GFM™ Accuracy Application Note

INTRODUCTION

Pivotal's GFM™ system provides real time, in situ gas flow measurements of mass flow controllers. The system is based on first principles, namely a rate of pressure drop over a known volume and temperature. As such the measurement error of flow measurement is extremely low and betters some of the best industry-standard off-line methods such as molbloc (±0.2%) and rate of rise (±0.5–1.0%).

This application note briefly discusses GFM's expected measurement error. As the paper will show, while the error of GFM is specified not to exceed ±0.5% of flow, its performance is actually much better at ±0.17%.

Pivotal's GFM system is a first principles rate of drop measurement system and therefore follows the Ideal Gas Law modified by the compressibility, Z.

With compressibility added, the Ideal Gas Law states:

$$PV = nZRT$$

Where:

- P = absolute pressure of the gas
- V = volume of the gas
- n = number of moles of the gas
- R = universal gas constant
- T = absolute temperature
- Z = compressibility factor

Therefore:

$$n = PV/ZRT$$

And finally:

$$\text{Flow Rate} = \Delta n/\Delta t = \Delta(PV/ZRT)/\Delta t$$

Figure 1: Typical Pressure Curve for GFM Measurements

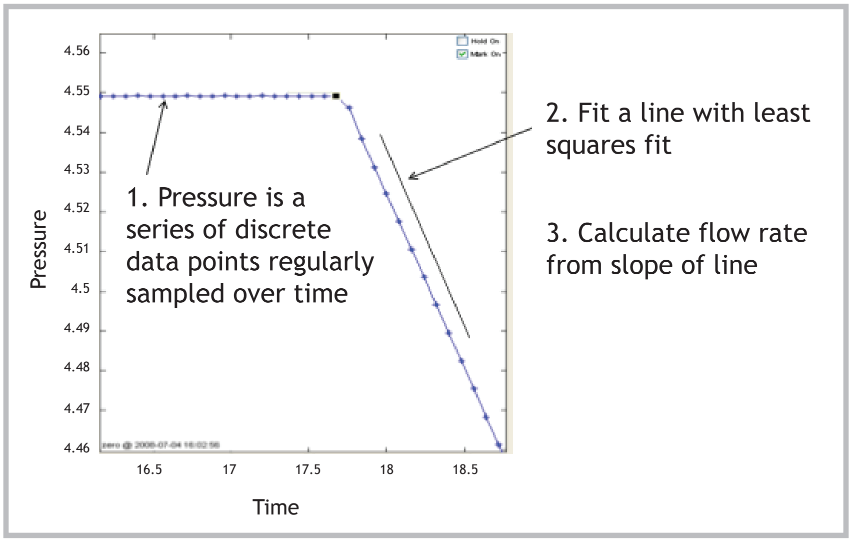


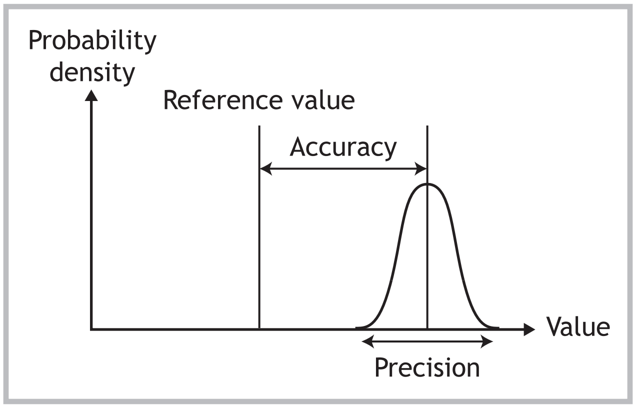
Figure 1 illustrates a typical pressure curve that is observed when a mass flow controller (MFC) begins to flow and the GFM's observed pressure begins to drop. With a known volume and temperature, the flow can be calculated in real time by observing the slope of pressure decline.

CALCULATING GFM MEASUREMENT ERROR

The error in GFM measurements is comprised of two parts: accuracy and precision (see Figure 2).

Accuracy is an indicator of the proximity of the measurement to the true value, while precision is defined as the repeatability (typically 3σ variability) of a particular measurement.

