Flow Calibration Services at NIST

John D. Wright[†] and Pedro I. Espina[‡]
National Institute of Standards and Technology
Gaithersburg, MD 20899, USA

Abstract

The Fluid Flow Group of the National Institute of Standards and Technology in Gaithersburg, Maryland offers calibration services for flow meters used in gas, water, and liquid hydrocarbon. Gas flow meters are calibrated using PVTt systems, piston provers, or bell provers for flows ranging from 0.04 L/min to 78,000 L/min. A critical nozzle based gas flow standard allows performance testing of flow meters in gas mixtures at temperatures up to 700 K for flows ranging from 60 L/min to 6,200 L/min. The water flow standard is a static gravimetric system that handles flows up to 38,000 L/min. A dynamic gravimetric flow standard provides hydrocarbon liquid flow calibrations between 0.04 L/min and 1,500 L/min. Further details of these calibration services are documented including the principle of operation and measurement uncertainties.

Introduction

As the national metrology laboratory for the United States, the National Institute of Standards and Technology (NIST) maintains primary standards of the seven *SI base units*[¶] and of numerous *SI derived units*[ç] to support equitable commerce and accurate measurements by the scientific community.[1] NIST also serves as a source for the key elements of a reliable calibration, traceability and proficiency.

A measurement or sensor is said to be *traceable* if it can be connected to a stated reference, usually a national standard, through an unbroken chain of documented calibrations with stated uncertainties.[2] A flow standard in a secondary metrology laboratory can be traceable to NIST on the basis of fundamental SI base units and yet have very poor agreement with a NIST flow standard. Hence the second calibration characteristic, *proficiency*, should be at least as important to the calibration customer as traceability. A laboratory proves proficiency by having well founded and performed calibration procedures and by demonstrating agreement with other laboratories via comparisons. For instance, for a flow laboratory, a flow meter transfer standard is calibrated in the secondary metrology laboratory as well as at NIST. The results from the two calibrations are compared to ascertain agreement within the expected uncertainty tolerance.[3] As this document does not deal specifically with proficiency testing, a more thorough treatment of the topic can be found in other publications.[1, 4] One of NIST's major functions is to conduct comparisons with the national metrology institutes of other countries to confirm that measurements of the same measurand conducted in two different countries agree within an

---

[†] Project Leader, Fluid Flow Group. Tel. 301-975-5937, email: john.wright@nist.gov
[‡] Group Leader, Fluid Flow Group. Tel. 301-975-6178, email: pedro.espina@nist.gov
[¶] The meter, the kilogram, the second, the ampere, the kelvin, the mole, and the candela.
[ç] Units formed by combining base units according to the algebraic relations linking the corresponding quantities.

acceptable level. In the following pages, the primary flow standards of NIST will be described, including their methods of operation, flow ranges, uncertainties, and other details relevant to metrologists seeking flow traceability and proficiency. Since the calibration measurement capabilities constantly change and improve, the most current information can be found at the NIST Fluid Flow Group web site, *www.nist.gov/fluid_flow*, and in the *NIST Calibration Services User's Guide*.[1]

Gas Flow Standards

The Fluid Flow Group maintains piston provers, bell provers, a pressure-volume-temperature-time (PVTt) facility, and a laboratory for testing the performance of flow meters in heated gas mixtures. What follows are brief descriptions of these facilities.

Bell Provers and Piston Provers

One of the oldest and most commonly used techniques for gas flow measurement is the piston prover. The NIST piston provers (see Figure 1) consist of a precision bore glass tube that contains a plastic piston slightly smaller in diameter.[5] A ring groove in the piston retains mercury to form a low friction seal between the piston and the tube. A bypass valve is closed to initiate the collection of gas in the glass cylinder. As the piston rises (by virtue of the small excess pressure, ≈ 0.5 kPa, in the gas flowing into the tube) it successively starts and stops a timer by blocking a pair of narrow light beams at the bottom and top limits of the measuring volume. The volumetric flow can be calculated by dividing the previously determined cylinder volume (*i.e.,* between the timer start and stop positions) by the collection time. The temperature and pressure of the gas entering the piston are measured and used to calculate the density of the collected gas. The density is used to convert the measured volumetric flow rate into a mass flow rate (often expressed as a volumetric flow at some reference temperature and pressure conditions).

