five years as a water meter. It was calibrated using dry compressed air based on six constant velocity tests. In these tests the velocity is nominally constant while the pressure is varied to achieve a range of mass flowrates. The air data cover a range of 0.01 - 1.6 [kg/s] and an absolute pressure range of 7.7 - 87 [bar].

This meter had been calibrated in the past using water; the data cover a range of 0.18 - 3.9 [kg/s]. The water calibration results are always within the manufacturer's specifications. A simple analog transmitter has been used when operating the meter to measure water flowrate in the CEESI lab. In the present test program a digital transmitter was used to allow for the collection of diagnostic information. As a result of the change in transmitter the air and water results cannot be directly compared.

4.1 Constant Velocity Test

A constant velocity test is designed based on a set of critical flow venturi (CFV) standards with different throat areas. Air flows through a CFV with unity throat Mach number, therefore the velocity is nominally constant. Varying the inlet pressure allows for variation of mass flowrate. Installing the CFV directly downstream of the Coriolis meter fixes the tube velocity while the mass flowrate varies with pressure.

The use of a CFV creates broad band noise that can affect the performance of some flowmeter technologies. The thermal dispersion, vortex shedding and ultrasonic meter are potentially affected by CFV based noise. The potential influence of CFV noise on a Coriolis meter is discussed in [6], it was only noted with one of the two meter tested. While CEESI has never noted any CFV noise effects on Coriolis meters the present testing and analyses have not included attempts to isolate any effects of CFV noise.

4.2 Numerical Zero Setting

The motion of a pair of nominally identical vibrating bent tubes is unlikely to be perfectly symmetrical due to inconsistencies in material properties and geometric details. Non-symmetry results in a phase difference or shift between the relative position of the tubes in two locations within the vibrating structure. In a Coriolis meter this phase shift results in a flow signal when no fluid is flowing through the meter. As fluid begins to flow the phase shift changes linearly with mass flowrate as a result of the Coriolis effect. The mass flow measurement is defined as the observed phase shift relative to the zero flow value.

In the present work a "meter zero" is defined as a mass flowrate value that is added to each reading allowing a curve fit of the data to intersect the origin. Each value is determined numerically based the entire data set. Typical data are contained in Figure 1. The abscissa is mass flowrate measured by the test facility, the ordinate is the difference between meter indication and mass flowrate. Two curve fits are shown based on the data; one is forced to intersect the origin, the other is not. Meter zero values are iterated until the two curves are judged to be coincident. In the figure the curves are indicated as a thinner black line and a thicker yellow line to judge coincidence. It is estimated that a 0.02 [kg/hr] shift in the iterated zero can be detected based on this method. This value can be interpreted as a measure of the uncertainty in the numerical meter zero.

The manufacturer claims a zero stability for this meter of 0.68 [kg/hr]; this is assumed to mean that repeated meter zero values will not vary by more than ±0.68 [kg/hr]. The six meter zero values from the current testing are contained in Table 1. The five lowest flowrates indicate a variation in the meter zero of ±0.73 [kg/hr] which is slightly higher than the manufacturer's claimed value. The highest flowrate value is clearly exceeds the specification. The data were reviewed for processing errors and none were found.

One possible source of zero shift is a change in stress induced in the meter upon installation. The induced stress will change the vibrational characteristics much like a guitar string is tuned by adjusting the tension. In the present testing the stress can change from one test to the next when a new CFV is installed. Zero shifts resulting from changing the flow standard have been observed at CEESI. In the present testing the six CFVs are similar in mass, the static load distribution of the test pipe system does not change significantly. The process of applying wrench loads to bolts and fittings and the re-positioning of pipe supports can change the stress distribution and might explain the zero shift.

A change in flowing pressure can change a meter zero. In the present testing the pressure is varied over similar ranges for each constant velocity test. It is unlikely that pressure variations are responsible for the zero shift. Returning to Table 1, the zero values do not appear to be correlated with volume flowrate. The order in which the data were obtained correspond to file number; the zero values don't appear to be correlated with time either.

One conclusion from the analysis thus far is that the meter zero is a topic that is worthy of additional study. Also, it is noted that this meter might be old enough to not meet current manufacturer specifications.

4.3 Data Analysis

The first view of the results is achieved by organizing the data based on the direct conditions of the testing. The results in this format are contained in Figure 2, each set of symbols corresponds to a nominally constant volume flowrate and tube velocity. The y-axis is labelled "deviation" which is the difference between the meter and flow lab values of mas flowrate expressed as a percentage. The term deviation will be used throughout this paper.

The AGA 11 report is commonly referenced in sales contracts to specify the measurement uncertainty limits of a Coriolis meter. The data of Figure 2 are evaluated based on four AGA 11 requirements. First, the report requires the data fall within ±1.0% between q_t and q_{max} where q_t and q_{max} are flowrates specified by the manufacturer. The present meter meets that criteria for q_t = 0.11 [kg/s], limited by the 5.17 [m^3/min] data. Second, the report requires the data fall within ±1.5% for flowrates less than q_t. If the meter is corrected within a flow computer it will meet this requirement, without corrections the meter fails. Third, AGA 11 requires repeatability of ±0.5% which is difficult to judge based on constant velocity testing. Strictly speaking the observed variation at a constant mass flowrate is reproducibility because conditions change from one data set to the next. The data points within a single test are clearly repeatable to within ±0.5%. A final requirement, often called the "peak-to-peak", is essentially non linearity. The five curves (excluding the 23.6 m^3/min data) are all reasonably linear. Two conclusions can be drawn at this point, the first being that this meter passes most of the AGA 11 requirements. Second, the AGA 11 criteria are not well established to evaluate constant velocity test data.

Except for the lowest flowrate (5.17 m^3/min) each data set meets the manufacturer's specification (±0.35%). The entire data set does not meet the manufacturer's specification.

Clearly the data of Figure 2 do not fall along a single line, thus indicating the presence of a physical effect that is secondary to mass flowrate. On the graph the data sets appear roughly in order of volumetric flowrate; highest flowrate with positive deviation, lowest with negative deviation. The curvature of the data sets also follows a pattern; the lower curves are concave up, the higher curve are concave down.

The one exception to the Figure 2 trends is the 23.6 [m^3/min] data set which appears with deviation values approximately 0.3% too low to fit the trend. This data set, shown in Figure 3, was reviewed for a possible explanation. The white symbols represent the data after determining a zero flow setting. Applying a simple second order polynomial fit to all the data was problematic. Only the three lowest flowrates were fitted based on the assumption that the predicted zero value would be more reliable than a prediction based on a poor curve fit. The resulting curve is shown in the plot as a solid line. The yellow symbols in Figure 3 are the result of re-processing the data excluding the lowest flowrate data point. They reflect the possibility that the lowest flowrate data represents an outlying condition. The data would appear above the 11.9 [m^3/min] points in Figure 2. The analysis leading to the yellow data identified a zero setting of -1.06 [kg/hr].