Figure 2: Definition of Accuracy and Precision



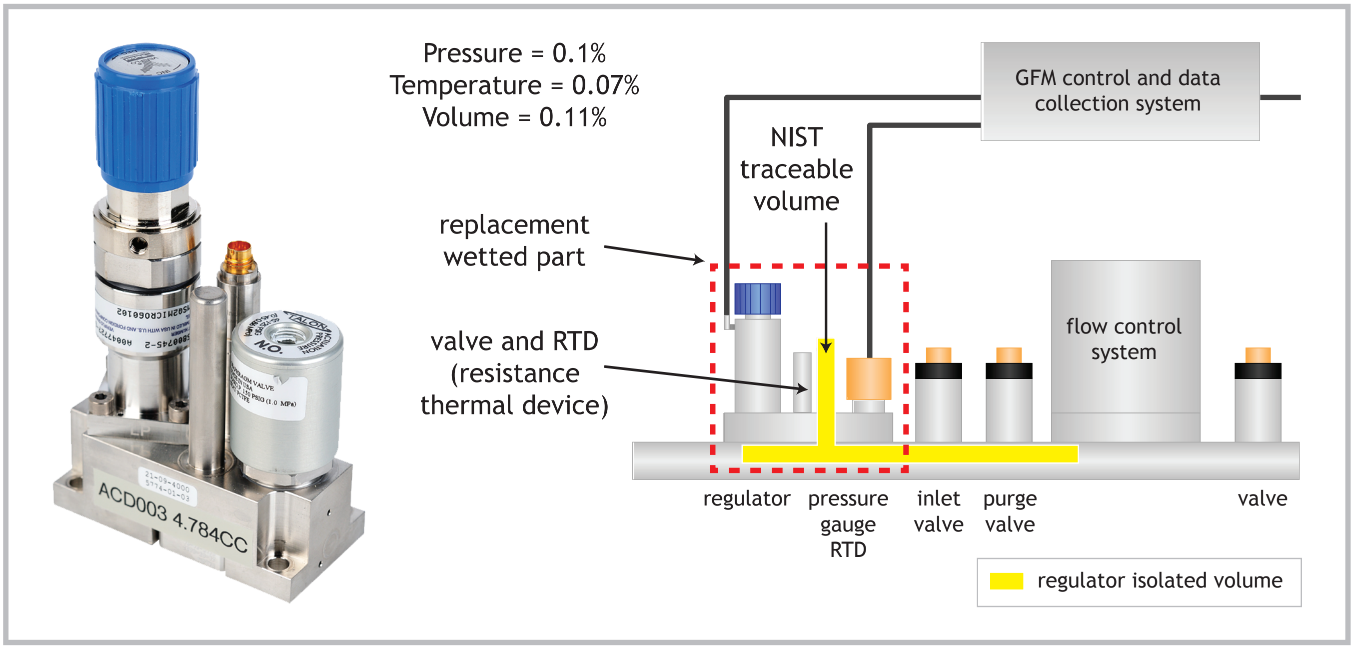
GFM Accuracy

In the case of GFM, accuracy is governed by the accuracy in the measurement of the individual constituent parameters in the first principles Ideal Gas Law equation above: P, T and V. Error in GFM measurement will thus be a root mean square error (RMSE) of the pressure, temperature and volume measurements. Accuracy as defined by this error is applicable only in the case of the GFM-800A product.

Pivotal uses the absolute calibration device (ACD) in the GFM-800A product to accurately calculate the isolated volume of the gas stick used in the pressure drop (see Figure 3). The ACD consists of a regulator, pressure transducer with RTD and a NIST traceable calibrated volume built onto a standard “two block” gas fitting. GFM uses the NIST calibrated volume (V_1) to calculate the total regulator isolated volume (V_2) using the derivative of the ideal gas law equation:

$$P_1V_1 = P_2V_2$$

Figure 3: Absolute Calibration Device Unit and Associated Gas Stick Volume



Hence, the error in the estimation of isolated volume is the error in the NIST traceable calibrated volume in the ACD. For the ACD used in GFM, the following are the errors in the individual parametric measurements.

GFM Precision

Precision in GFM is governed by the variability in the estimation of the slope of the pressure curve in Figure 1, which is the error in the ordinary least squares (OLS) estimate of the slope. OLS is a linear regression model of multiple observations, which in this case are the pressure measurements at different time instances. The linear regression model can be described by the following equation:

$$y_t = \beta_1 + \beta_2 t + u_t,\ t = 1,2, \ldots T_{SCW}$$

Where:

- t = time index
- T_{SCW} = slope calculation window
- y_t = pressure data
- u_t = system noise

OLS minimizes the sum of squared distances between the observed responses in the dataset, and the responses predicted by the linear approximation to estimate the slope. In case of the GFM, this regression analysis boils down to the following 3σ variability $\varepsilon_{precision}$:

$$(\varepsilon_{precision})^2 = 12 \bullet (1116 \bullet V \bullet \varepsilon_{pressure})^2 \bullet T_{sampling} \div (Flow^2 \bullet (T_{SCW})^3)$$

Where:

- $\varepsilon_{precision}$ = error in precision of GFM measurement
- V = volume of the gas stick
- $\varepsilon_{pressure}$ = error in pressure measurement
- $T_{sampling}$ = minimum time sampling interval
- Flow = gas flow
- T_{SCW} = slope calculation window

In case of the GFM-800 product, precision is the single metric of GFM performance given that accuracy is specified by the available calibration method used to calculate the isolated volume.