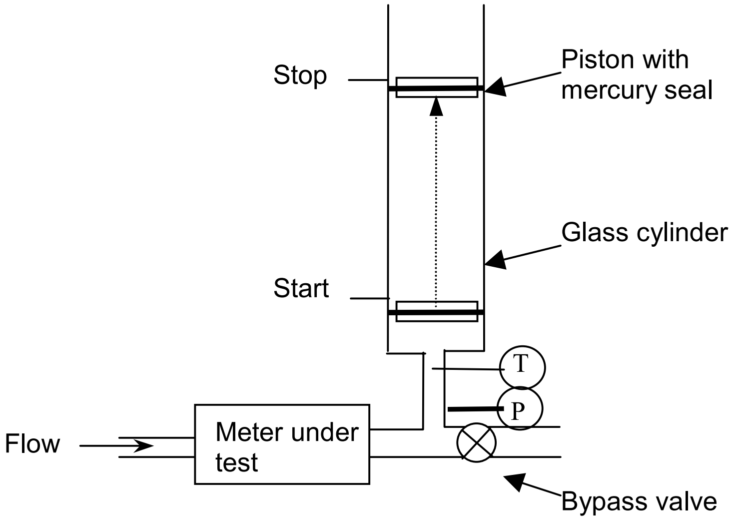

Figure 1. Schematic of NIST's mercury sealed piston prover.

The NIST bell prover systems are based on principles similar to those described for the piston provers. The bell prover (see Figure 2) consists of a cylindrical tank open at the top and a central “dry well”, which together form an annulus that is nearly filled with low vapor pressure sealing oil. An open bottom, cylindrical tank with a dome-shaped top (*i.e.,* the bell) is inserted into this oil filled annulus. Its weight is nearly balanced by counterweights thus allowing it to raise or lower with just a small differential pressure (< 1 kPa); this enables the collection and measurement of a known volume of gas. A smaller counterweight is mounted on a cam to provide a correction for buoyancy effects due to the bell immersion in the sealing oil. Rollers and guide rods provide lateral stability to the bell as it moves upwards.

Once flow conditions through the flow meter under test are deemed stable, a bypass valve is closed thereby directing gas into the bell. The volume of gas held within the bell, between the collection start and stop sensors has been previously determined by careful dimensional measurements. During a flow calibration, the time required for the bell to travel between the start and stop sensors is measured. The collection volume of the bell prover is divided by the collection time to obtain a volumetric flow. The mass flow or the standard volumetric flow is calculated using the temperature and pressure of the collected gas to determine its density.

