Technical Article

A Primer on Gas Flow

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Abstract

The intent of this technical article is to assist those wishing to develop a basic understanding of the major gas flow measurement regimes, their associated measurement technologies, and the tradeoffs of each.

Introduction

Gas flow is the motion of a gaseous fluid. The motion of gaseous fluids can be quantified via several measurement regimes. The focus here will be on the mass flow and volumetric flow regimes. These regimes have both advantages and disadvantages. Hence, the most appropriate regime for a particular situation must be determined with a careful evaluation of the trade-offs present in each. These, trade-offs will be explained in this technical article.

Background

Compressibility

One very important point to convey before discussing the gas flow measurement regimes is that gaseous fluids are readily compressible. As such, their enclosed volumes are greatly affected by changes in pressure. A fundamental understanding of this point is a prerequisite to everything that follows.

Standard Temperature and Pressure

Standard temperature and pressure (STP) is terminology that is commonly used in the scientific community. This terminology is poorly chosen as it is inherently misleading. It would lead one to believe that there is a universal "standard" set of conditions. In fact, there are many commonly used STPs. Table I shows some of these. Some even choose to reference humidity in addition to temperature and pressure. The existence of so many reference conditions can confuse those interested in making flow unit conversions. STP should be more appropriately referred to as "reference conditions". This is the terminology that will be used hereafter.

Table I: Common reference conditions.

Temperature	Pressure	Relative Humidity	Publishing or establishing entity
0°C	100.000 kPa	–	IUPAC
0°C	101.325 kPa	–	IUPAC, NIST, ISO 10780, SEMI E12-0303
20°C	101.325 kPa	–	EPA, NIST
25°C	101.325 kPa	–	EPA
25°C	100.000 kPa	–	SATP
15°C	100.000 kPa	–	SPE
60°F	14.696 psia	–	SPE, U.S. OSHA, SCAQMD
60°F	14.73 psia	–	EGIA, OPEC, U.S. EIA
15°C	101.325 kPa	0%	ICAO's ISA, ISO 13443, EEA, EGIA
20°C	100.000 kPa	0%	CAGI
20°C	101.3 kPa	50%	ISO 5011
59°F	14.503 psia	78%	U.S. Army Standard Metro
59°F	14.696 psia	60%	ISO 2314, ISO 3977-2
70°F	29.92 in Hg	0%	AMCA

Control Systems

A basic understanding of control systems is necessary to fully comprehend some of the concepts discussed hereafter. A short reference on this topic, titled *A Primer on Control Systems*, is available www.restek.com.

Flow Regimes

While several gas flow regimes exist, the scope of this document is limited to discussing the 2 that are more commonly used, specifically mass flow and volumetric flow.

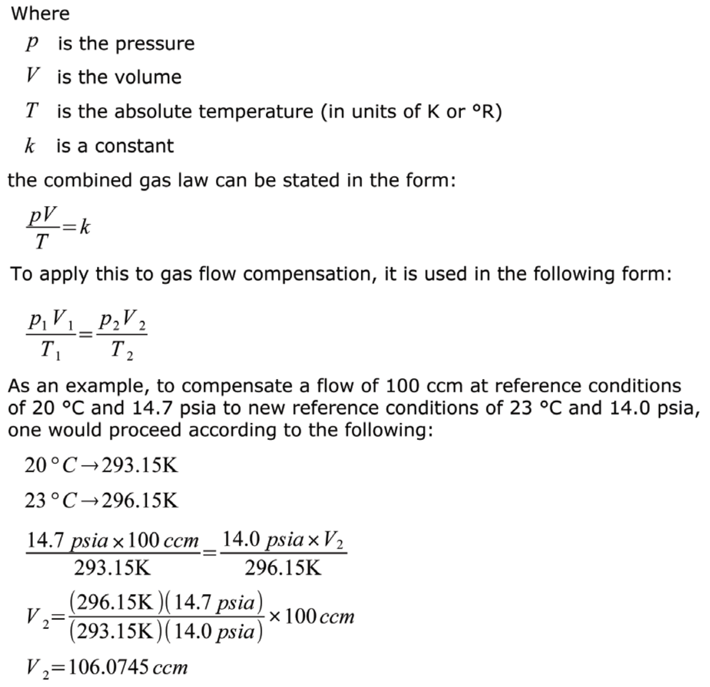
Mass Flow
Mass flow measurement deals with quantifying the movement of a gas relative to its mass over time. A fixed composition of gas has a mass that is constant regardless of changing environmental conditions. If a temperature and/or pressure change is introduced to a gaseous fluid flow, its mass flow will remain constant so long as the gas composition remains constant. Mass flow is useful for controlling chemical reactions where the number of molecules present is of importance. A process such as chemical vapor deposition, where gases are often heated, is dependent upon this. While temperature and pressure independency is often seen as an advantage of the mass flow measurement regime, the dependence of mass flow on gas composition can be a disadvantage. In order to measure mass flow, one must know the exact gas composition. Furthermore, the measurement instrument must be configured to use the particular gas composition. When changing gases, the measurement instrument must first be completely purged of the prior gas and a new gas composition selected before commencing new measurements. The successful measurement of mass flow rates for unknown, exotic, or custom mixed gas compositions can prove to be impractical, if not improbable.

