HIGH DEFINITION *flow*

From pharmaceutical production to the natural gas market, exact flow measurements are critical. Here's how NIST helps keep us all on the same page.

By John Wright and Michael Moldover

Many important things, from simple money to human health, rely on precise control of process flows.

The manufacture of pharmaceuticals and semiconductors require the accurate control of flowing mixtures of feedstocks. Frequently, these mixtures are prepared when and where needed by combining tightly controlled flows of components.

Maximizing the energy generated by the combustion of fuel in turbines requires precise control of the flow of fuel and air.

Billions of dollars are transferred from buyers to sellers of natural gas in pipelines. These transactions rely on accurate measurements of gas flow and gas composition.

In the United States, it is the job the National Institute of Standards and Technology to maintain and disseminate standards for measuring all of these flows as accurately as required by U.S. industry. NIST conducts research to improve standards and operates a laboratory to test the accuracy and provide traceability for flow meters submitted by meter manufacturers and other customers.

NIST's primary flow standards for gases determine mass flow by filling an array of cylindrical tanks in a water bath thermostatted with an uncertainty of only 0.005 K. There are two tanks that hold a precise mass of gas. One contains 34 liters and the other, 677 liters. Their internal volumes are periodically confirmed by weighing the gas required to fill them to known pressures.

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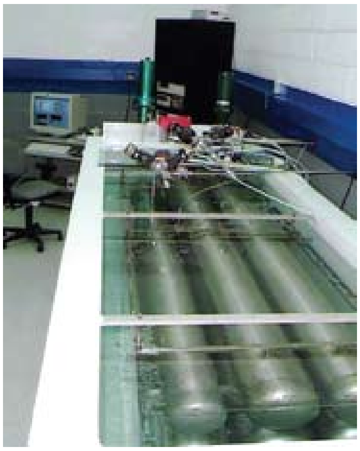


Mass flow tests in these tanks give NIST calibration uncertainties of 0.025 percent at a 95 percent confidence level.

To calibrate a manufacturer's flow meter, the tanks are evacuated and then refilled by flowing a test gas through the meter into the tanks. NIST measures the time required for refilling the tanks as well as the temperature and pressure inside the tanks. Because the gas (composition, temperature, and pressure) after refilling is similar to the gas used during the weighing, the time-consuming, labor-intensive weighing procedures have been replaced with automated temperature and pressure measurements with only a small increase of uncertainty.

When used in this way, the tanks are called a PVTt standard because the measured quantities are pressure, volume, temperature, and time. For flows in the range of 0.01 standard liter per minute to 2,000 slm, the PVTt system achieves calibration uncertainties of 0.025 percent at a 95 percent confidence level.

To ensure reliability, NIST maintains an array of check standards that are either substituted for the customer's meter or used in series with the customer's meter during calibrations. For low flows, NIST's check standards are laminar flow meters (functionally equivalent to capillary tubes) and, for high flows, the check standards are critical flow venturis (nozzles).

NIST's check standards are passive artifacts with documented histories of reliability and stability; however, these passive artifacts are not the best devices for flow measurements in many situations. For example, the proper operation of a critical flow venturi requires a significant pressure drop (typically, at least 10 percent of the intake pressure). Furthermore, the dynamic flow range—the range that is between maximum flow and minimum flow—accessible to one venturi is much narrower than the dynamic range of other flow meters.

The performance of laminar flow meters and critical flow venturis depends upon the thermophysical properties of the test gas in ways that are well understood. Therefore, these devices can be calibrated using one gas in a narrow temperature and pressure range, and then used with confidence to measure the flow of other gases at other temperatures and pressures. NIST provides the necessary thermophysical property data for many gases used as fuels, working fluids in heat engines, process gases for the semiconductor industry, etc.

To achieve the lowest possible calibration uncertainty, NIST subjects the customer's meters to extensive testing lasting several days. Consequently, NIST flow meter calibrations are expensive. Routine calibrations cost nearly $5,000 per instrument. Special tests that require unusual setups may cost much more. Thus, NIST calibrates only a tiny fraction of all flow meters manufactured in the United States, and NIST does not compete with commercial calibration laboratories.

THE TRACEABILITY CHAIN

Most calibrations are done by commercial labs using techniques of measurement traceable to NIST with quality assured by accreditation.

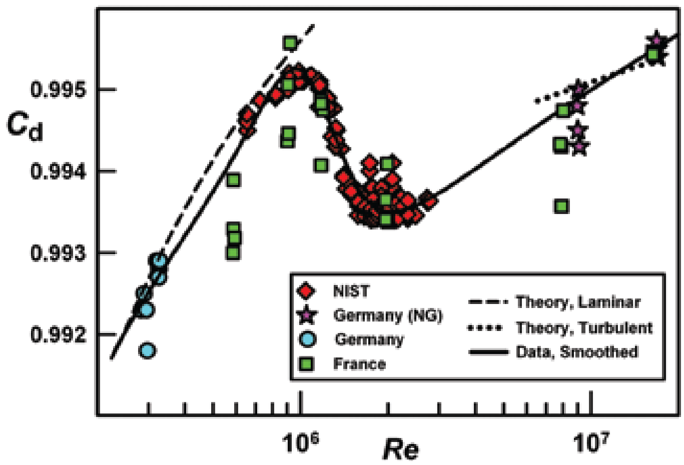
Consider, for example, the calibration of thermal mass flow controllers that are used to prepare gas mixtures and deliver them at controlled rates to semiconductor processing tools. One manufacturer calibrates several thousand units each week using working standards that are devices similar to those sold to customers. The manufacturer calibrates its working standards against its own primary standards (piston provers or bell provers). Periodically, the manufacturer calibrates a transfer standard flow meter (perhaps a laminar flow meter) and pays NIST to calibrate the same transfer standard. If the transfer standard is stable, the calibration results of the manufacturer and NIST should agree within the combined uncertainty of the manufacturer's prover and NIST's standards.