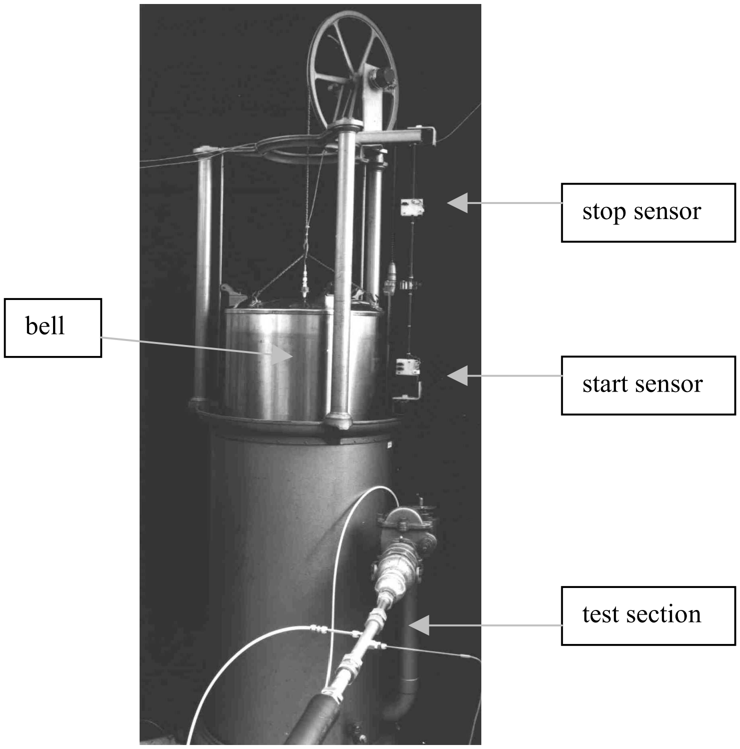

Figure 2. A partially elevated bell prover with a meter under test.

The NIST piston and bell provers are used with non-flammable, non-corrosive, and non-toxic gases, typically dry air, nitrogen, or noble gases. The Fluid Flow Group uses three piston provers to cover the flow range from $3.72\text{x}10^{-2}$ L/min to 29.7 L/min, and two bell provers to cover the flow range from 16.1 L/min to 1,440 L/min. Mass flow measurements made with piston and bell provers are subject to uncertainties in the determination of the gas density, collection volume, collection time, uncertainties related to the velocity profile at the meter under test, and other categories.[5] The mass flow uncertainty of the NIST piston provers ranges between 0.16%[*] and 0.19% depending on which piston prover is used, and the uncertainty of the bell provers is 0.17%. Meter types that are commonly calibrated with the piston and bell provers include critical flow venturis, laminar flow meters, turbine meters, and positive displacement meters. National Pipe Thread, A/N, and other common fittings are available from 0.6 cm (0.25 in) to 10 cm (4 in).

Numerous comparisons with national metrology institutes and secondary metrology laboratories have been conducted using the piston and bell provers.[3] These include comparisons to the national metrology institutes of France, Japan, Mexico, and Taiwan, all of which support the specified uncertainties for the NIST flow standards.