Volumetric Flow
Volumetric flow measurement deals with quantifying the movement of a gas relative to its volume over time. An advantage to volumetric flow measurement is its nature of being independent from gas composition. A volumetric flow measurement can be successfully attained without any knowledge of gas composition. The primary disadvantage of the volumetric flow regime is its susceptibility to changes in temperature and pressure. Any change in either will result in a change in the volumetric flow rate.

Measurement

Native Measurements
A measurement in its purest form is a native measurement. A native volumetric flow measurement can only be achieved via a sensor that quantifies a volume of gas over time. If a sensor measures .005062 cubic feet of a gas over a 4.65 second time period, it measured a native volumetric flow of .001089 ft3/sec or 1850.223 ccm. Changing a unit does not constitute a non-native flow measurement because it involves a simple mathematical scaling.

Given that a rate of volumetric flow will change with changes in temperature and pressure, any volumetric flow rate with a known gas composition and known reference conditions can be compensated to a differing set of reference conditions. This compensation is easily approximated using the combined gas law. The combined gas law incorporates Boyle's law, Charles' law and Amonton's law. Alternatively, it can be derived from the ideal gas law by removing the components of Avogadro's law.



Where

p is the pressure
V is the volume
T is the absolute temperature (in units of K or °R)
k is a constant

the combined gas law can be stated in the form:

$$\frac{pV}{T}=k$$

To apply this to gas flow compensation, it is used in the following form:

$$\frac{p_1V_1}{T_1}=\frac{p_2V_2}{T_2}$$

As an example, to compensate a flow of 100 ccm at reference conditions of 20 °C and 14.7 psia to new reference conditions of 23 °C and 14.0 psia, one would proceed according to the following:

$$20\,°C\rightarrow 293.15\text{K}$$

$$23\,°C\rightarrow 296.15\text{K}$$

$$\frac{14.7\,psia\times 100\,ccm}{293.15\text{K}}=\frac{14.0\,psia\times V_2}{296.15\text{K}}$$

$$V_2=\frac{(296.15\text{K})(14.7\,psia)}{(293.15\text{K})(14.0\,psia)}\times 100\,ccm$$

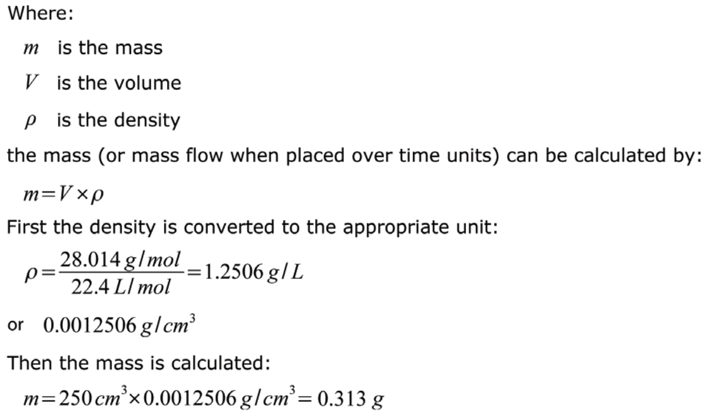
$$V_2=106.0745\,ccm$$

Derived Measurements
It's a common occurrence in industry to see mass flow measurements reported in sccm. A question that is often asked is:

"If milliliters per minute (mL/min.) is equivalent to cubic centimeters per minute (ccm) and they are both volumetric flow units, how is standard cubic centimeters per minute (sccm) a valid mass flow unit?"