An unbroken chain of measurement values extends from NIST's standards to the end user's mass flow controller, establishing traceability through flow measurements. This traceability chain contains many steps. At each step, additional uncertainty is introduced; therefore, the manufacturer expects NIST to provide calibration uncertainties that are much smaller than the uncertainties delivered to the end user. To meet this expectation, NIST has reduced the uncertainties of its gas flow standards by as much as a factor of 7 during the past eight years.

When the manufacturer and NIST calibrate the same transfer standard, they are, in effect conducting a proficiency test. A successful proficiency test demonstrates that the manufacturer properly maintains its primary standards and the operators have the proper training to make flow measurements that are accurate within their uncertainty statements.

Many meter manufacturers participate in accreditation programs such as the National Voluntary Laboratory Accreditation Program, a non-profit, fee-supported program established by NIST to facilitate and promote acceptance of calibration and test results among countries to avoid barriers to trade. Accreditation requires the establishment of traceability with stated and documented uncertainties, a quality system compliant with the appropriate internationally recognized standards,

▼ Check standards for high flows use a plate holding twenty-one 25mm critical flow venturis, each like the one shown in close-up at right.



▲ International comparison of flow standards using four nozzles as a transfer standard conducted between 3,000 slm and 3.6 × 10^5 slm. The discharge coefficient, C_d, equivalent to actual flow divided by model flow, is plotted as a function of the Reynolds number (Re). Laboratories are consistent because the four sets of data fall within 0.05 percent of a single curve. The jog in the curve near $Re = 1.5{\times}10^6$ indicates the transition from laminar flow to turbulent flow.

periodic third-party technical and quality assessment, correction of non-conformities, and successful completion of proficiency tests.

An alternative to relying on a manufacture's chain of calibrations is direct calibration by NIST. Consider, for example, the calibration of large meters for natural gas flows in pipelines.

As world consumption of natural gas has increased, the world market for large natural gas flowmeters has grown too. American and European manufacturers compete in this market for the sale of ultrasonic and turbine meters, some as large as 30 inches in diameter and costing more than $60,000 each. National standards for calibrating large natural gas flows are well established in the Netherlands, Germany, and France, and European manufacturers rely on these standards for a competitive advantage. To support American meter manufacturers, NIST began developing a calibration service in 2003, the service was approved by NIST's Measurement Service Advisory Group in May 2008, and the first customer calibration was performed in April 2009.

NIST does not have the facilities to calibrate large natural gas meters on its sites in Maryland and Colorado, so it rents facilities from a qualified commercial vendor of calibration facilities, the Colorado Engineering Experiment Station Inc.

CEESI operates a high flow natural gas calibration facility in Iowa. The working standard turbine meters there are traceable to NIST's PVTt flow standards. Using NIST's PVTt primary standard, small venturis were calibrated, one at a time. Then, several small venturis were installed in a single plate so that the flow through the plate was the sum of the flow through the array of small venturis. The parallel array of venturis was used to calibrate larger venturis, one at a time. The process of calibration in series and use in parallel was repeated to scale up NIST's calibration flow range by a factor of nearly 600 and also to scale up the maximum pressure by a factor of 10.

For natural gas metering, every measurement in the scale-up chain was controlled by NIST's staff and all the auxiliary instruments used during the scale-up (thermometers, pressure transducers, frequency counters, gas chromatograph, etc.) were calibrated and maintained in conformity with NIST's quality system. Furthermore, the scale-up will be repeated at intervals consistent with NIST's quality manual. Therefore, NIST itself is responsible for the calibration of the large working standard turbine meters at CEESI.

After the scale-up is repeated, the uncertainty of the calibrations at the largest flows (4×10^7 slm) are 0.21 percent at a 95 percent confidence level. If the end user pays NIST to supervise a calibration at the CEESI site, the calibration will be a NIST calibration.

Informal flow comparisons between NIST and the national metrology institutes of other countries have been conducted for decades to ensure that calibrations performed in one country are equivalent, within claimed uncertainties, to calibrations performed in other countries.

During 1999, the procedures for international comparisons were formalized in a "Mutual Recognition Arrangement" that applies to national measurement standards and to calibration and measurement certificates issued by national metrology institutes. This arrangement strengthens the technical basis for international trade, commerce, and regulation, and now applies to 45 nations.

Under the Mutual Recognition Arrangement, metrology institutions engage in formal "key comparisons," which involve the calibration of the same transfer standards in several countries. This process is essentially equivalent to a proficiency test that might occur within a single country, albeit with smaller measurement uncertainties and correspondingly greater costs.

Outputs from the key comparisons include a database of Calibration and Measurement Capabilities and key comparison results. The results of these key comparisons prove that NIST itself is proficient and in fact achieves its claimed uncertainties. ■

To Learn More

Publications giving details of the theory, operation, uncertainty, and comparison results for NIST's flow standards are available at www.nist.gov/cstl/process/fluid/index.cfm.

The NIST Data Gateway, which provides access to scientific and technical data, is available on line at srdata.nist.gov/gateway/.

Online resources from the International Bureau of Weights and Measures include the database of Calibration and Measurement Capabilities at kcdb.bipm.org/AppendixC/default.asp, and key comparison results at kcdb.bipm.org/AppendixB/KCDB_ApB_search.asp.