Pressure-Volume-Temperature-Time (PVTt) System

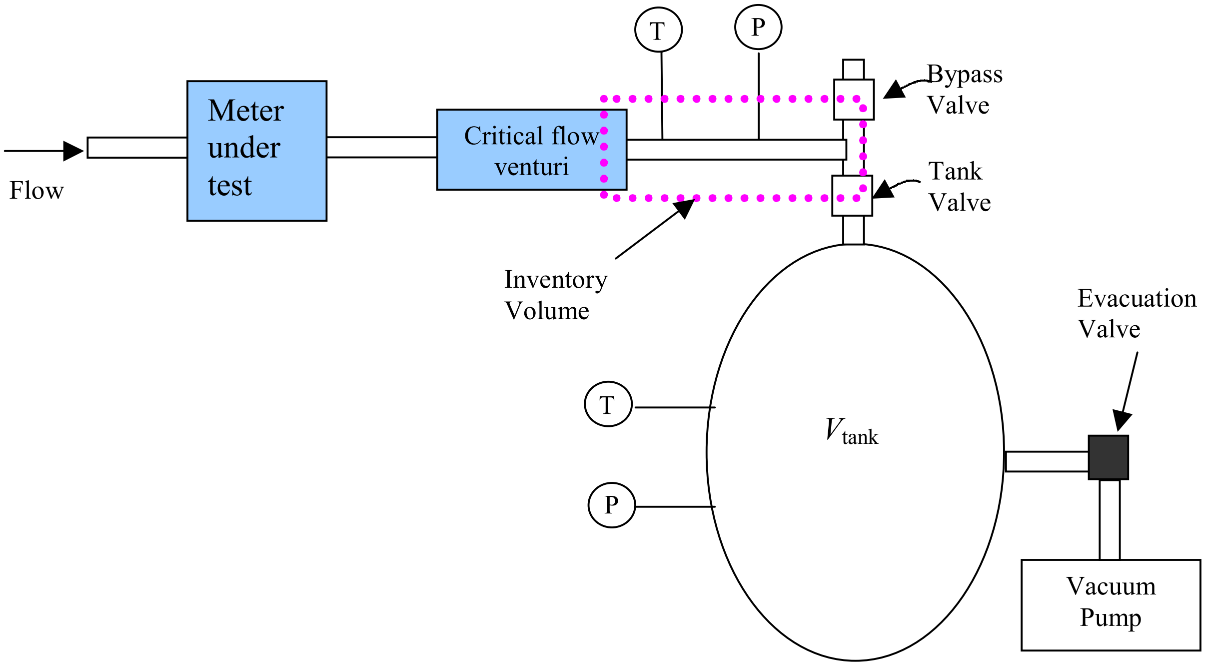

Figure 3. Arrangement of equipment in a PVTt system.

A PVTt system measures the mass of gas collected in (or dispensed from) a tank over a measured period of time. The initial and final mass of gas in the tank and inventory volumes are determined by measuring the gas temperature and pressure, calculating density from an equation of state, and multiplying the density by the appropriate volume. The components of the gas collecting PVTt system at NIST consist of: a compressor (*i.e.,* flow source), valves for diverting the flow, a collection tank, a vacuum pump, various pressure and temperature sensors, and a critical flow venturi (see Figures 3 and 4). The critical flow venturi serves to isolate the meter under test from the pressure variations in the downstream piping and tank, thus maintaining

---

[*] All of the uncertainties herein were determined by following the ISO Guide to the Expression of Uncertainty in Measurement (1995), using a coverage factor $k = 2$, and hence are 95% level of confidence values unless otherwise stated.

stable conditions at the test section even though extreme pressure variations occur downstream of it due to the operation of the diverter valves and pressure changes as the collection tank fills.

The NIST PVTt system is used for calibrations using dry air at flows ranging from 862 L/min to 78,000 L/min. An uncertainty analysis of the NIST PVTt flow standard gives expanded uncertainties of 0.20%. Uncertainty components include the collection volume, the inventory volume, the tank pressures and temperatures (both initial and final values), the inventory volume temperatures and pressures, the collection time, and the gas equation of state. Uncertainties related to sampling errors are significant in a PVTt system. For instance, the filling and evacuation process leads to temperature gradients in the tank and gas. These temperature gradients make it difficult to obtain low uncertainty average temperature measurements. Also, there are rapid temperature and pressure fluctuations during the measurement of the initial and final inventory volume conditions. These pressure and temperature fluctuations lead to uncertainties in the estimation of the mass in the inventory volume.

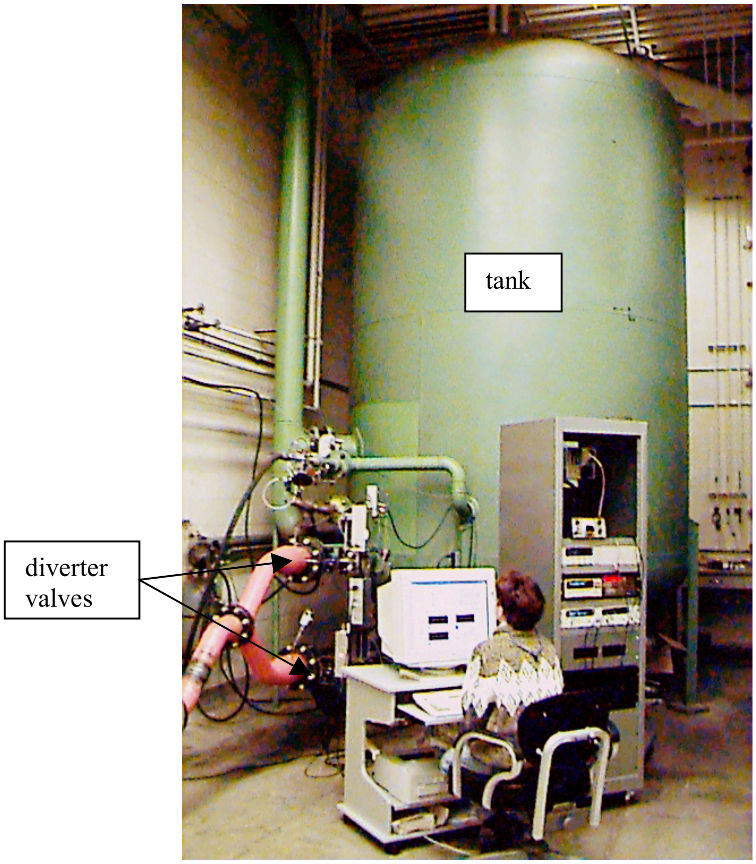

Figure 4. The NIST PVTt flow standard for flows up to 78,000 liters/min.

