# INTERACTIONS BETWEEN GAS FLOW MEASUREMENT INSTRUMENTS AND GAS FLOW SOURCES

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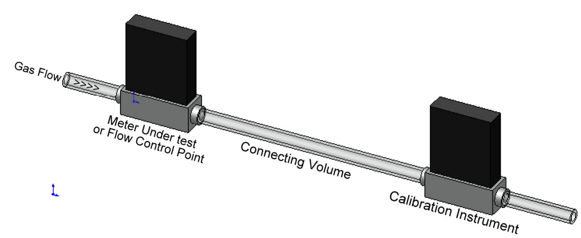
## I. ABSTRACT

The interconnections and procedures followed when using gas flow measurement instruments are critical to obtaining accurate flow measurements. Errors can be introduced from; interactions between flow sources and flow measurement instruments, interconnecting plumbing, thermal instabilities and pressure variations. The introduced uncertainties can be especially large when measuring gas flow in situ at industrial installations. Many end users have little knowledge or appreciation for these effects and as a result measurement errors are often introduced in gas flow measurements. In this paper, we report and quantify measurement errors when using a positive displacement piston prover to calibrate gas flow in industrial installations.

When flow measurements are taken, a temperature change or dynamic pressure change in the gas volume (connecting volume) between a flow source and the calibration instrument will cause a measurement error. We have previously studied typical well defined connecting volume errors in laboratory settings. Our field experience with industrial applications has found that connecting volume is often larger and more complex than the simplistic models previously investigated. Plumbing interconnections between a flow source and a flow measurement instrument in industrial applications often is a complex network of undefined volumes. We present the resulting uncertainty of gas flow measured with large connecting volumes similar to installations we have observed in industrial settings.

## II. INTRODUCTION

As a manufacturer of portable gas flow instruments, we encounter end-users with requirements for measuring gas flow rates in situ on industrial equipment. Unlike laboratory environments with well controlled and understood measurement uncertainty and interconnecting plumbing, in situ industrial measurements are often performed on systems with an unknown plumbing configuration in uncontrolled environments. Industrial installations often have interconnecting plumbing that introduces a large volume of gas between the point of flow control and the point of flow calibration. The gas volume between two flow measurement locations is called connecting volume. Typically in industrial applications, the first location is the gas flow control point and the second location is for the gas flow calibrator (Figure 1).




Fiqure 1 – Connecting Volume

If the gas temperature or the gas pressure changes in the connecting volume, the contained gas will expand or contract in response to this pressure or temperature change. The expanding or contracting gas will produce a net change in the flow between the two measurement points. Figure 2 shows a typical laboratory calibration with a small known volume of interconnecting tubing between the flow meter under test and the flow calibrator. Figure 3 is a representative photograph of a semiconductor gas panel with interconnecting plumbing of unknown volume.

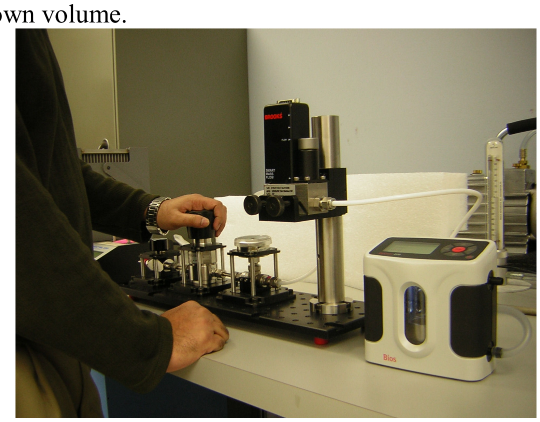


Figure 2

Figure 3

Gas flow from a meter under test (or from a flow control point) through a connecting volume and then through a calibration meter can be expressed by the law of conservation of mass as:

$$\dot{M}_{cal} = \dot{M}_{cv} + \dot{M}_{mut} \qquad (1)$$

where:

$\dot{M}_{cal}$ mass flow rate at the flow rate calibrator

$\dot{M}_{cv}$ mass change in the connecting volume during the measurement interval

$\dot{M}_{mut}$ mass flow rate at the meter under test

Ideally $\dot{M}_{cv}$ is equal to zero resulting in a flow rate at the measurement calibrator equal to the flow rate at the unit under test. Converting mass flow to a change in gas density for the given connecting volume during the measurement interval gives:

$$\dot{M}_{CV} = V_{cv}\left(\frac{\rho_i - \rho_f}{\Delta t}\right) \qquad (2)$$

where:

$V_{cv}$ connecting volume
$\rho_i$ initial gas density in connecting volume
$\rho_f$ final gas density in connecting volume
$\Delta t$ measurement interval

Reducing the connecting volume will proportionally reduce connecting volume measurement errors. Assuming an ideal gas, and uniform gas temperature and pressure through the connecting volume, the gas density in the connecting volume can be stated as:

$$\rho = \frac{P}{RT} \qquad (3)$$

where
$\rho$ gas density
$P$ gas pressure
$R$ gas constant
$T$ gas temperature

Gas density will increase with an increasing gas pressure and decrease with increasing temperature. Reducing pressure changes, temperature changes and connecting volume reduce measurement errors.

