HIGH ACCURACY
MASS FLOW VERIFIER (HA-MFV)

MASS FLOW VERIFICATION

There are only seven independent physical properties (mass, length, time, temperature, electric current, luminous intensity, and amount of substance) that can be measured in terms of fundamental physical units. Other physical and system properties (e.g., density, volume, pressure, concentration, etc.) must be measured in terms of these independent properties (e.g., density = mass/ length^3; volume = length^3; concentration = amount of substance/ length^3; gas flow rate = volume/time; etc.). Reference standards that have been measured in terms of the seven independent properties are available for many of these derived physical and system properties and these can be used to calibrate the accuracy and precision of local measurements.

Flow rate measurements, however, have no reference standards that can be used for the calibration of local measurements. Rather, primary flow calibration and verification must be accomplished through the collection of a measured mass or volume of the flowing fluid over a measured time interval, under conditions of steady flow and fluid properties (i.e., with measured conditions of e.g., temperature and pressure, that have been calibrated to fundamental reference standards). This is accomplished by collecting a measured volume or mass of flowing fluid under steady conditions of flow and fluid properties, with all measured quantities such as temperature and pressure referenced to established fundamental standards.

$$\mathbf{0} = \frac{\delta}{\delta t}\int_V \boldsymbol{\rho}\cdot d\boldsymbol{V} + \int_A \boldsymbol{\rho}\cdot\bar{\boldsymbol{v}}\cdot d\bar{\boldsymbol{A}} \qquad (1)$$

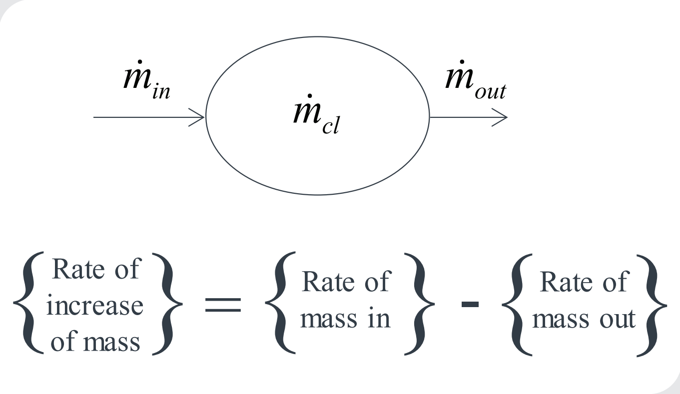

Figure 1. Primary flow verification.

Primary flow verification is based on simple conservation of mass in a controlled volume (Figure 1) where ρ is the fluid density, $\delta/\delta t$ is the partial derivative with respect to time, ν is the fluid velocity, $d\bar{A}$ is the unit vectoral surface area element normal to the control surface surrounding the control volume, and *V* is the stationary control volume for the mass balance (Equation 1). The conservation of mass can be conveniently expressed in terms of mass flow rate, *Q* using the Ideal Gas Law:

$$\boldsymbol{k}\cdot\frac{d\,(P\cdot V/T)}{dt} = \boldsymbol{Q}_{in} - \boldsymbol{Q}_{out} \qquad (2)$$

where *P* is the pressure and *T* the temperature in the control volume *V*, Q_{in} is the mass flow rate into the control volume, and Q_{out} is the mass flow rate out of that volume and *k* is a conversion constant.

There are currently three methods that use Equation (2) in a primary flow calibration standard: the Piston Prover; the Bell Prover; and the Constant Volume Prover.

Piston Prover

The piston prover is based on the measurement of the time interval required to collect a known volume of gas under standard conditions of temperature and pressure (typically near ambient). The measurement device (Figure 2) consists of a precision-bore glass tube in which a

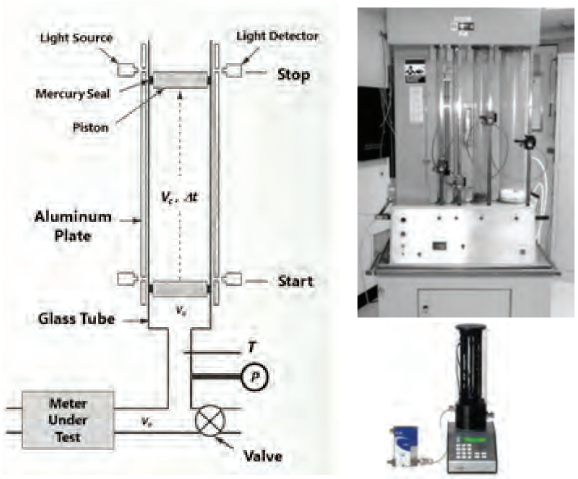

Figure 2. Schematic diagram and examples of a piston prover flow verification system.