Each flow determination obtained using the PVTt facility averages about 1 hour in duration. This imposes limitations in the workload output of the facility and leads to expensive calibrations. At times when the application allows for the flow meter to be calibrated at higher uncertainties, customers may choose to have their devices calibrated against the NIST master sonic nozzles (*i.e.*, a set of working standards). These nozzles are regularly calibrated against the PVTt facility and their expanded uncertainties are no larger than 0.3% of reading.

In 1999, an international comparison demonstrated agreement between the NIST PVTt and the standards of the national laboratories of Japan, England, Korea, and Taiwan. This test made use of a set of three critical venturis and was piloted by the Ford Motor Company.[3, 6] This year, the NIST participated in a European Union intercomparison using the PVTt facility. This test, known as EUROMET Project No. 307, made use of a single cylindrical throat critical venturi and showed agreement between the national metrology laboratories of Canada, France, Germany, the Netherlands, Switzerland, and England.

Typical flow meter types calibrated in the PVTt facility are critical flow venturis, laminar flow meters, and ultrasonic flow meters. The PVTt flow standard can accommodate ASA 150 lb, 300 lb, or 600 lb flanges, A/N fittings, National Pipe Threads, or other common fitting types, between 2.5 cm (1 in) and 20 cm (8 in) in diameter.

Heated Gas Mixture Flow Facility

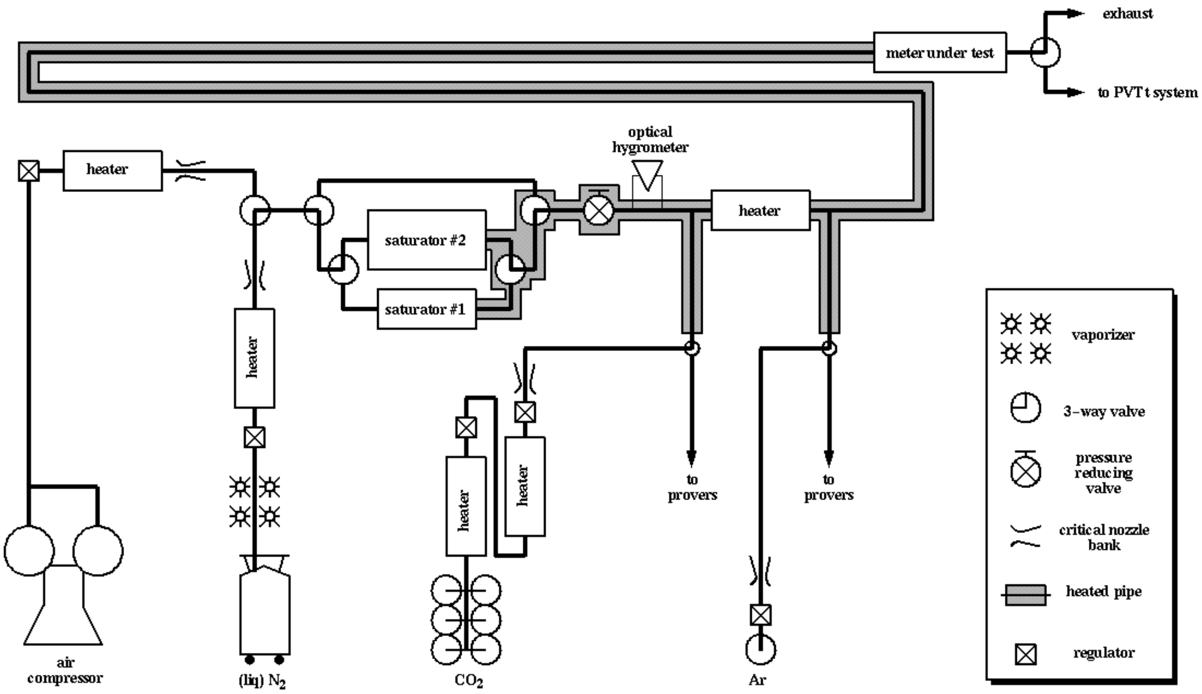

Figure 5. A schematic diagram of the Heated Gas Mixture Flow Facility.