It is known that pressure will affect a coriolis meter. The data of Figure 2 were obtained with the pressure compensation turned off so that a pressure correction could be applied based on the data. Figure 4 shows the data plotted against pressure, it is noted that a single continuous curve cannot relate deviation and pressure. While pressure might be a secondary effect, it is not the only effect. As was the case with Figure 2, the data sets form curves that appear in order of volume flowrate, except for the 23.6 [m^3/min] data.

In Figure 5 the data have been segregated by pressure. Curve fits are shown for selected data sets, they appear similar in shape but are apparently shifted based on pressure. The data of Figure 5 suggest a simple pressure correction may collapse all the data into a single curve expressing deviation as a function of mass flowrate. The results of applying a correction are contained in Figure 6; a pressure correction value was applied to each curve based on visual judgement of agreement between the curves. The correction values along with a curve fit are contained in Figure 7, two observations are made. The first observation is an apparent contradiction of the discussion accompanying Figure 4 which did not appear to support a simple pressure correction. Second, the pressure correction is slightly non-linear, and the magnitude is rather large, approximately 0.029% per bar.

Continuing the analysis the data of Figure 5 are plotted against volume flowrate in Figure 8. Figure 8 returns to the basic design of a constant velocity test; the data are obtained at six values of volumetric flowrate obtained using six different CFVs. The low pressure (7.9 bar) data are significantly above the rest at 5.17 [m^3/min]. This difference becomes less significant as the volume flowrate increases. The data are quite repeatable without correcting for pressure; the 115 [m^3/min] data, for example, are with ±0.16% (at a 95% confidence level) of the mean. Both observations are more clearly evident from Figure 4. The data of Figure 8 show a clear trend of deviation as a function of volume flowrate. The trend is also observed in Figures 2, 4 and 5, but Figure 8 shows it more clearly.

The graphs of Figures 6 and 8 appear to illustrate two approaches to interpreting the data. Figure 8 does not require a pressure correction, but does require a correction for volumetric flowrate or velocity while Figure 6 is based only on a correction for pressure. A question arises is whether each graph represents an independent correction, or two methods to correct for the same effect. An increase in pressure corresponds to an increase in density when temperature is controlled to a constant value. Pressure changes correspond to mass flowrate changes, the same with velocity changes. The pressure correction shown in Figure 7 is approximately an order of magnitude larger that the manufacturers typical claim, likely indicating the need for two separate corrections.

The low pressure data (7.9 bar) of Figure 8 do not follow exactly the same trend as the other data. The difference is likely the result of the very low density, with relatively less mass to develop a Coriolis force. Figure 9 shows the lower flowrate data of Figure 8 without the low pressure data. A solid line has been added that attempts to capture the curve shape; the 11.9 [m^3/min] data indicate a "hump" in the curve. The unusual curve shape can easily be linearized within a flow computer.

5 Meter 2

Meter 2 is a three inch, ANSI 600, double bent tube design meter recently purchased from the manufacturer. It was calibrated using a set of three constant velocity tests. The calibration covers the mass flowrate range of 0.12 - 3.9 [kg/s] and the absolute pressure range of 7.7 - 70 bar. The zero values were established using the procedure described for Meter 1, the results are contained in Table 2. The manufacturer's specification of zero stability for this meter is 6.8 [kg/hr], the tabulated values are well within this range.

Figures 10 shows the deviation as it varies with mass flowrate, the data fall within the ±1.0% AGA 11 criteria. The symbols represents data taken with different CFVs. The results are similar to those of Meter 1 in that the three curves roughly follow a trend with volume flowrate. The results differ from Meter 1 because they appear to lie along one of two different curves indicated by the solid lines. Interestingly, some of the 47.2 [m^3/min] data seem to lie on each line. The other two data sets are each characterized by one line.

Figure 11 shows the deviation as it varies with volume flowrate. The trend of deviations increasing in the positive direction is similar to Figure 7 without the hump.

With only three flowrates, it is difficult to plot the data against pressure and proceed with the analysis. Some observations are made based on the limited data. Meter 2 data are clearly different from Meter 1, several differences are noted. The line sizes are different but the basic design is the same. Meter 2 is several years newer and possibly includes new technology. Meter 1 has been in service for a number of years.

6 Analysis of Massed Calibration Results

The second part of the study is based on detailed calibration data from twenty four meters provided by a calibration customer on the condition of anonymity. The database contains ten half inch meters, nine one inch meters, four two inch meters and a single three inch meter. Data were obtained over two flowrate ranges. The flowrate values are expressed as percentages of the maximum meter capacity (symbolized as %FS) so that different size meters can be compared. The high flowrate data cover the 5 to 70% range, the low flowrate data cover the 0.3 - 1.6% range. The average calibrated range is 85:1, the maximum is 136:1 and the minimum is 37:1. The pressure corrections were disabled to allow for off-line application of a correction value.

The high flowrate calibration data (deviation vs mass flowrate) for each meter are fitted to a third order polynomial. 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 are observed to exhibit some consistent shapes. The high flowrate data have been first qualitatively organized based on two different shapes; Group A contains eight calibrations while Group B contains six. The two groups are shown in Figures 12 and 13. The black lines represent the individual meter calibration curve fits, the red lines represent statistical intervals that contain 95% of the data. The Group A interval width is ±0.132% and the Group B value is ±0.102%.

The data from Groups A and B clearly meet the AGA 11 ±1.0% specification. The non-linearity (peak-to-peak) requirement is more difficult to visually judge. Several of the calibration curves exhibit potentially large positive slopes that might exceed the peak-to-peak requirement. The repeatability specification will be discussed later in this paper. Groups A and B are similar in shape but differ in flowrate range. Both show a gradual increase in deviation with flowrate, 0.2% for A and 0.4% B. The data are asymmetrical, meters in these groups will read high.

The classification of the remaining calibrations is based on observed variations between calibrations, the data are plotted in Figures 14 and 15. The six Group C curves exhibit less variation between calibrations compared to the four in Group D. The Group C data are characterized by three higher flowrate calibrations that are very linear and three lower flowrate calibrations that are more non-linear. The higher and lower flowrate calibration ranges are very similar. Being the last in the discussion, the Group C and D data do not necessarily represent Coriolis meters with poor performance. In fact five of the meters exhibit better linearity than many of the Group A and B calibrations. The Group C and D calibrations are much more symmetrical than Groups A and B. Based on either Figure 5 or 6 the detailed data from Meter 1 would fall into Group D regardless of the calibration pressure. Based on the limited data in Figure 10, Meter 2 would likely fall into Group D as well.