plastic or ceramic piston of slightly smaller diameter is placed. The piston has a low-friction mercury seal to the interior surface of the glass tube. Piston prover measurements determine the time that is required to collect a known volume of gas in the glass tube. The piston prover is termed a "dynamic" system since the fluid collection is initiated and terminated by the moving piston blocking light beams that determine the beginning and end of the measurement. Prior to a calibration measurement, flow from the meter being calibrated is first established through the approach piping and a bypass valve. The bypass valve is initially opened, and the piston is at the start position. All flow is diverted into the bypass line. The valve is then closed to divert all flow to the measurement cylinder, causing the piston to rise into the collection volume. As soon as the piston reaches the stop position, the bypass valve is switched to the open position allowing flow to divert to the bypass line again and the piston to drop to its starting position. During flow measurement, the bypass valve is completely closed and the time between the passage of the piston between the start and stop light beams is determined. Gas temperature and pressure are measured over the gas collection period and averaged. Normally, multiple repeats of the above measurement are required for a calibration.

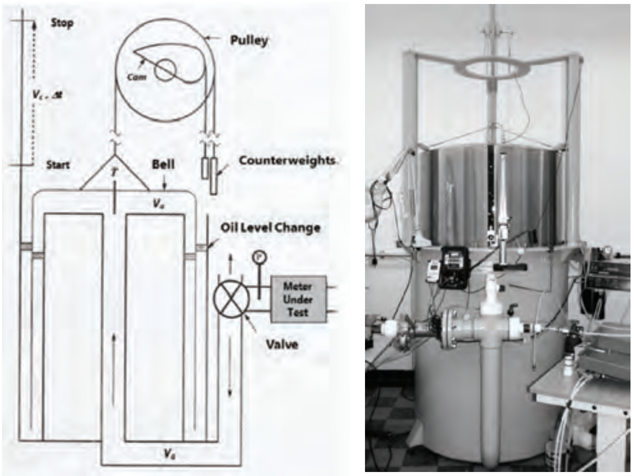

Figure 3. The bell prover, schematic and actual.

Bell Prover

The bell prover system is based on the same principle as the piston prover but is configured for high flow calibrations. The bell prover employs a cylindrical tank that is open at the top and has a cylindrical "dry well" in the center. Together, the tank and well form an annulus and this annulus is nearly filled with sealing oil (Figure 3). An inverted bell, open at the bottom with a dome-shaped top, is lowered into the annulus as shown in Figure 3. The weight of the bell is nearly balanced by counterweights so that a small (0.3 kPa) differential pressure can raise or lower the bell, allowing it to collect and measure a volume of gas. The cam with associated counterweight that is shown in Figure 3 corrects for buoyancy effects changes due to different immersion levels of the bell.

Constant Volume Prover

Constant volume systems fill a precisely known volume while monitoring pressure and temperature. There are two types of constant volume provers – Pressure, Volume, Temperature, and time (PVTt) provers and Rate-of-Rise (RoR) provers.

The PVTt prover in use at the National Institute for Standards and Technology (NIST) (Figure 4b and c) is useful for demonstrating how constant volume provers

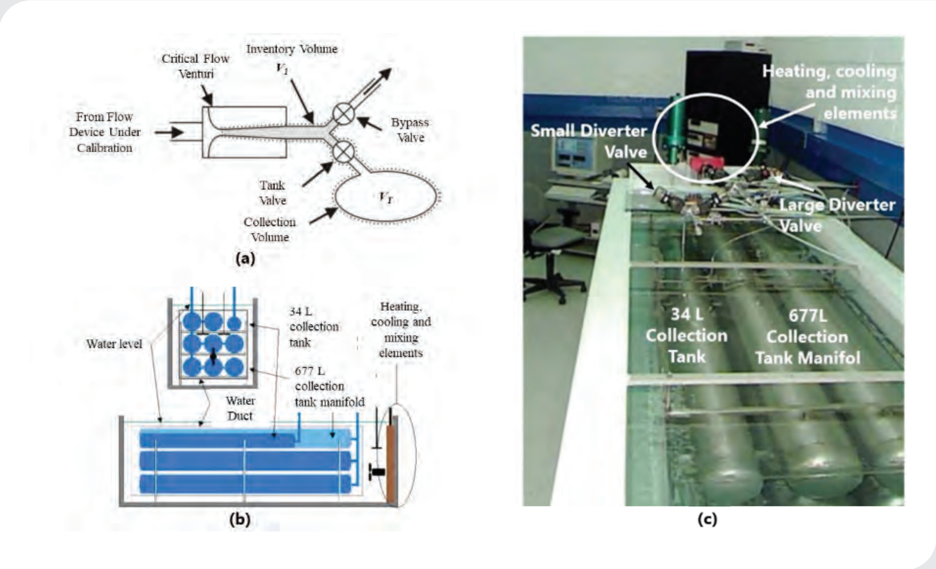

Figure 4. The NIST PVTt constant volume prover.