This is fairly counterintuitive, and is it an example of a non-native or derived measurement. The sccm is a volumetrically based mass flow unit. It is generated by compensating a native volumetric flow measurement to a set of reference conditions. Using this "standardized" volume of gas, one can derive the actual associated mass by referencing the gas density (in the desired units) at the reference conditions. Over time, this quantifies the theoretical mass flow rate without physically measuring it via a sensor.

As an example, suppose a meter reports a mass flow of nitrogen (N_2) @ 250 sccm. The first important thing to determine is the reference conditions to which the meter manufacturer standardizes. Most meter manufacturers will standardize to reference conditions of 0 °C and 101.325 kPa since all gases have a volume of 22.4 L/mol at these conditions, which makes the determination of density at these conditions very convenient. If alternative reference conditions are used, a compensation to these reference conditions can first be performed as per the previous procedure. The next thing to determine is the density of N_2 at the reference conditions. The periodic table shows that the relative atomic mass of N is 14.007 g/mol; therefore, we can determine that the molecular weight of atmospheric N_2 is 28.014 g/mol.



Where:
m is the mass
V is the volume
ρ is the density

the mass (or mass flow when placed over time units) can be calculated by:

$$m = V \times \rho$$

First the density is converted to the appropriate unit:

$$\rho = \frac{28.014\, g/mol}{22.4\, L/mol} = 1.2506\, g/L$$

or $0.0012506\, g/cm^3$

Then the mass is calculated:

$$m = 250\, cm^3 \times 0.0012506\, g/cm^3 = 0.313\, g$$

Over units of time, this results in a rate of mass flow equivalent to the measured volumetric flow.

Loading

One of the most important concepts to understand in the volumetric regime is loading. Loading occurs when the act of trying to measure the flow induces a change in the flow. This has the most significant impact in open loop flow control systems. A couple of analogies can aid in the understanding of the loading concept. Perhaps the simplest to understand is an analogy in the temperature realm. Imagine trying to get an accurate temperature measurement of a cup of warm liquid using a thermometer that was stored in the freezer. When inserted into the liquid, the cold thermometer will remove heat from the warm liquid. When the temperature stabilizes, the water will have a temperature lower than that which existed prior to taking the measurement. Granted this is an exaggerated example, but it serves to illustrate the concept of loading.

Those familiar with the electrical realm will recognize this as the reason why ammeters are designed to have ultra low impedance. Otherwise, simply placing the meter inline would effect the electrical current being measured. Jumping back to the gas flow realm, the perfect gas flowmeter would present no impedance to gas flow, just as a perfect ammeter would present no impedance to current flow, or as the perfect thermometer would either have no thermal mass or be the exact same temperature as the fluid which it is measuring.

Illustrating loading with a few examples may help clarify the concept. These examples will utilize a rotameter for the open loop gas flow control system, and an orifice of decreasing size to present increasing loads to the system.

To start, a no-load flow of approximately 50 L/min. is set. This can be seen in Figure 1. This unloaded configuration contains no orifice and is limited only by the 0.180" inside diameter of the tubing connected to the exhaust port. Figure 2 shows the same configuration with a 0.093" orifice added to the exhaust port. No changes to the flow setpoint have been made. As a result, the flow has dropped to approximately 40 L/min. due to the increased loading of the system. To take this a step further, when the orifice is exchanged for one with a 0.051" diameter, the load on the system is significantly increased, which causes the flow to drop to about 15 L/min. as shown in Figure 3.

Figure 1: Base flow through rotameter (0.180″ ID tubing).