The low flowrate data are divided into two groups (E and F) that are shown in Figures 16 and 17, the red lines again represent the statistical interval that includes 95% of the data. The interval width varies from ±0.307% (at 1.5%FS mass flowrate) to ±1.072% (at 0.5%FS mass flowrate). The Group E data are very symmetrical, a meter is equally likely to read high or low. At low flowrates the curve shapes are very similar; increasing deviations are observed as the mass flowrate decreases. The curves may gradually increase (positive deviation), decrease (negative deviation) or indicate a constant deviation. Group E was judged to contain most (18) of the calibrations while Group F contains a few (6) that are outside the range of E.

The calibration data used in the present study were obtained over a range of flowing pressure and meter diameter values. The next step in the analysis is to identify a potential correlation between the grouping of the data and either pressure or line size, data are shown in Figure 18. The flowing pressure is clearly related to the shapes observed in Groups A and B. In contrast, there appears to be less correlation between pressure and the Group C and D classifications. In general the data form a clear trend, the higher the pressure, the lower the maximum calibrated mass flowrate. This is likely the result of a maximum recommended velocity.

Regarding meter size, all one inch and half inch meters are in Groups A and B. The unique curve shapes characterizing these groups may be limited to small meters. Similar curve shapes are noted in Figure 5, a one inch meter. Groups C and D each contain three meter sizes (½", 1" and 2"). The single three inch meter, positioned in the lower right hand corner of Figure 18, is in Group C.

The data in Figures 12 and 13 are replotted as a function of tube velocity in Figure 19. The tube velocity is calculated based on inlet density, the velocity at the outlet will be higher as a result of the pressure drop through the meter. Clearly noted in Figure 19 is that the Group A and B data collapse into a single trend with velocity. The dashed lines represent a statistical interval assuming a linear trend with velocity, the interval width ±0.155%. The maximum velocities noted in Figure 19 correspond to a Mach number of approximately M = 0.3. This value corresponds to recommendations from at least two meter vendors. The velocities are higher than the limiting values reported with the older meters in [7, 9], likely a result of improving technology.

The final analysis organizes the random effects observed during the calibrations. While the polynomials indicate the average deviation as it varies with mass flowrate, they contain no information about random effects (repeatability). During a typical calibration between four and ten data points are obtained at each flowrate. The standard deviation of these data points represents the random effects. Two standard deviations is interpreted to represent the repeatability at a 95% level of confidence. The standard deviation data are shown in Figure 20. Three lines are shown in the plot. The dashed lines represent the repeatability specifications from AGA 11 assuming q_t = 3%FS. Out of 200 data points, 16 (8%) are above the specification. Out of these 16 points, 11 are from three different calibrations. Most of the calibrations meet the specifications for repeatability. The solid line represents a curve fit of the data. It reflects a gradual increase with decreasing flowrate that is observed with every measurement process. In the case of Coriolis meters it is likely the result of the uncertainty in the measurement of time and zero stability. If the meter zero varies during the time of the calibration, it will have a larger effect at lower flowrates. The solid line increases slightly at higher flowrates, possibly a result of turbulence or excitation of different vibration modes.

Summary and Conclusions

Two meters were tested in to help identify parameters that affect Coriolis meters in compressible flow applications. Both were double bent tube designs, a one inch and three inch meter.

The meter zero was not included in the present study because it is not a factor that is limited to compressible flow. The analysis of the one inch indicates that the meter zero is a topic that is worthy of additional study.

Figures 6 and 8 appear to illustrate two approaches to correcting the meter output; one correction is for pressure, the second for velocity. An excessively large pressure correction suggest a second parameter, perhaps velocity, might be considered.

The three inch meter data and analyses were less extensive than the one inch meter. The data that were considered indicate flow behavior that is quite different.

Air calibration data from twenty four meters were classified based on curve shapes. The classification indicates that Coriolis meter compressible flow calibration data can vary quite a bit.

Two of the classifications, Groups A and B, were observed to be similar in shape. Plotting the data against velocity instead of mass flowrate collapsed the data into a single curve.

Random effects are plotted against mass flowrate. The low flowrate distribution is consistent with a typical measurement process. A slight increase at high flowrate is thought to be the result of high velocity. The averaged data a very low flowrate data, below 1.5% of maximum, also show random effects that increase as the flowrate decreases.

In general most of the testing and most of the meters show compliance with AGA 11. Lower uncertainty can be achieved by calibrating using a compressible fluid at flowing pressure. The uncertainty can be further reduced by utilizing a curve fit function in a flow computer to linearize the calibration data.

Future Plans

The constant velocity testing is currently very limited. Future plans include additional line sizes and other meter designs.

The massed data include only 24 out of 350 calibrations. Additional meters will be added to the database.

The Coriolis meter offers diagnostic parameters that were collected but not included in the analysis. Future plans include investigating the diagnostics to see if they correlate with any of the potential compressible flow effects.

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Table 1 - Meter 1 Numerical Zero Values

File Number	Volume Flow [m³/min]	Zero [kg/hr]	File Number	Volume Flow [m³/min]	Zero [kg/hr]
472	5.17	-0.21	434	48.0	0.10
387	11.9	0.62	433	115	1.25
447	23.6	1.11	430	174	-4.34