work. This system consists of a flow device under test, valves for diverting the flow, a collection tank of precisely known volume, a vacuum pump, pressure and temperature sensors, and a critical flow venturi that isolates the meter under test from pressure variations downstream (Figure 4a). During flow rate calibration, the collection volume, V_T, is first evacuated and initial conditions of pressure and temperature in the tank are determined. These values are used to determine the residual mass of gas in the collection volume. Similarly, pressure and temperature are recorded for the inventory volume, V_I, to determine the residual mass of gas in that part of the apparatus. Then the collection volume is filled to a pressure of about 1 bar while the time for the filling process is precisely measured. The initial and final densities of the collected gas are calculated from the P/T data and combined with the known collection volume, are used to determine the mass of the gas collected over the collection time. The PVTt method, by measuring stable states at the beginning and end of a measurement period, reduces dynamic errors. This equipment and approach allow NIST to determine flow rates with an uncertainty of less than 0.025% (95% confidence level) for flows up to 2000 L/min.

Rate-of-Rise (RoR) measurements are determined using a constant volume apparatus similar to PVTt equipment. In RoR measurements, multiple determinations of the pressure and temperature in the collection volume are obtained during the filling procedure. Using this data, RoR flow rate calibrations infer dynamic flow from the same state equations as PVTt methods.

MASS FLOW CONTROL VERIFICATION SYSTEM

Figure 5. High Accuracy Mass Flow Verifier

MKS Instruments has developed the High Accuracy Mass Flow Verifier (HA-MFV), a high accuracy, pressure Rate-of-Rise flow verification system that can be used on process tools to verify mass flow control flow rates in-situ (Figure 5). It combines RoR and PVTt technologies to provide significantly improved accuracy of flow verification. It can verify MFC flow with the actual process gas significantly better than older rate-of-rise devices or process chamber rate-of rise methods.

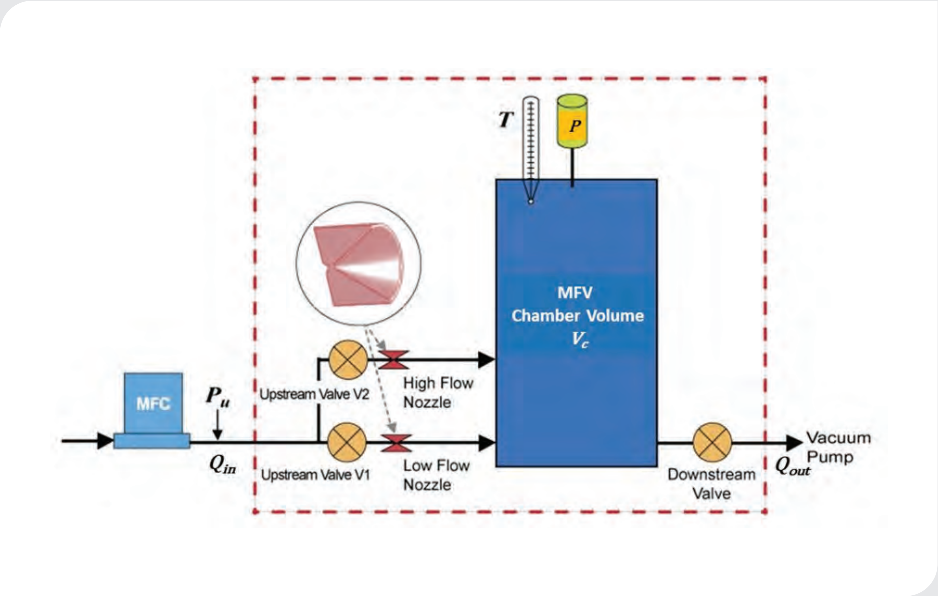

Figure 6. Block diagram of MKS Instruments' High Accuracy Mass Flow Verifier (HA-MFV).

Based on pressure and temperature measurements, the HA-MFV can be used for flow verification of multiple gas types. It is insensitive to external volume conditions (the volume between the MFC and the HA-MFV) which ensures more precise matching of HA-MFV measurements on multiple tools and improved tool-to-tool process matching. The HA-MFV is designed for use on process tools to verify mass flow control rates between 0.1 and 3000 sccm in situ to a measurement accuracy of 1% of Reading, measurement repeatability of 0.1% of Reading, and measurement reproducibility of 0.4% of Reading. It supports multiple process gas panels and has available EtherCAT® or DeviceNet™ communications capabilities.