The Heated Gas Mixture Flow Facility (Figure 5) was build in 1996 as a laboratory for testing flow meters in conditions similar to those found in vehicle exhaust and other combustion processes.[7] The facility uses calibrated critical nozzles to meter pure gases (air, nitrogen, carbon dioxide, and argon). Water vapor is added to the dry carrier gas in a saturator vessel and the dew point of the humidified gas is measured with a chilled mirror hygrometer. The total mass flow of the mixture is determined by summation of the pure gas streams. The temperature of the mixture can be controlled with an electric circulation heater to set points between 295 K and 700 K. The flow range of simulated combustion products is 60 L/min to 2000 L/min. In an alternate mode of operation, the facility can provide humidified air flows from 85 L/min to 6200 L/min. The facility delivers the flow of the gas mixture with an uncertainty of 1%. Meter types tested in this facility include ultrasonic flow meters, laminar flow meters, vortex shedding meters, and dilution type flow meters.

Liquid Flow Standards

Water Flow Standards

The NIST gravimetric flow standards for water are essentially “bucket and stopwatch” systems using a weigh scale. A schematic of such a standard is shown in Figure 6. ISO and ASME standards have been written giving guidance on the construction, operation, and uncertainties of liquid gravimetric facilities.[8, 9] Typically these system are comprised of a steady flow source, flow control valves, a flow conditioner, a pipeline that holds the meter under test, a flow diverter, and a collection tank mounted on a weigh scale. During operation, the diverter directs flow either to the collection tank, or to a supply tank and flow re-circulation system. To operate the system, the collection tank is drained and an initial tank mass (or tare mass) is measured. Steady state conditions of flow, temperature, and pressure are established through the meter under test and the connecting piping (this often takes 10 minutes or more). Flow is very rapidly diverted into the collection vessel and a collection start time is measured. When the tank fills to some prescribed mass (collection times of 30 seconds or greater are used), the flow is diverted back to the re-circulation system and the stop time is measured. After a sufficient delay for settling, the final tank mass is measured. The change in tank mass (the mass of liquid collected) is divided by the collection time to obtain the mass flow. The mass flow can be converted to the volumetric flow if the density is known. A relationship between the liquid temperature and its density is developed for this purpose.

The method of operation described above constitutes a *static gravimetric* system since the mass is measured before and after the collection in a static manner (with flow diverted away from the tank and while the tank mass is not changing). The static gravimetric technique is conceptually simple and the results are easily verified and convincing. Components of uncertainty for a static gravimetric flow standard include: the weigh scale uncertainties (calibration and resolution), the uncertainty of the buoyancy correction to the mass measurements, the uncertainty of the timer, the timing uncertainties related to the diverter, uncertainties due to evaporation or splashing out of the collection tank or gas content of the liquid, the uncertainty due to storage effects in the inventory volume, the uncertainty of fluid property measurements, and uncertainties related to the velocity profile at the meter under test. If volumetric flow is the quantity of interest, the collected liquid temperature measurement and the uncertainty in the density calculations must be included. The uncertainty of the volumetric flow measurements made in the NIST water flow facilities is 0.12 %.

The NIST water flow standard was recently compared with equivalent standards at the national laboratories of England, Japan, Mexico, and the Netherlands. The results of this comparison support the NIST specification of uncertainty for the water flow standard.