Table 2 - Meter 2 Numerical Zero Values

Volume Flow [m³/min]	Zero [kg/hr]
47.2	10.3
114	11.6
175	14.2

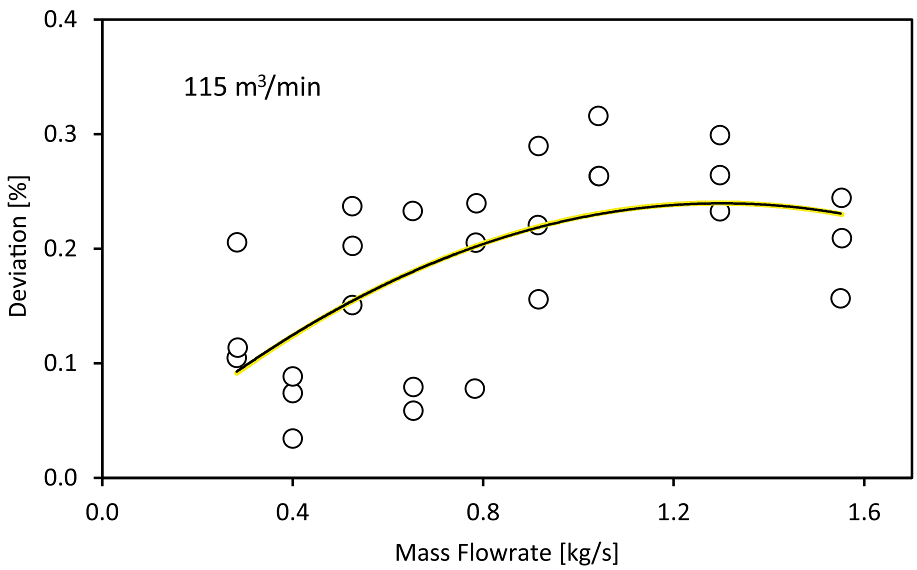

Figure 1 - Typical Data With Curve Fits Applied to Determine a Numerical Zero

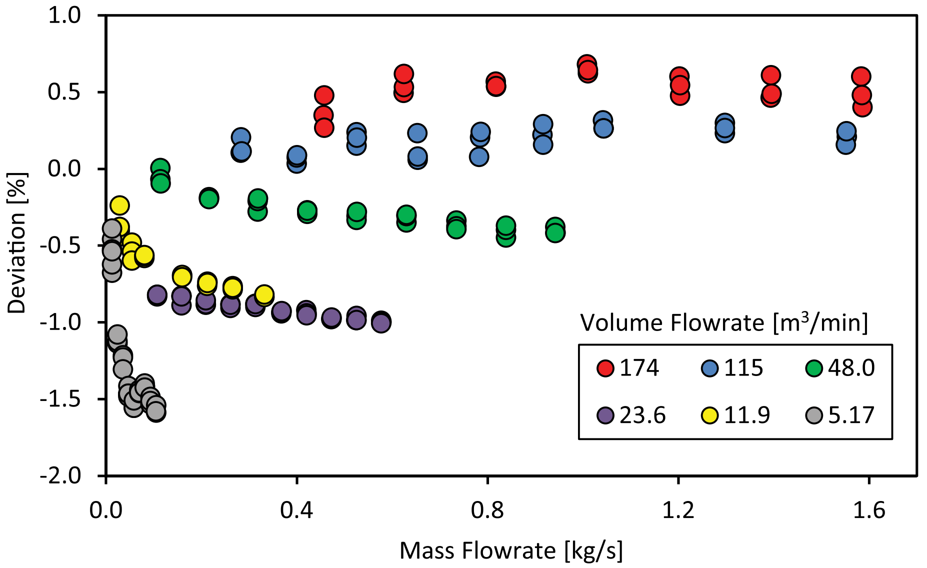

Figure 2 - Meter 1 Deviation as a Function of Mass Flowrate, Segregated by Volume Flowrate

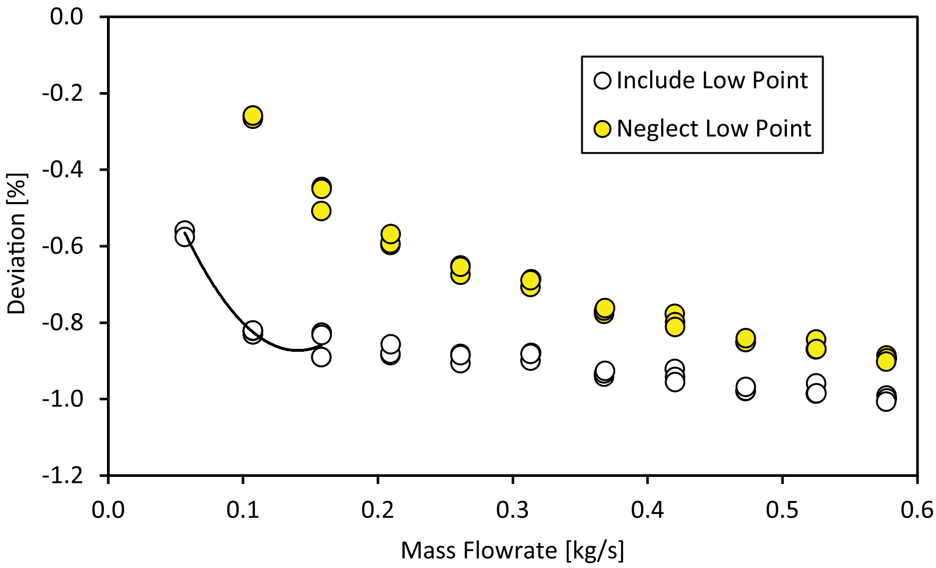

Figure 3 - Recalculating Meter 1 Zero Setting for the 11.9 [m³/min] Data Set

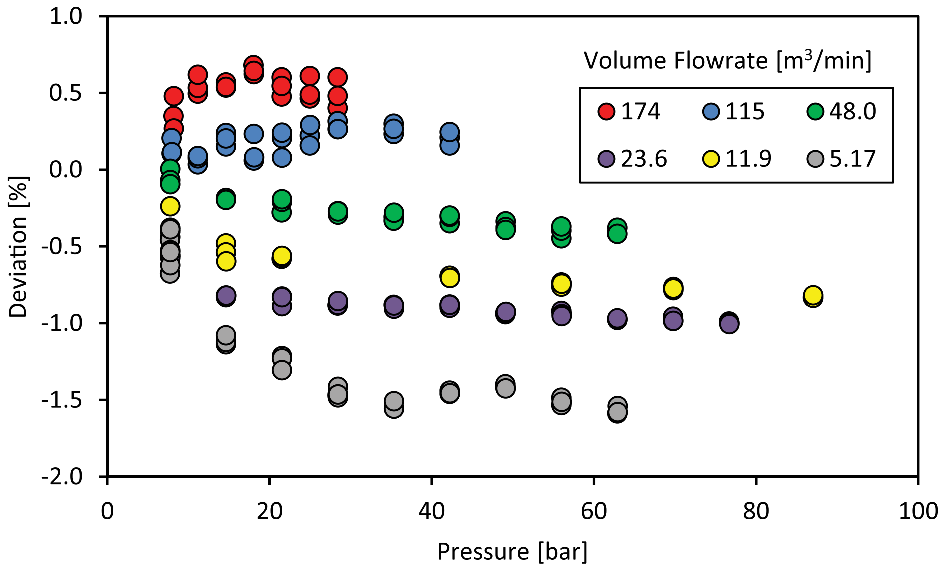

Figure 4 - Meter 1 Deviation as a Function of Pressure, Segregated by Volume Flowrate