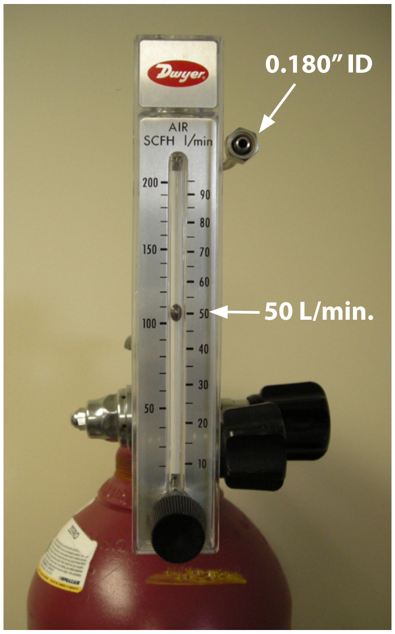


Figure 2: Decreased flow through rotameter when loaded with a 0.093″ ID orifice.

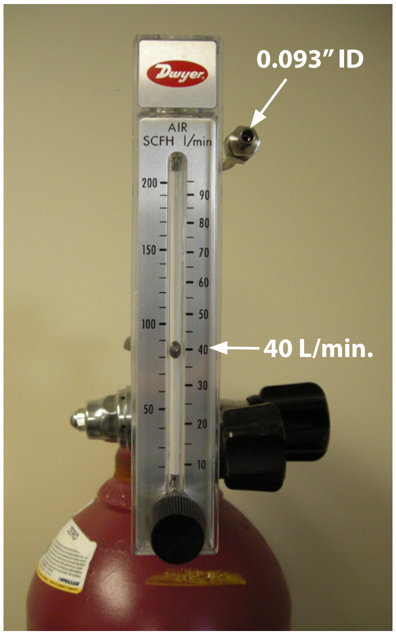
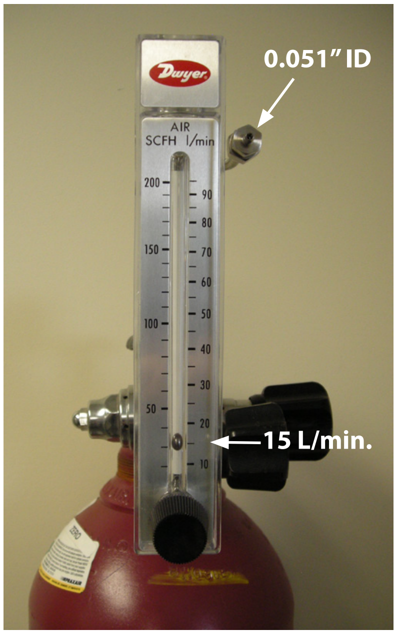


Figure 3: Further decreased flow through rotameter when loaded with a 0.051″ ID orifice.



The same reaction can be illustrated by using an actual flowmeter. This time a different flow scale will be used to show that the loading is not purely dependent on the overall rate of flow. Figure 4 shows a rotameter with a 0.109" diameter orifice on its exhaust port. This will be used as a hose nipple to ease connection to the flowmeter. The flow is set to 50 ccm as a baseline unloaded flow. When a Fluke (formerly DH Instruments) 50 sccm molbloc® laminar flow element is connected to the system as shown in Figure 5, the added load causes the flow to drop to 10 ccm.

Figure 4: Base flow through rotameter (0.109″ ID hose nipple).

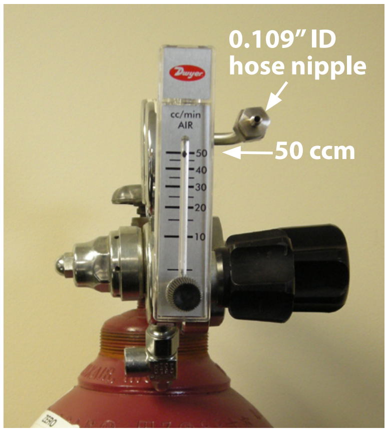
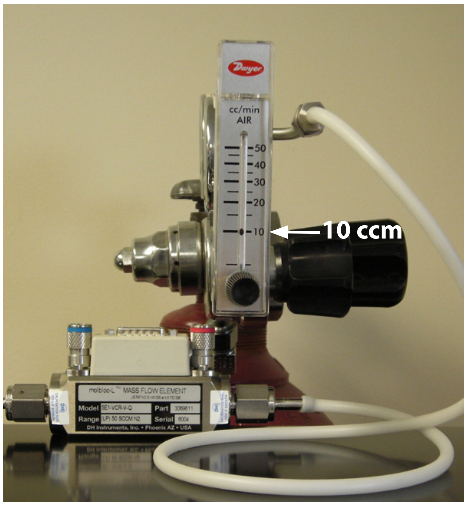


Figure 5: Decreased flow through rotameter loaded with a molbloc® gas flow standard.



