Achieving accurate gas flowmeter calibration

Positive displacement methods combined with computer control provide new primary standards.

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The calibration of gas flowmeters and/or flow controllers is one of those important, inescapable tasks that can be something of a nuisance to the engineer responsible for getting the job done. Sending flowmeters back to the manufacturer for recalibration can be expensive and cause production delays. For this reason, most big users of flowmeters opt for in-house calibration. This approach is often best—that is, as long as the user makes the required investment in the equipment needed to do the job the right way. Make-do calibration setups can waste a lot of time, only to produce inaccurate results. Such practices often lead to a degradation of process quality, excessive downtime, and increased labor costs coupled with reduced productivity.

This article describes gas calibration methods that have the highest accuracy potential—specifically, those based on the positive displacement principle. In each approach, the calibration gas displaces a measured volume over a measured elapsed time, $t_2 - t_1$. The displaced volume V is divided by the elapsed time to obtain Q, the volumetric flow rate—i.e., $Q = V/(t_2 - t_1)$. The gas mass flow rate, m, is obtained by simply multiplying the volumetric flow rate by the density ρ of the calibration gas—i.e., $m = \rho Q$.

Usually the mass flow rate of gases is expressed as the volumetric flow rate Q_s, referred to standard conditions (typically, 0°C and 1 atmosphere). In this article, we'll express the mass flow rate as $Q_s = (\rho/\rho_s)\ [V/(t_2 - t_1)]$, where the subscript s refers to standard conditions. For perfect gases this becomes:

$$Q_s = P/P_s \times T_s/T \times V/(t_2 - t_1) \qquad (1)$$

where P and T are the actual measured pressure and temperature of the calibration gas, and P_s and T_s are the standard pressure and temperature, respectively.

Because the positive displacement method of flow calibration is based on standard measurements of length and time, it is considered a primary standard by the National Bureau of Standards. Flow calibration using this technique should carry documentation of traceability to NBS.

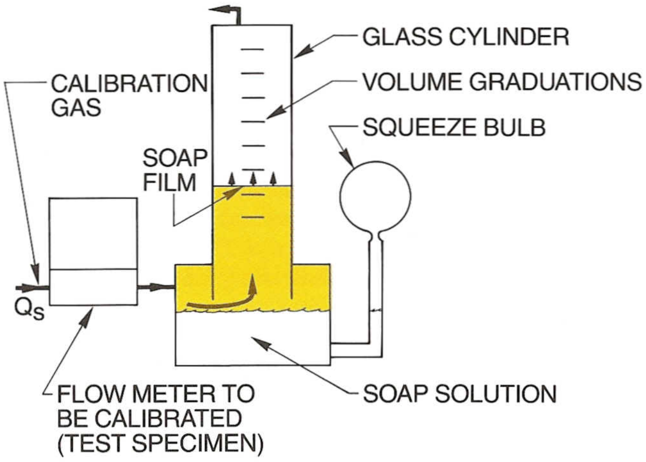
The practical flow rate range of all positive displacement methods is approximately 1 to 3,000,000 sccm. Accuracies from 0.2 to 5% of reading are typical, depending on the calibration equipment used. Flows higher than 3,000,000 sccm usually are calibrated with flow transfer standards, such as precision orifice plates, venturi meters, large laminar flow elements, or thermal mass flowmeters. The only other limitation of positive displacement methods is that they do not measure the instantaneous flow rate. This is because you must wait until the displaced volume is measured with sufficient resolution. However, this drawback has been overcome in today's computerized calibration equipment.

Three common positive displacement methods are bubble meters, bell provers, and piston meters. Of these, the piston meter is the most accurate. There are three versions in use: manual, semiautomatic, and computer-controlled.

Bubble meters

Figure 1 shows a schematic of a typical bubble meter, the

Fig. 1: The simplest form of a positive displacement flow calibrator is this bubble meter.