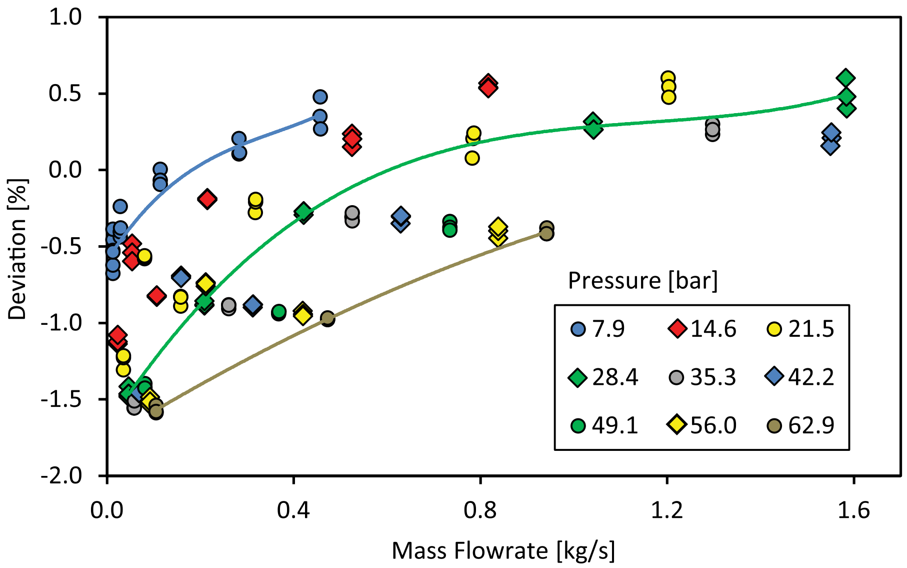

Figure 5 - Meter 1 Deviation as a Function of Mass Flowrate, Segregated by Pressure

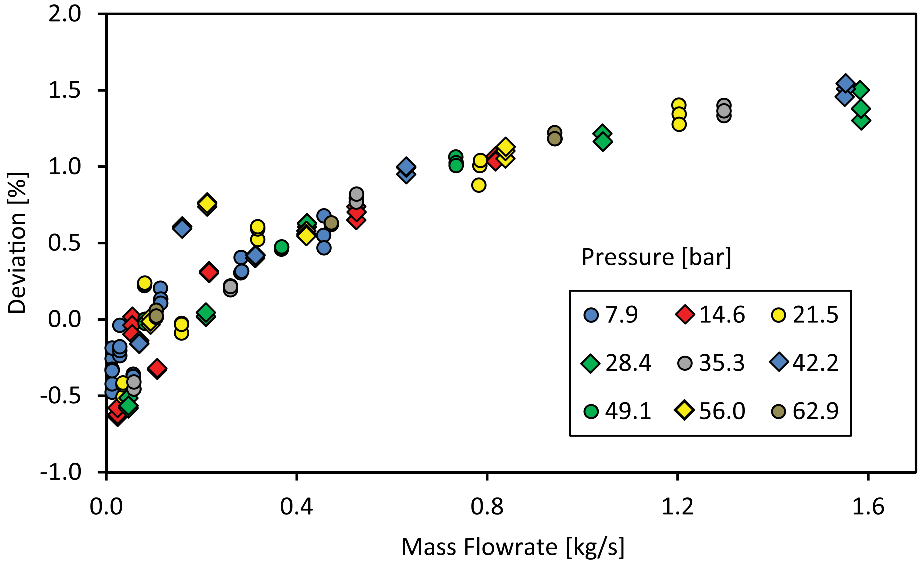

Figure 6 - Meter 1 Deviation
With Numerical Pressure Corrections

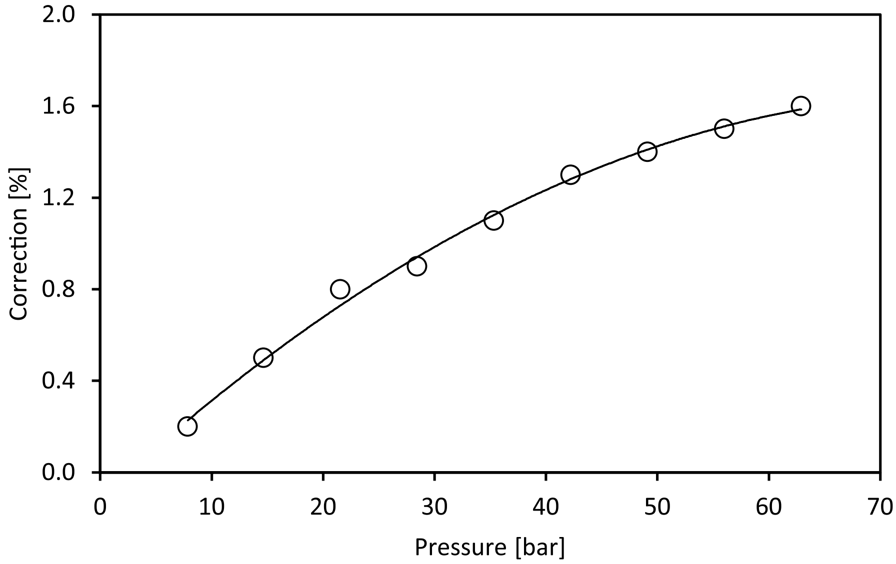

Figure 7 - Meter 1 Summary of Numerical Pressure Corrections
Applied to Figure 6 Data

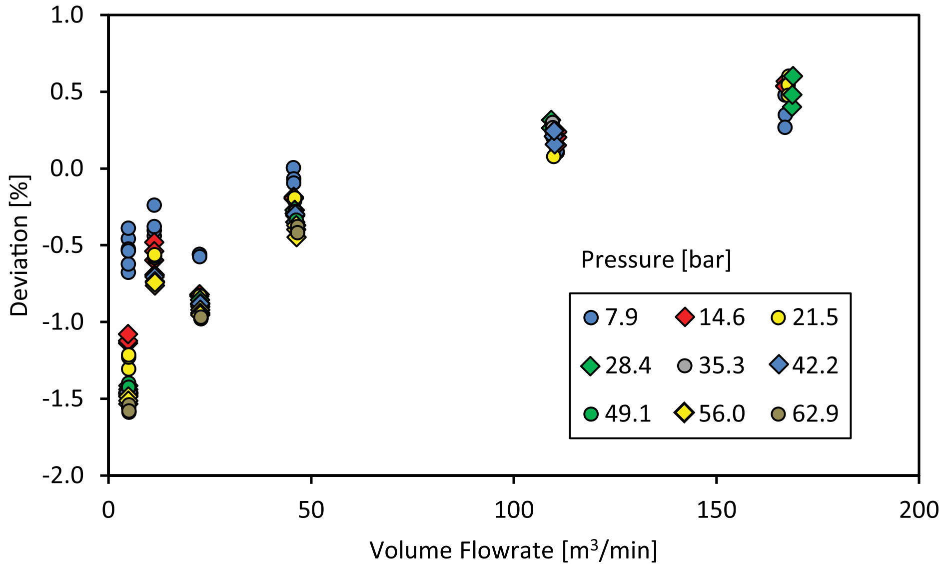

Figure 8 - Meter 1 Deviation as a Function of Volume Flowrate, Segregated by Pressure