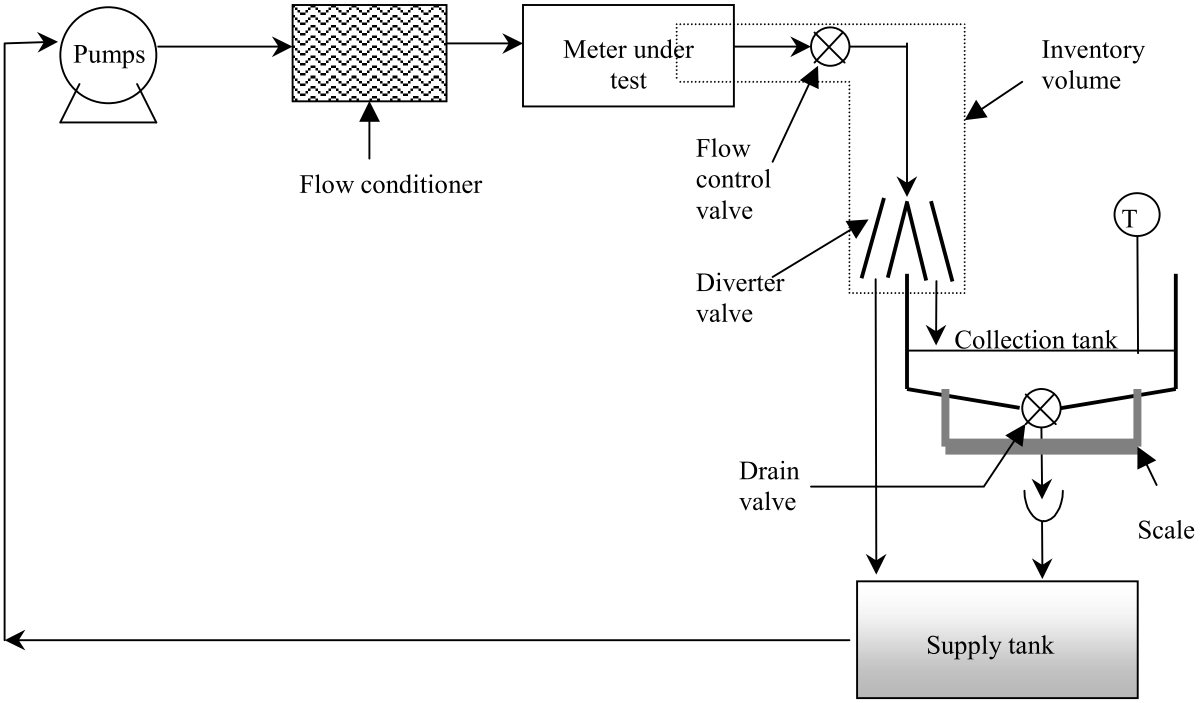

Figure 6. Schematic diagram of a static gravimetric liquid flow standard. Liquid is diverted into a collection tank mounted on a weigh scale for a measured time period.

Due to weigh scale and time measurement uncertainty issues, four gravimetric flow systems are used at NIST to cover the flow range from 8 L/min to 38,000 L/min. Pipe sizes between 2.5 cm (1 in) and 40 cm (16 in) with ASA 150 lb flanges, Victaulic couplings, National Pipe Threads, or other common fittings can be accommodated. Pressures at the meter under test can be set within the range of 100 kPa to 1,100 kPa. The water flow standard does not have heat exchangers for temperature control. Hence temperatures are nominally 296 K, but during continuous operation, the water temperature rises as high as 310 K due to work from the pumps. Typical meters tested in this facility are orifice plates, venturi tubes, turbine meters, nozzles, ultrasonic flow meters, and electromagnetic flow meters. The water flow standard is presently undergoing an upgrade to improve its level of automation and other operational aspects.