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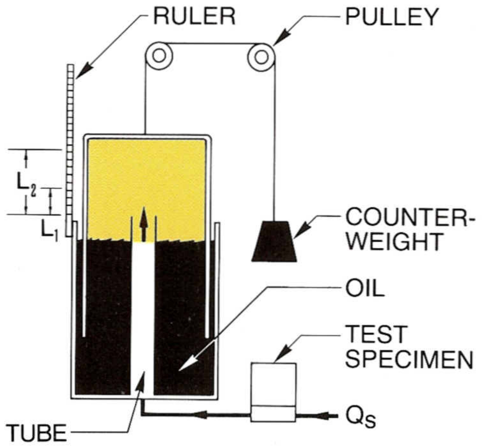


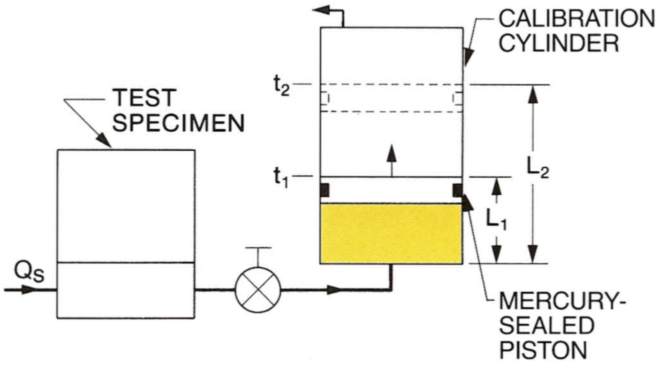


Fig. 2 (left): The bell prover shown here handles flow rates of 20,000 to 3,000,000 sccm.

Fig. 3 (above): Typical accuracy of the manual piston meter is 0.5 to 1.5% of the reading.

simplest version of a positive displacement gas flow calibrator. In this device, the bulb is squeezed, raising the soap solution to the cylinder's entrance where a soap film is created. The bulb is then released and the soap solution drops to expose the cylinder entrance. The calibration gas entering the volume-graduated cylinder forces the soap film to rise. The operator uses a stop watch to time the ascent of the film as it passes the volume graduations. The difference in volume V divided by the elapsed time $t_2 - t_1$ is the volumetric flow rate. The pressure of the calibration gas is the local ambient (barometric) pressure P_a corrected for the partial pressure P_{wv} of the water vapor that evaporated from the soap solution. Referring to Equation (1), we find that the mass flow rate of the calibration gas is:

$$Q_s = (P_a - P_{wv})/P_s \times T_s/T \times V/(t_2 - t_1) \qquad (2)$$

If the water vapor is fully saturated and the calibration gas is air, P_{wv} is easily found from psychrometric tables. At typical room temperatures, the P_{wv} correction is about 3%, not an insignificant quantity. If the calibration gas is not air, or if the water vapor is not completely saturated in the calibration gas, as in the case of higher flow rates, the P_{wv} correction may be unknown. Another source of inaccuracy with bubble meters is the possible waving of the soap film as it ascends and the presence of small bubbles at the film/cylinder interface, both of which degrade reading resolution. Bubble meters have been semiautomated by locating photodiodes at two heights on the cylinder to detect the film as it passes by, thereby automatically starting and stopping a digital clock to measure the elapsed time, $t_2 - t_1$. The typical range of bubble meters is 1 to 30,000 sccm, and their accuracy is 2 to 5% of reading.

Bell prover

Bell provers are used for higher flow rates than can be handled with a bubble meter, roughly 20,000 to 3,000,000 sccm (Fig. 2). Gas flows into a cylindrical bell which is usually sealed with a low vapor-pressure oil. The bell's distance of ascent is measured with a rule along its side. The distance the bell travels, $L_2 - L_1$, times its cross-sectional area A, is the volume displaced. The elapsed time $t_2 - t_1$ is measured with a stop watch. From Equation (1), the bell prover's expression for mass flow rate is:

$$Q_s = P/P_s \times T_s/T \times (L_2 - L_1)A/(t_2 - t_1) \qquad (3)$$

Bell provers have a typical accuracy of 1 to 2% of reading.

The manual piston meter

A piston meter, shown in Fig. 3, is similar to the bubble meter and bell prover, but the sealing is done with mercury. In the manual piston meter, the calibration gas issues from its source, passes through the meter under test, and enters one of several precision-bore borosilicate glass cylinders. Each cylinder has a low friction mercury-sealed piston, usually constructed of PVC. As the gas enters the cylinder, the piston rises, and its rise $L_2 - L_1$ is measured with a precision rule along the side of the cylinder. The elapsed time $t_2 - t_1$ is measured with a stop watch. The diameter, and therefore the cross-sectional area A of the cylinder, is known precisely. Thus, the vertical distance swept away by the piston in the measured period of time is the volumetric displacement over that time period. Based on Equation (1), the mass flow rate of the calibration gas is:

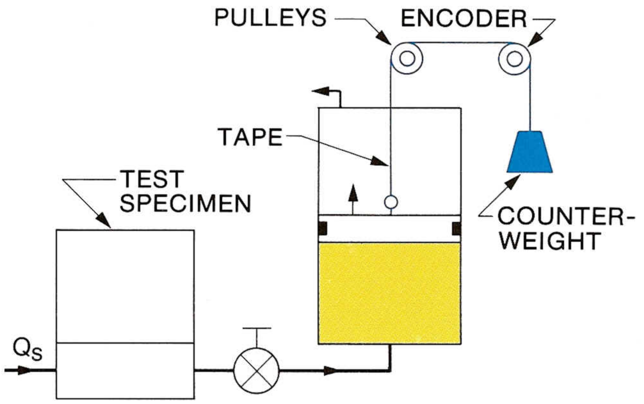
$$Q_s = P/P_s \times T_s/T \times (L_2 - L_1)A/(t_2 - t_1) \qquad (4)$$

which is the same as the bell prover.

In piston meters, as many as seven calibration cylinders can be deployed to cover a flow range of 1 to 30,000 sccm. Because of the human errors associated with hand-eye coordination in stop watch use, and with visualization errors associated with peering at the piston through the glass cylinder, the piston must travel a long distance to get a sufficiently accurate reading. Thus, the time needed for measurement can be excessive. In addition, this method assumes that the flow rate is constant during this time period, which may not be the case. The manual piston meter has the potential for an exceptionally high accuracy approaching 0.2% of reading, but the manual nature of its operation yields a practical accuracy of about 0.5% to 1.5% of reading.

Semiautomated piston meters

The manual piston meter shown in Fig. 3 has been semiautomated by installing photodiodes at the top and bottom of each cylinder. When the piston passes the bottom photodiode, a digital clock starts; when it passes the top photodiode, the clock is stopped. This eliminates the potential for human errors and measures elapsed time with high accuracy. However, it still requires long test times. In addition, resolution of the triggering of the photodiodes is sometimes impaired due to light reflections from the mercury seal,



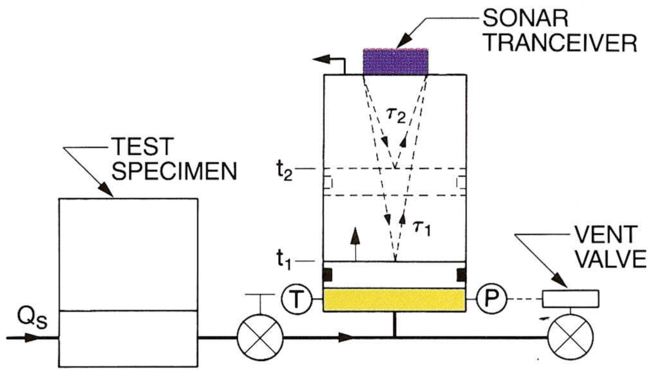


Fig. 4 (left): A semi-automatic piston meter has an accuracy of 0.2% of reading.

Fig. 5 (above): Operation of an automatic piston meter is computerized.

false triggering from ambient light, and to the inability to precisely measure the actual trip points.

Another semiautomatic piston meter is shown in Fig. 4. In this device, the distance of the piston's ascent is measured with an encoder mounted to the shaft of one of two pulleys. The encoder generates pulses equivalent to increments of displaced volume. The total displaced volume is expressed as $V = C/K$, where C is the total number of counts and K is a calibration constant expressed as counts per ccm. The elapsed time $t_2 - t_1$ is the total time to accumulate C counts. Based on Equation (1), the mass flow rate is expressed as:

$$Q_s = P/P_s \times T_s/T \times C/K(t_2 - t_1) \qquad (5)$$

In operation, the operator activates start and stop switches, and the elapsed time is measured with a precision digital clock. After the measurement, the total count and elapsed time are entered into a preprogrammed hand calculator to obtain the mass flow rate. In a semiautomatic mode of operation, the elapsed time corresponding to a precalculated flow rate is displayed and rapidly updated to allow adjustment of the flow to a preselected value. Two 0.6 meter high cylinders are used to cover a 20 to 50,000 sccm flow range. The stated accuracy of this type of semiautomatic piston meter is 0.2% of reading.