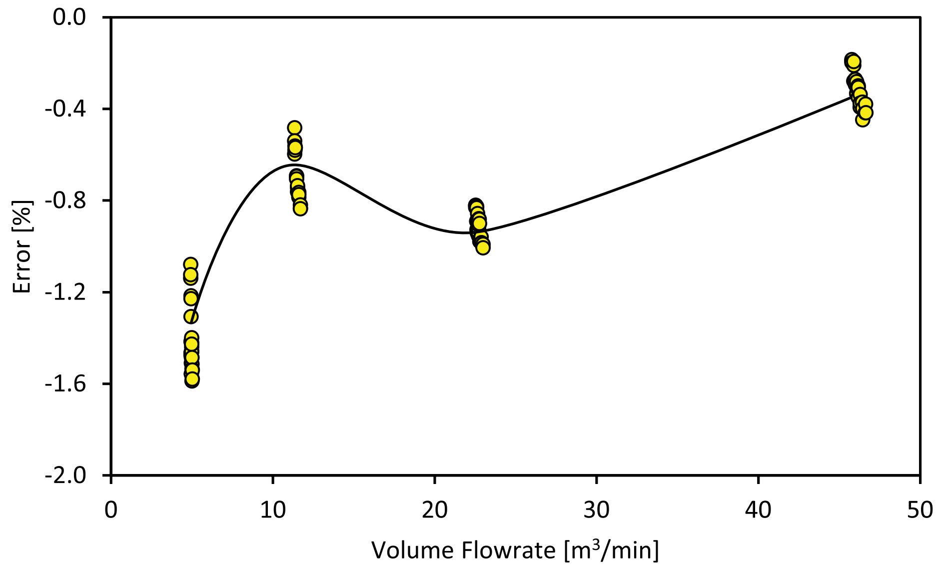

Figure 9 - Meter 1 Deviation as a Function of Volume Flowrate, 7.9 [bar] Data Excluded

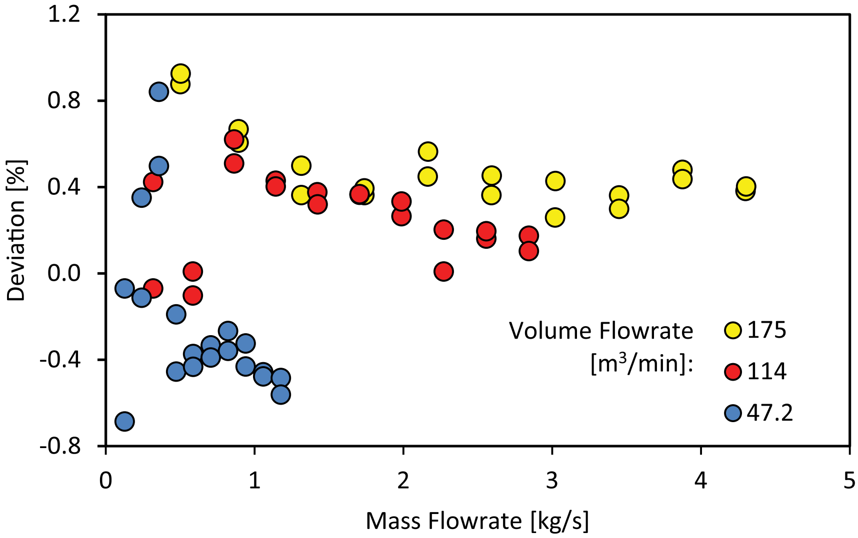

Figure 10 - Meter 2 Deviation as a Function of Mass Flowrate, Segregated by Volume Flowrate

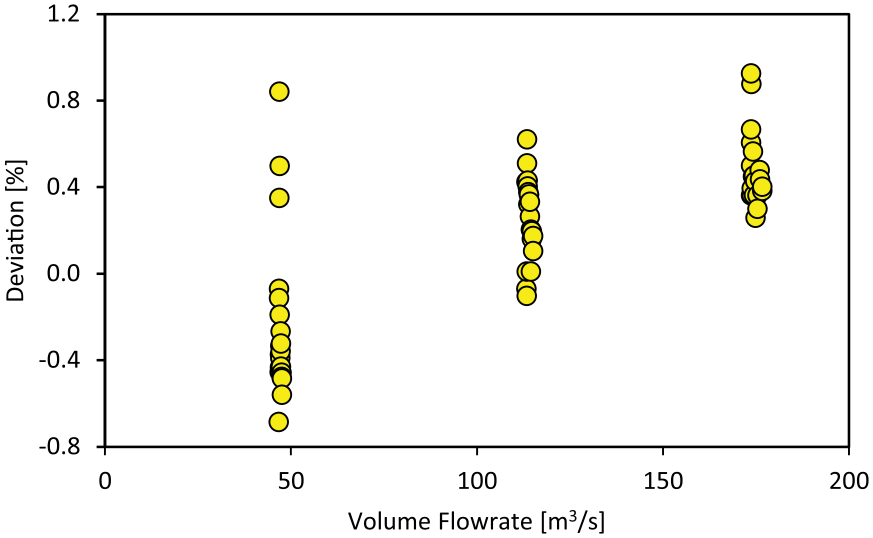

Figure 11 - Meter 2 Deviation as a Function of Volume Flowrate

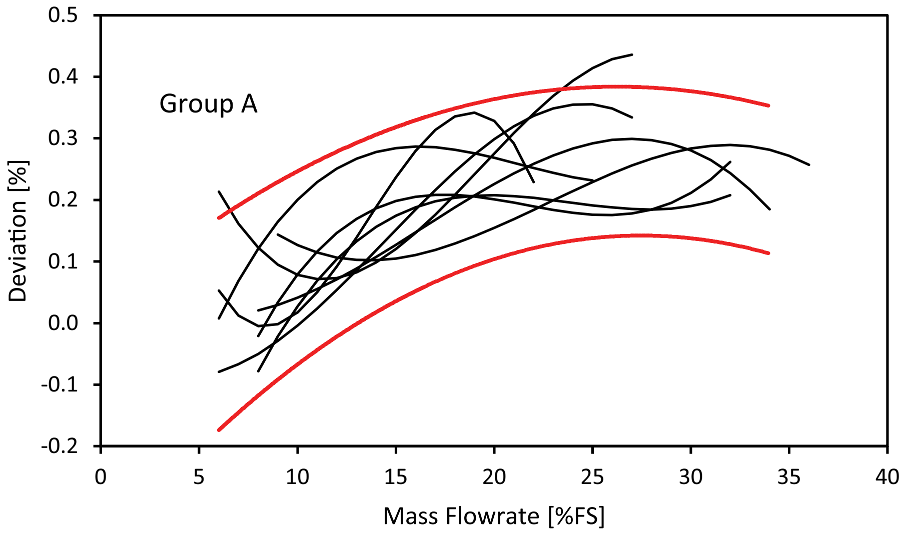

Figure 12 - Massed Data Group A Deviation as a Function of Mass Flowrate With a 95% Confidence Interval in Red