For our high-speed piston prover systems in laboratory installations connecting volume effects can be quantified and an uncertainty contribution of 0.031% to 0.010% has been reported [1]. Our piston provers are designed to minimize connecting volume effects by not measuring piston displacement until after the piston has been displaced a fixed distance prior to flow measurement initiation. This allows the pressure rise required to accelerate the piston to stabilize before flow measurements are taken.

Our piston provers feature a correction algorithm for gas density changes in the instruments known internal connecting volume from a pressure change [2]. By measuring gas pressure at the beginning and end of the measuring interval and assuming an ideal gas under isothermal conditions, a correction for the piston provers internal connecting volume can be derived as;

$$F_{cor} = F\left[\frac{P_2}{P_a} + \left(\frac{P_2 + P_1}{P_a}\right)\frac{V_{con}}{V_{mea}}\right] \qquad (4)$$

where:

Fcor flow corrected for connecting volume
F measured flow
P2 gas pressure at end of gas flow measurement interval
P1 gas pressure at beginning of flow measurement interval
Pa standardizing or ambient gas pressure
Vcon known connecting volume
Vmea known measured volume of gas

This correction only accounts for pressure changes in our instruments internal connecting volume. Due to the high-speed nature of our instruments, temperature variations in the connecting volume are typically small due to the short time interval of measurement. We also provide guidance for acceptable connecting volume that will not introduce significant measurement uncertainties. Typical acceptable connecting volumes are .03 to .3 liters for our instruments [3]. To understand what happens for situations that do not follow this guideline we investigated much larger connecting volumes of 2.9 liters and 9.8 liters installed between our equipment and a controlled flow source.

## III. CONNECTING VOLUME TIME CONSTANT

The large connecting volume in our test was placed between the flow source and the calibration meter. We also modeled this arrangement as being analogous to a simple electrical RC circuit with the gas volume representing a capacitance C and the calibration instrument as a resistance R. In this comparison, pressure is equivalent to voltage and current is equivalent to the gas flow rate. With a step change in flow, the calibration instrument recorded the expected exponential change in flow. From the exponential flow change a time constant tau ($\tau$) was calculated being equal to the product of flow resistance and the capacitance of the connecting volume. Figure 4 shows a step change in the flow of dry air entering a 9.8 liter connecting volume as measured by a laminar flow element. An exponential curve was fitted to the results and the resulting time constant Tau was calculated.

This same measurement was repeated using a connecting volume of 2.9 liters. Additional tests were done with a lower resistance 40 slm laminar flow element and a high- speed piston prover of even lower flow resistance. From these tests time constants in Figure 5 were calculated.

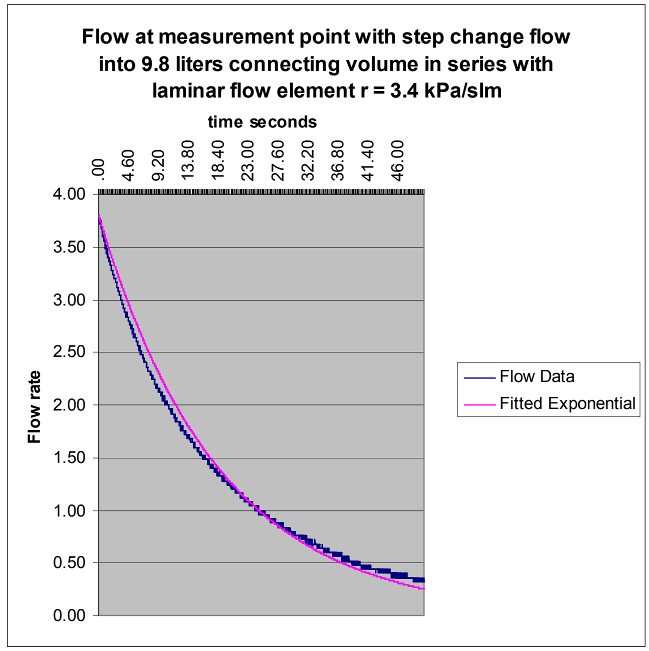



Figure 4

| | Connecting Volume (liters) | Calibration instrument Resistance (kPa)/SLM | Time Constant (seconds) |
|---|---|---|---|
| 10 SLM Laminar Flow Element | 2.7 | 3.5 | 29.1 |
| 40 SLM Laminar Flow Element | 2.7 | 22.6 | 5.7 |
| Piston Prover | 2.7 | 0.13 constant pressure | 0.23 |
| | | | |
| 10 SLM Laminar Flow Element | 9.8 | 3.5 | 84 |
| 40 SLM Laminar Flow Element | 9.8 | 22.6 | 17.6 |
| Piston Prover | 9.8 | 0.13 constant pressure | 1.3 |