This example shows that even the most accurate flow standards can load a system. In reality, all flowmeters have some degree of impedance to gas flow, however slight. The presence of this impedance means that the simple act of connecting a volumetric flowmeter to a gas stream will load the system, induce a pressure drop and hence, change the volumetric flow rate of the gas stream.

The source of this impedance is varied and its magnitude is dependent on the type and internal configuration of the individual measurement instruments. A few of these are detailed in Table II.

Table II: Sources of flow impedance for various flow measurement technologies.

Measurement Method	Examples	Source of Flow Impedance
volume displacement	bubble meter	liquid surface tension and glass tube friction
volume displacement	paddle wheel	friction of bearing / bushing system and inertia
volume displacement	balloon & timer	changing elastic tension
acoustic displacement	ProFLOW & ADM	orifice, valve closure, and diaphragm tension
laminar flow element	Alicat	flow path restriction
laminar flow element	MOLBLOC	flow path restriction and filtration frit

All of these measurement instruments have different internal mechanical configurations. When attached to a flow source, these configuration differences will load the flow source to differing magnitudes. Because the load is different for each meter, the change in the volumetric flow rate of the gas stream will also be different. For this reason, it is improper to directly compare the measurement outputs of volumetric flowmeters of different types and models.

A meter that loads the system more will cause a greater pressure drop and will result in a greater drop in flow. This phenomenon is independent of measurement accuracy. Case in point, the molbloc® system from Fluke is an exceptionally accurate, off-the-shelf flow measurement instrument. It is used by many (including National Institute of Standards and Technology [NIST]) as a flow calibration standard. The internal construction of the molbloc® is that of a laminar flow element. This design inherently causes a system loading that is substantially greater than most consumer flowmeters. As a result, it will also load a system more than most.

On the opposite end of the spectrum, is the age-old ubiquitous bubble meter. One of its finer attributes is that it presents a very low impedance to flow. Removing this type of meter from an open loop control system post measurement will result in a rather small change in flow.

Up until now, the focus has been on open loop flow control systems. One may start to wonder what relevance this has compared to closed loop flow control systems. Specifically, if the output flow, or process variable, is constantly sensed and adjusted in an attempt to drive it towards the desired setpoint, how is the loading of the source even relevant?

Figure 6: Absolute comparison of flow source response to various meter loads.