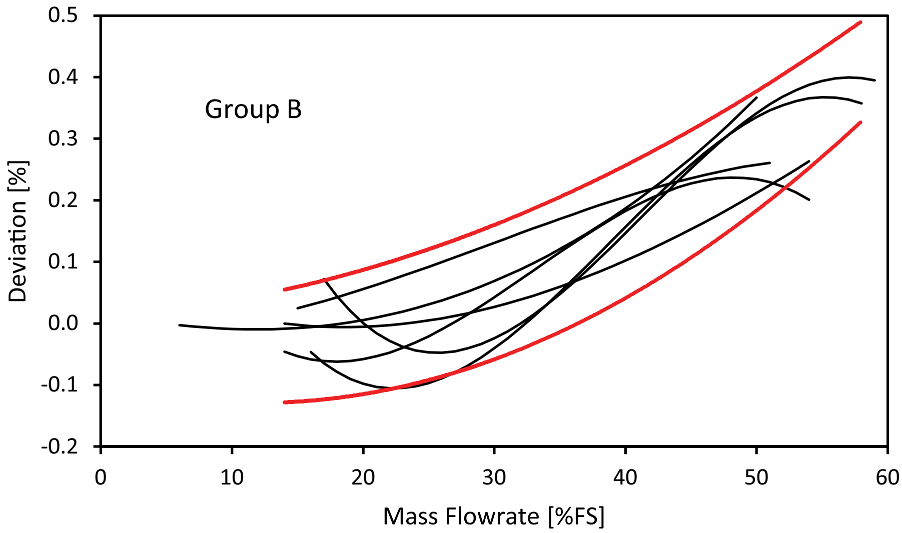

Figure 13 - Massed Data Group B Deviation as a Function of Mass Flowrate With a 95% Confidence Interval in Red

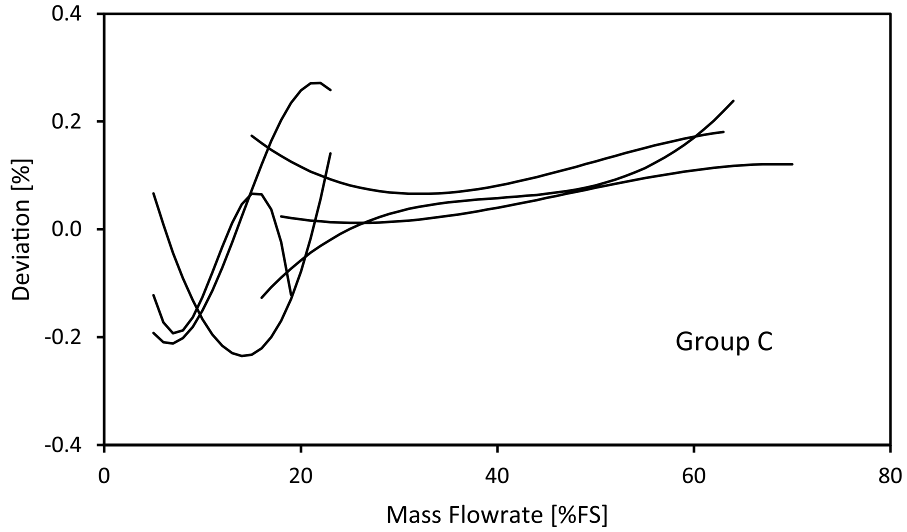

Figure 14 - Massed Data Group C Deviation as a Function of Mass Flowrate

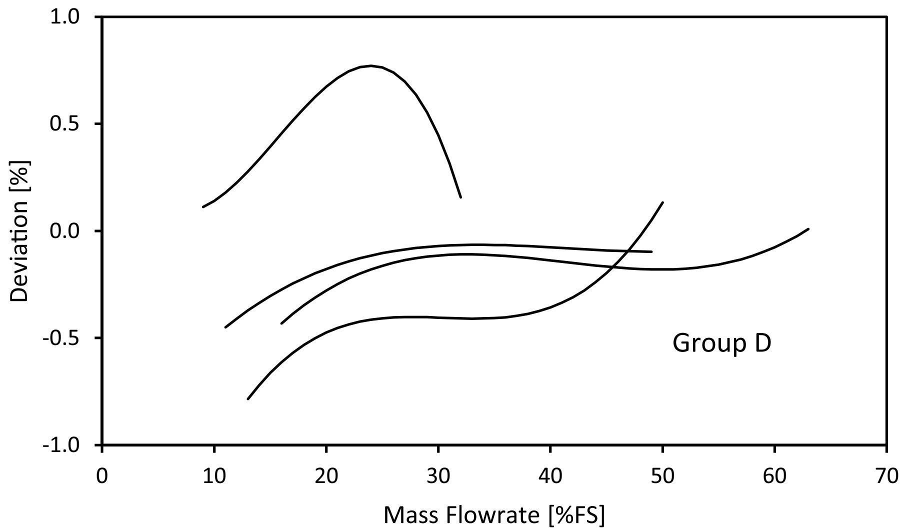

Figure 15 - Massed Data Group D Deviation as a Function of Mass Flowrate

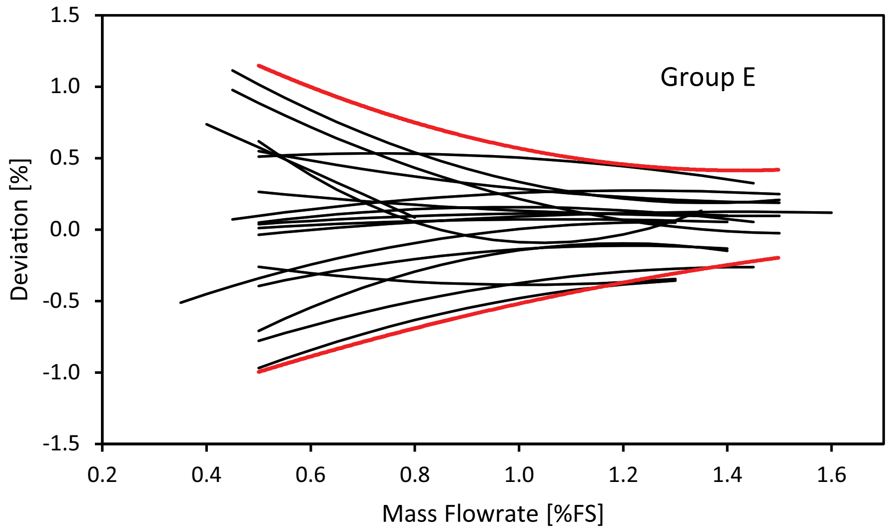

Figure 16 - Massed Data Group E Deviation as a Function of Mass Flowrate With a 95% Confidence Interval in Red