Figure 6 shows a block diagram of the HA-MFV. At the start of an MFC calibration cycle, the system is first evacuated and both the upstream and the downstream valves are opened. A flow set point is issued to the MFC, and a steady state gas flow is established into the MFV chamber volume. In the next step, the downstream valve is closed. Pressure and temperature data in the MFV chamber volume are continuously measured and recorded as the pressure rises in the volume V_C. As soon as the pressure reaches a target value, the downstream valve is opened for evacuation of the MFV volume and a single cycle of flow verification is finished.

Multiple-cycle flow verifications can be done by simply closing the downstream valve again. In the final step of the calibration procedure, a zero setpoint is issued to the MFC and the system is completely evacuated for the next test. The flow rate of gas through the MFC under calibration is determined using the RoR equation for gas flow:

$$Q = V_C \cdot \frac{d}{dt}\left(\frac{P}{T}\right) \tag{3}$$

Figure 7 shows a graph of the pressure rise in the MFV chamber during a single cycle in an MFC calibration, along with the calculated gas flow rate through the MFC in test.

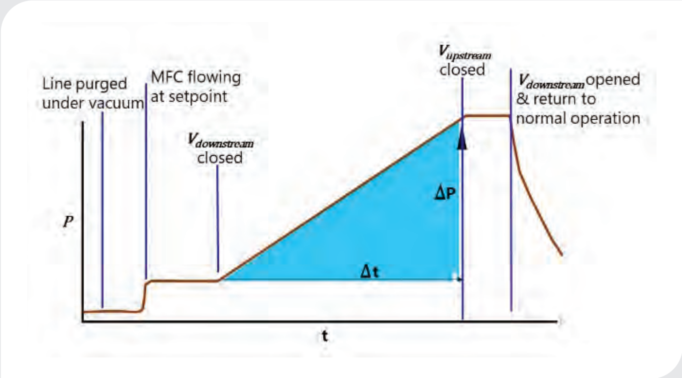

Figure 7. Rate-of-Rise (RoR) single-cycle flow rate verification.

A key attribute of the HA-MFV is the fact that it is insensitive to the external volume upstream of the MFV. The HA-MFV's External Volume Insensitivity (EVI) technology is achieved by maintaining the upstream sonic nozzles (shown in Figure 6) in a critical flow condition during the entire measurement cycle. Under these conditions, the internal HA-MFV pressure remains below the critical flow limit and the linear rise in pressure within the MFV is not sensed by the MFC, resulting in a minimum downstream pressure disturbance to the steady-state MFC performance. Measurements using the HA-MFV are performed as a sequence of short-duration rate-of-rise determinations over which the instantaneous flow rate is calculated and averaged as shown in Figure 8. Since EVI technology eliminates the effect of any variations in the external volume between the MFC and the MFV on an MFC calibration, the HA-MFV can be integrated into a process gas panel and used to verify the calibration of multiple MFCs that have varying distances to the MFV.

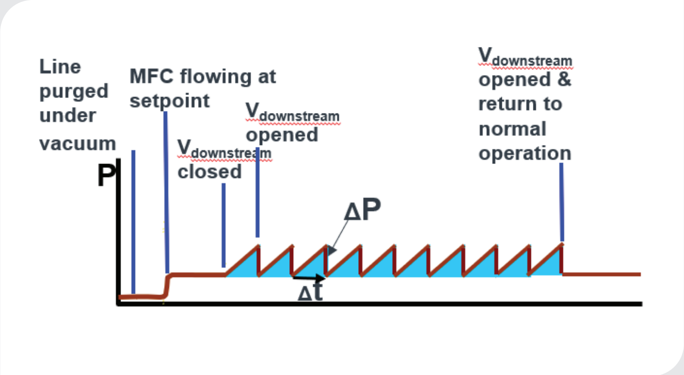

Figure 8. High Accuracy Mass Flow Verifier (HA-MFV) multiple-cycle flow rate verification.

CONCLUSION

MKS Instruments' HA-MFV mass flow verification system provides high speed, high accuracy gas flow rate calibrations to match the high accuracy of modern MFCs. The HA-MFV's multi-gas capability and wide measurement range make it ideal for use with process gas panels having a variety of gas control circuits. MKS' breakthrough EVI technology is used by the HA-MFV to produce high accuracy flow rate measurements that are independent of the placement of the instrument in the gas control system. This allows a single verifier to be used for the calibration multiple MFCs and multiple gas panels, making the HA-MFV the most cost-effective means for gas flow rate verification available today.

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