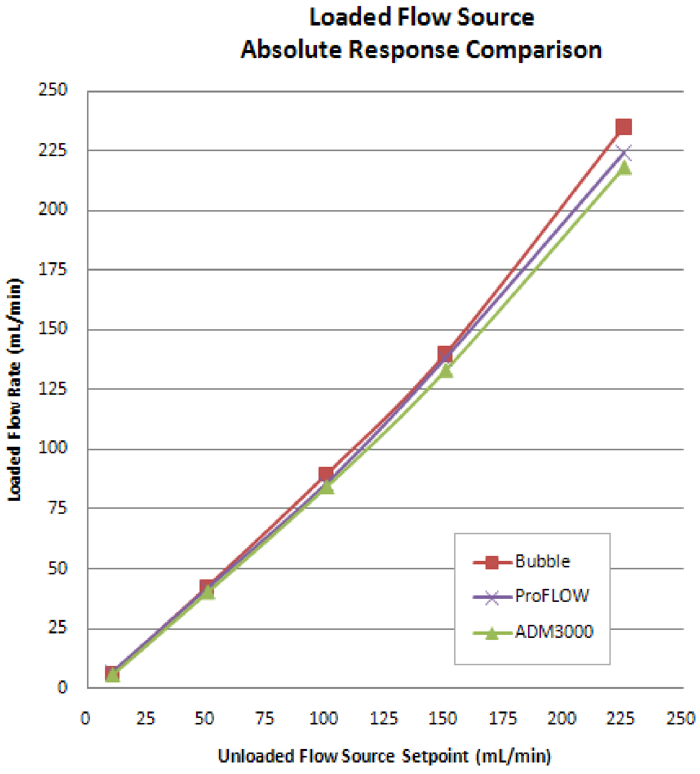
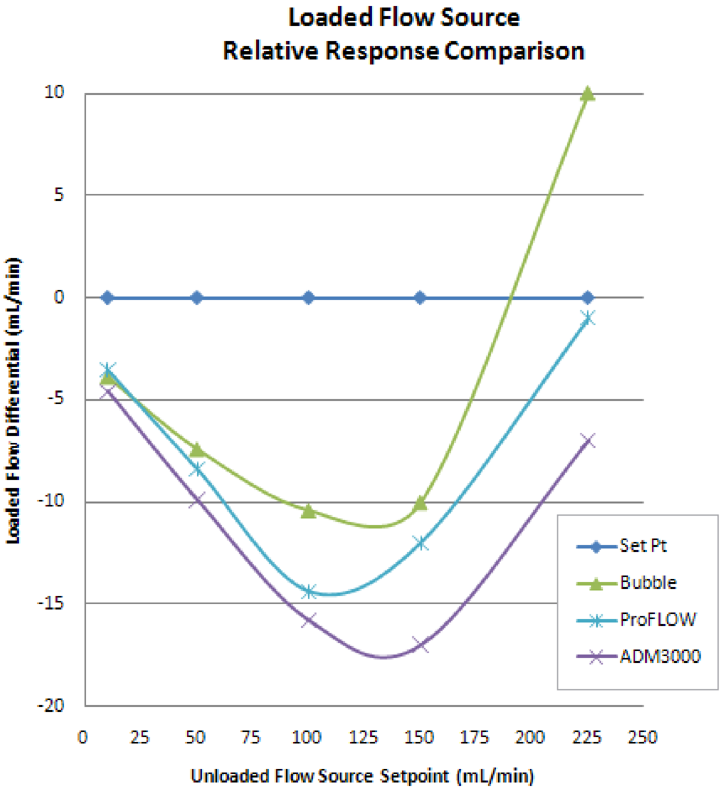


Figure 7: Relative comparison of flow source response to various meter loads.



That topic can be investigated by switching the flow source from a rotameter to a gas chromatograph (GC). Figure 6 shows the loading profiles for 3 different volumetric flowmeters on a GC. The graph shows each meter's relative loads by plotting their measurements against the GCs unloaded flow setpoint. Note that the flows tested are within the specified accurate ranges of all the meters used.

Perhaps a better way to visualize this relationship is to use a delta plot, which plots the differential of the meter's measurement from the GCs unloaded flow setpoint against that setpoint. Figure 7 shows this concept in practice.

When the same procedure is performed again on 6 different GCs, the resulting responses all differ. These responses are shown in Figure 8.

Upon examination of this data, two questions should come to mind. First, why is the relative response so different from one instrument to the next? Second, how can a loaded flow create a positive differential (i.e. a loaded flow that is greater than the unloaded flow)?