Figure 5

As the time constant increases into tens of seconds, temperature effects begin to become significant in measurement uncertainties. At faster time constants temperature variations are less likely to cause measurement uncertainty. The laminar flow elements tested have high resistance to gas flow and result in long time constants. The piston prover tested has a low resistance to flow resulting in a fast time constant. However, the piston prover causes a pressure variation when initiating a reading [1, 2]. To prevent this pressure pulse from introducing measurement uncertainty, the piston prover uses a fixed acceleration distance before measuring the displacement of the piston. Under the fastest flow rate for a typical unit the time to displace the piston through this distance is on the order of 0.5 seconds. A connecting volume of 9.8 liters (30 times the recommended maximum amount) has a time constant of 1.3 seconds causing significant flow measurement errors. With the recommended connecting volume ten time constants pass before a reading is initiated. This fast time constant and the dynamic pressure pulse correction for internal instrument connecting volume has been found effective in minimizing connecting volume errors.

On industrial systems of unknown connecting volume, a diagnostic tool for estimating connecting volume would be to apply a step change in pressure at the measurement point and observe the flow response of the system. If the flow resistance of the calibration meter is known, the connecting volume can be estimated.

## IV. CONNECTING VOLUME, CONNECTED VIA TUBING

We also investigated connecting volumes not directly placed between the flow source and the calibration instrument. Some industrial sites have connecting volumes separated from the gas flow path with interconnected tubing. To simulate this, we connected a 9.8 liter volume of gas with 0.5 meter long 0.5cm inside diameter tubing; this was connected to a T connection located mid point on a 1 meter length of tubing between the flow source and the piston prover.

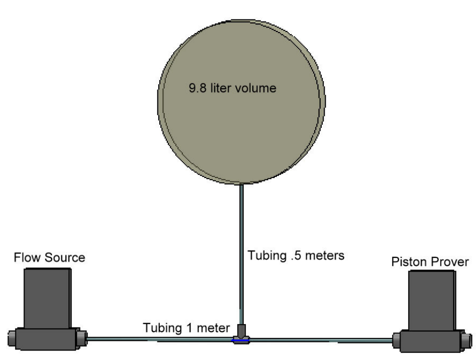



Figure 6

Using a step change in flow we recorded the gas flow change as observed at the piston prover. The flow change observed (Figure 7), was a fast change in flow as the gas density in the 1 meter section of 0.5 cm diameter tubing stabilized followed by the previously observed exponential decay of the large connecting volume.

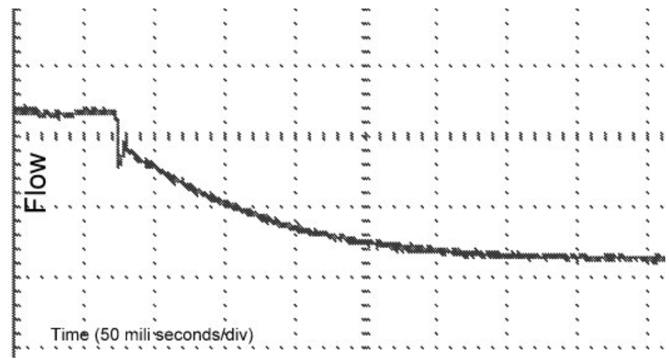



Figure 7

## V. TECHNIQUE TO ISOLATE CONNECTING VOLUME

We investigated ways to reduce connecting volume effects with our piston prover. The simplest method is to limit the maximum flow reading taken by our instruments by the ratio of the maximum recommended connecting volume to the actual connecting volume. For an instrument with a recommended maximum 0.3 liters of connecting volume, used with 0.6 liters of connecting volume, the maximum flow measured to maintain the stated instrument uncertainty is reduced by 50%. The reduced maximum measurable flow rate will delay measurement in the piston prover sufficiently for the time constant of the 0.6 liter connecting volume.

A second method we tested was inserting a commercial backpressure regulator in front of the measurement calibrator to provide a degree of pressure isolation. The commercial back pressure regulator was adjusted to provide a backpressure of approximately 4kpa between the connecting volume and the piston prover. The backpressure regulator provides some degree of isolation between the flow source and the piston prover, improving the piston provers ability to measure gas flow with previously unacceptable large connecting volume. Figure 8 shows the measurement deviation with connecting volumes of 2.9 liters and 9.8 liters with and without the back-pressure regulator inserted between the connecting volume and the flow calibrator. The backpressure regulator reduced the measurement error on the 9.8 liter connecting volume by 50%. On the smaller 2.9 liter connecting volume, the backpressure regulator was even more effective in reducing connecting volume effects.