Error in GFM Measurement

Overall GFM measurement error is an RMSE of the individual parametric accuracy of pressure, volume, temperature and precision of GFM measurements. As such, overall GFM error is defined as:

$$(\varepsilon_{GFM})^2 = (\varepsilon_{pressure})^2 + (\varepsilon_{volume})^2 + (\varepsilon_{temperature})^2 + (\varepsilon_{precision})^2$$

GFM MEASUREMENT ERROR RESULTS

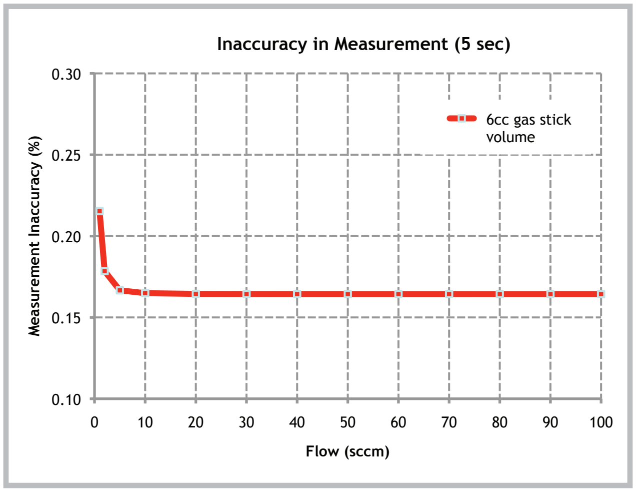
The error in GFM measurements is comprised of two parts: accuracy and precision (see Figure 2).

Accuracy is an indicator of the proximity of the measurement to the true value, while precision is defined as the repeatability (typically 3σ variability) of a particular measurement.

Steady-State Measurement Error

Figure 4 shows the GFM measurement error ε_{GFM} as a function of flow rate for a steady-state GFM measurement with a 5-second T_{SCW}. The $\varepsilon_{precision}$ tends to zero as the flow increases and even for small flows this value is fairly small. Hence, the GFM measurement error for steady-state measurements is predominantly governed by the accuracy of the individual parametric (pressure, volume and temperature).

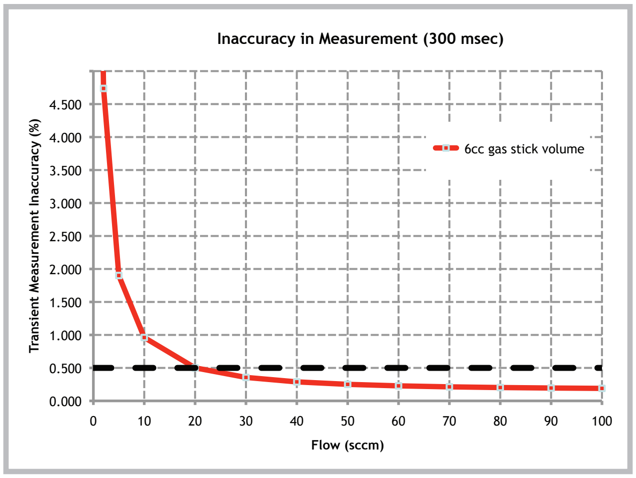
Figure 4: Steady-State GFM Measurement Error as a Function of Flow for a 6cc Gas Stick, 5sec Measurement Time



Transient Measurement Error

Figure 5 captures the GFM measurement error ε_{GFM} as a function of flow rate for a transient measurement using a 300-millisecond T_{SCW}. Here again, $\varepsilon_{precision}$ tends to zero as the flow increases. However, due to the short measurement duration for flow range between 20 to a few hundreds of sccm, $\varepsilon_{precision}$ has a higher inaccuracy than the errors in the individual parameters and hence governs the overall GFM accuracy more significantly.

Figure 5: Transient GFM Accuracy as Function of Flow for a 6cc Gas Stick, 300msec Measurement Time



Based on this information, Table 1 summarizes the GFM accuracy performance for these two GFM products.

Table 1: Summary of GFM Error for Steady-State and Transient Measurements Using GFM-800 and GFM-800A (With ACD)

Steady-State Measurement Error

	GFM-800	GFM-800A (With ACD)
Accuracy	N/A	0.17%
Precision	0.03	N/A

* For flows > 5 sccm, based on 6cc volume stick and a measurement duration of 5 sec.

Transient Measurement Error

	GFM-800	GFM-800A (With ACD)
Accuracy	N/A	0.5%
Precision	0.5%	N/A

* For flows > 20 sccm, based on 6cc volume stick and a measurement duration of 300 msec.

GFM is currently specified to have a measurement error that does not exceed ±0.5% of the actual flow for GFM-800A. For GFM-800, measurement error is specified to not exceed ±0.5% of the accuracy of the calibration method used to calculate the isolated GFM volume. Per Figure 6, while transient measurement error is ±0.5%, steady-state measurement error is far better at ±0.17%, and rivals some of the best industry-standard off-line methods such as molbloc (±0.2%) while providing the added benefits of providing gas flow measurements during wafer processing as well as real time MFC transient measurements.