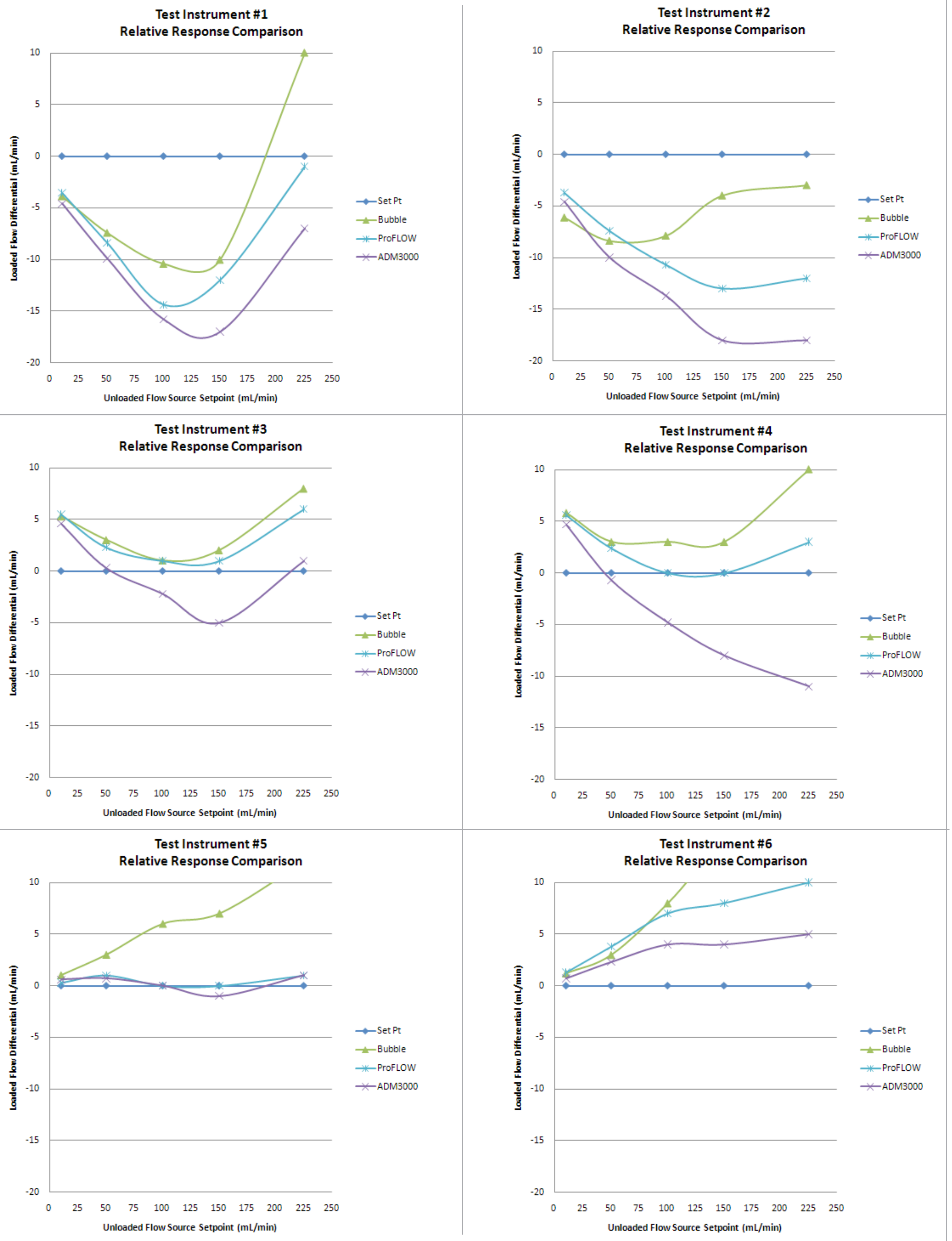
The answer to both of these questions lies in the fact that all of the systems tested use closed loop systems for controlling flow. There are many names for these systems such as electronic pneumatics control (EPC), advanced pressure/flow control (APC/AFC), electronic pneumatic module, digital inlet pneumatics, and many other naming variations. Regardless of the assigned moniker, they are all closed loop gas control systems.

As per any closed loop control system, each system has unique control parameters which must be tuned to the process. Adding a load to the process changes its dynamics and, hence, the control response. A system using control parameters that are not tuned to the system dynamics can develop a multitude of undesirable response characteristics. Overshoot, sluggish response, ringing, and steady state error are only a few.

Additionally, some GCs reference flow rates to normal temperature and pressure (NTP) or 25 °C and 1 atmosphere. This means that the flows displayed on the front of the GCs are only valid for the aforementioned reference conditions. The actual flow (which volumetric flowmeters display correctly) will differ based upon how much the present conditions vary from those reference conditions.

In closing, hopefully this has provided readers with a better basic understanding of measurement in the major gas flow regimes. As with most things, each regime has specific trade-offs. There is no universal rule for applicability of a certain regime to a situation. Users should carefully examine the advantages and pitfalls of each and utilize the regime that is most appropriate to their application.

Figure 8: Flow source responses of various instruments to different meter loads.



The instruments used for testing, in random order, are: Agilent 7890A, Shimadzu GC-2010, PerkinElmer Clarus® 600, Thermo Scientific Focus® GC, Thermo Scientific Trace GC, Thermo Scientific Trace GC Ultra.

Acknowledgements
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