Automatic computer-controlled piston meter

Figure 5 shows a newer development in positive displacement gas flow calibrators. Its operation is completely automatic and computerized. Each cylinder has a sonar transceiver that continuously senses the distance of the piston's vertical ascent. The height of the piston so measured is $a\tau/2$, where a is the speed of the high frequency sound wave in the air above the piston, and τ is its total transmission time measured with high precision by the transceiver. The time of ascent is measured by means of a quartz crystal time base with a resolution of 0.000001 seconds. The distance the piston travels in the elapsed time $t_2 - t_1$ is $(a/2)\ (\tau_1 - \tau_2)$. The basic equation for mass flow rate therefore is:

$$Q_s = P/P_s \times T_s/T \times (a/2)(\tau_1 - \tau_2)A/(t_2 - t_1) \qquad (6)$$

Figure 6 shows a completely automated computerized system. Three one meter high cylinders, each with its own sonar transceiver, facilitate gas flow calibration over the range of 1 to 30,000 sccm. With a slight degradation in accuracy, the upper range can be extended to 50,000 sccm. An IBM PC or compatible computer controls the system, and a printer provides a hard copy of all data.

The temperature T of the calibration gas is measured by a precision RTD to within ±0.1°C. The gas pressure is $P = P_a + P_b$, where P_a is the local ambient pressure measured with a precision barometer to within ±0.2 mm of mercury, and P_b is the measured back pressure under the piston. The computer automatically corrects for P_b. The cross-sectional area for the cylinder selected is $A = (\pi/4)D^2$, where D is the cylinder's diameter. The computer calculates the speed of sound using the following expression:

$$a = \sqrt{\gamma R g_c T_r}$$

where γ is the ratio of specific heats for the mixture of air and any small amount of water vapor in the room air; R is the universal gas constant for the air/water-vapor mixture; g_c is the local gravitational constant; and T_r is the local room temperature measured with a precision RTD to within ±0.1°C. The values of γ and R for the air/water vapor mixture are determined by measuring the relative humidity ϕ of the room to within 1%. At the beginning of a calibration run, the operator enters T, P_a, P_b, T_r, and ϕ into the computer, which then makes the required calculations.

The software assists the operator with data entry via screen prompting. Operation modes include calibrating for a single gas or gas mixtures (basic mode); automatically generating a preselected mass flow rate by using a high resolution servo-controlled electromagnetic valve in series with the test specimen (generate mode); making final calibration quality control checks; testing the time response of flowmeters or flow controllers; and verifying the transceiver's distance measuring calibration with manual length standards. The system calculates mass flow rates in a few seconds, allowing quick adjustment to the desired volume, either manually by adjusting a valve or automatically via a computer controlled servo valve. A typical five point calibration is completed in 15 minutes and yields an overall maximum system accuracy of 0.2% of reading for all three cylinders.

About the authors

Dr. John G. Olin received his Ph.D. degree in mechanical engineering from Stanford University, majoring in fluid mechanics. He holds eight patents and has published more than twenty-five papers in the field. Dr. Olin is the founder

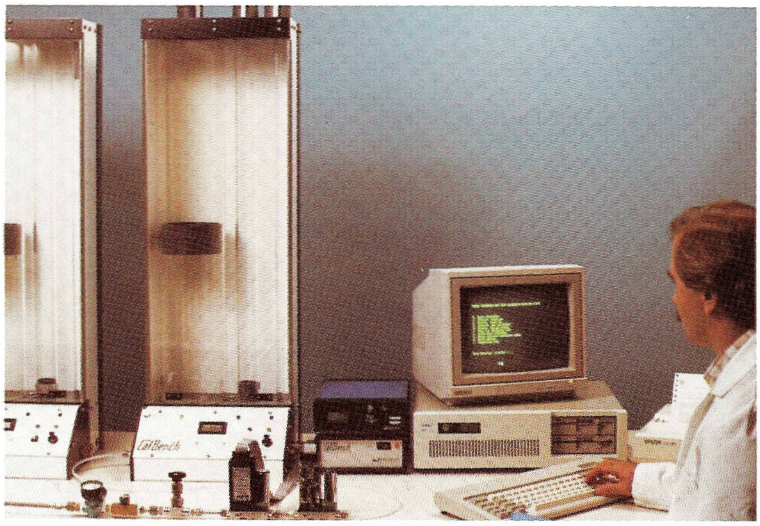


Fig. 6: A computerized flow calibration system featuring an automatic piston meter includes three measuring tubes for improved accuracy.

of Sierra Instruments, Inc., and is the president and chief scientist of the company.

David M. Korpi is the senior vice president of Sierra Instruments, Inc., and was responsible for the development of Sierra's Series 100 Cal-Bench Automated Primary Gas Flow Calibration System. He received his B.S. degree in mechanical engineering from the University of California at Berkeley.

John Olin and Dave Korpi will be available to answer any questions you may have about this article. During normal business hours they can be reached toll free at (800) 345-8725 or in California at (408) 659-3177.