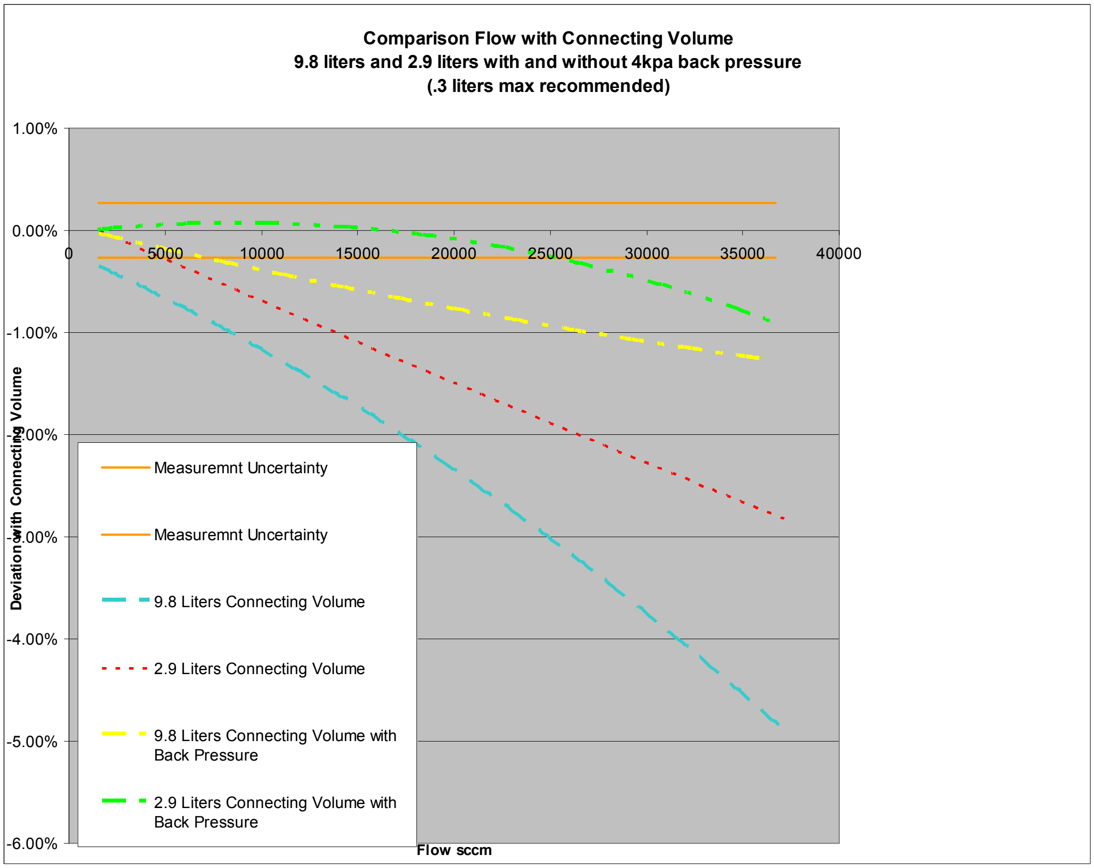



Figure 8

Investigations into the dynamics of back-pressure regulators may be productive in developing additional techniques to isolate pressure pulses. When measuring gas flow the current algorithm in our piston prover assumes the process is isothermal with a homogeneous pressure throughout the gas volume being measured. While in laboratory conditions this is a valid assumption, large connecting volumes result in additional pressure dynamics throughout the system. It may be possible to enhance our current pressure correction algorithm for internal connecting volume to include pressure and temperature changes in the total installed connecting volume. Improvements in monitoring the gas pressure and gas temperature during the measurement cycle may also be useful in improving the accuracy of the piston prover.

## VI. CONCLUSION

As a manufacturer of flow calibration equipment we educate end-users on how connecting volume can effect gas flow measurement. We also quantify the error introduced with very large connecting volume for customers that have no option but to accept measurement errors associated with large unavoidable connecting volumes. Further studies are ongoing to determine techniques to reduce connecting volume errors and develop instruments that minimize connecting volume effects. From our experience the use and connection means of gas flow measurement calibration equipment can be as important as the type of calibration equipment used.

### REFERENCES

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[2] H. Padden, "Development of a 0.2% high-speed dry piston prover", 2003 Measurement Science ConferenIK. Elissa, "Title of paper if known," unpublished.

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