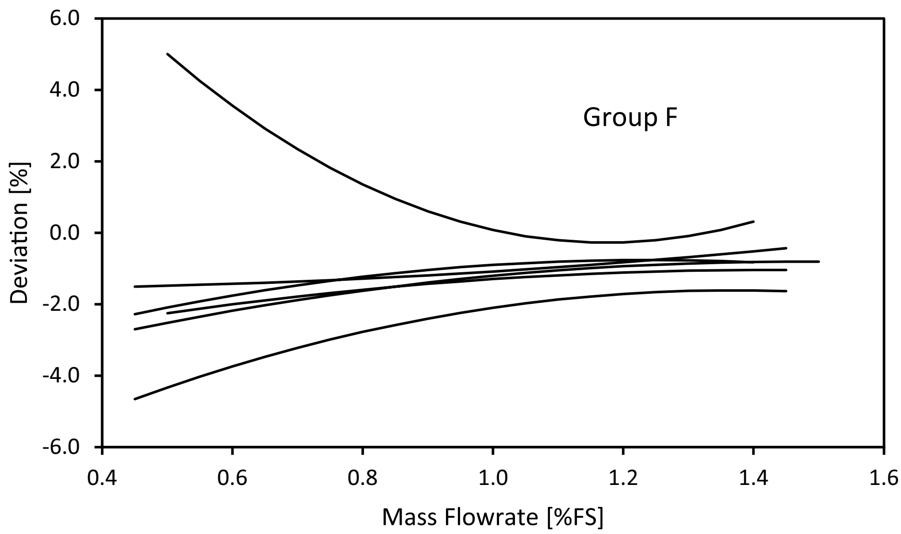

Figure 17 - Massed Data Group F Deviation as a Function of Mass Flowrate

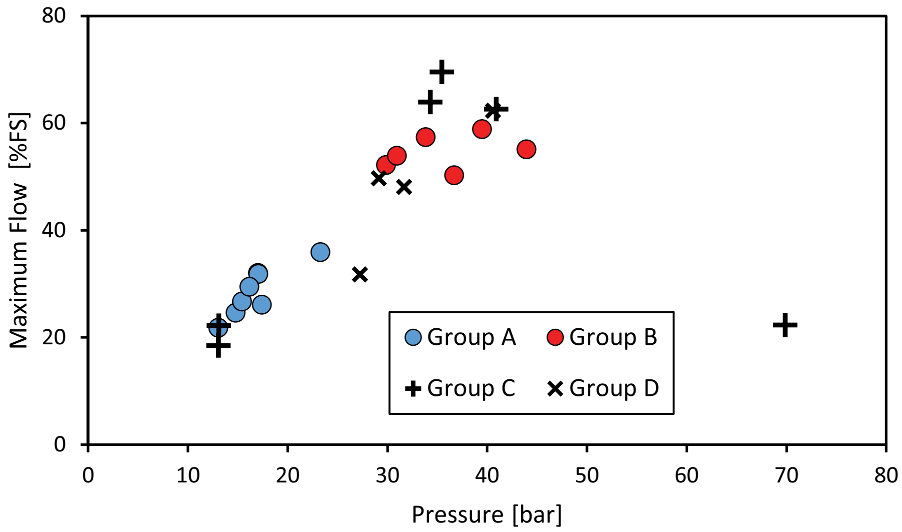

Figure 18 - Massed Data Maximum Mass Flowrate as a Function of Pressure, Segregated by Group

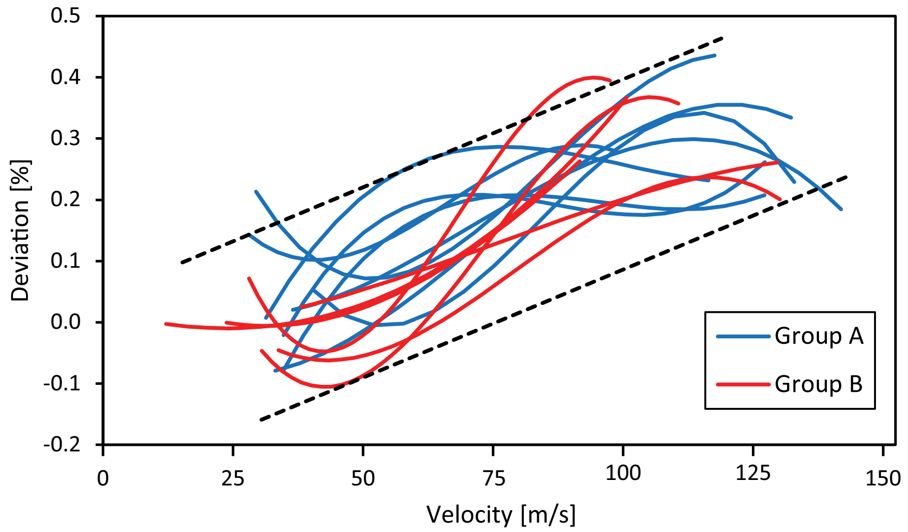

Figure 19 - Groups A and B Deviation as a Function of Velocity

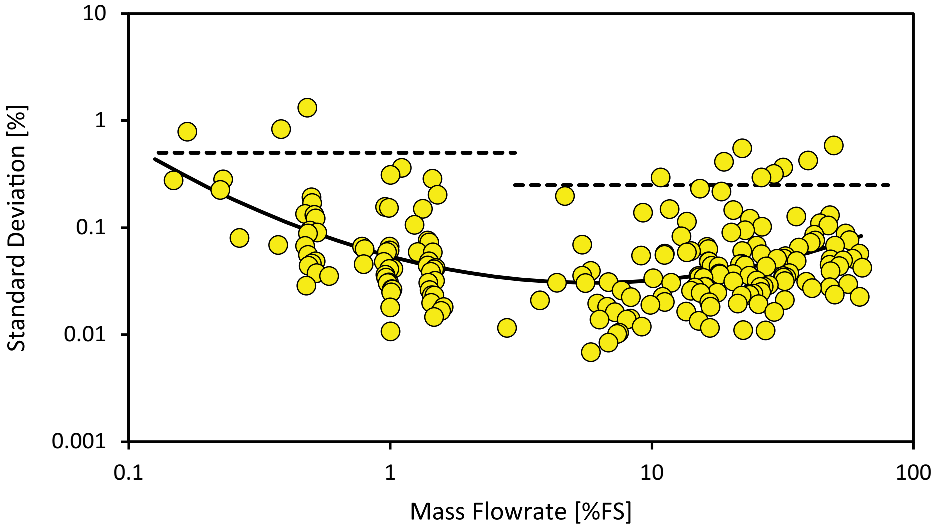

Figure 20 - Repeatability of Massed Calibration Data Compared to AGA 11 limits (dashed)