Hydrocarbon Flow Standards

NIST uses a dynamic gravimetric flow standard to deliver calibrations of flow meters for hydrocarbon liquids. In the flow standard, the start and stop times are acquired when the mass indicates certain lower and upper values as the tank is being filled, not when the diversion begins and ends. Referring to the schematic in Figure 7, flow is pumped from a supply tank, through flow conditioners, the meter under test, flow control valves, and finally into a collection tank. Initially, the collection tank drain is left open so that flow returns to the supply tank from which the pump draws liquid. The collection tank is supported by one side of a beam balance and is not connected to the piping at the tank inlet or drain. To initiate a flow measurement, a certain lower mass value is placed on the opposite side of the balance from the tank and the drain valve is closed. When the mass of the tank and collected liquid causes the beam balance to tip, a start trigger signal generated by an electrical contact on the balance initiates timing. While the tank is filling, a certain upper mass value is placed on the opposite side of the beam balance. When the tank and contents attain the upper mass value and tip the weigh scale, a second trigger signal stops the timing.

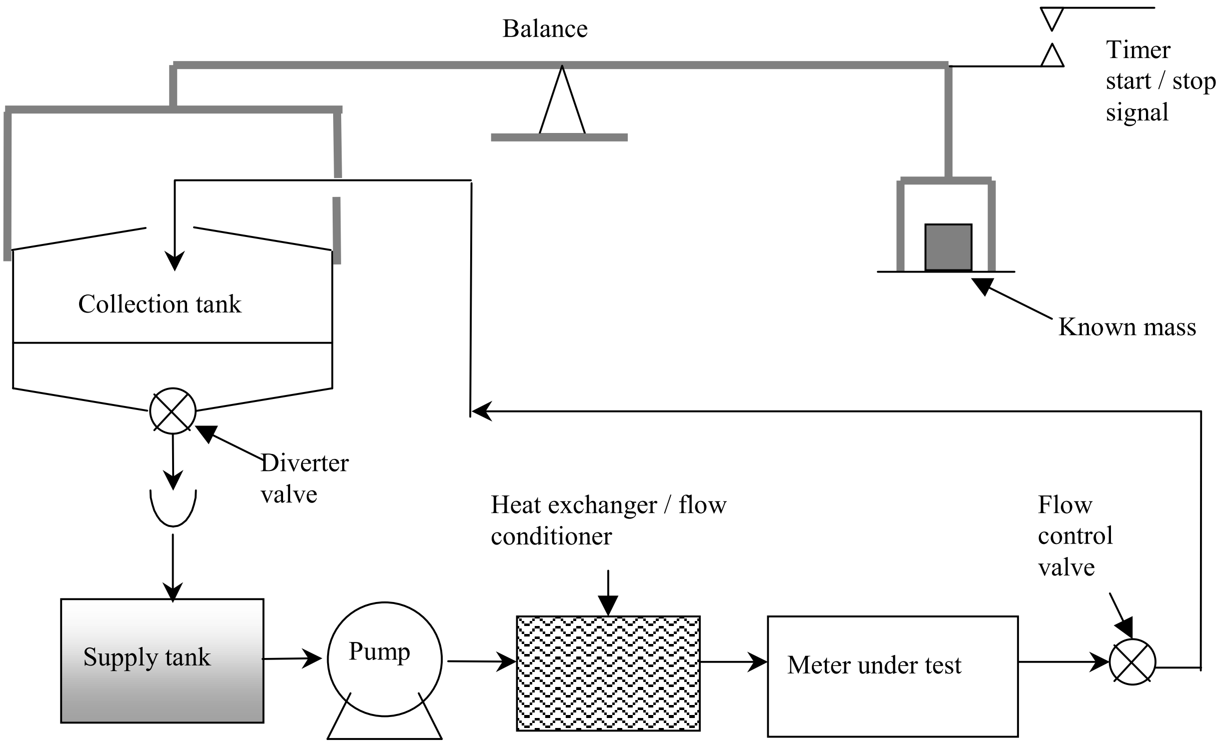

Figure 7. Schematic diagram of a dynamic gravimetric flow standard for liquid flow which uses a beam balance.

Uncertainty components related to the beam ratio and the action of the beam on the knife-edge must be considered in this system. Also at issue in the uncertainty of the dynamic gravimetric standard are: 1) differences in the impact force of the falling liquid between the start and stop conditions, 2) extra liquid in the collection due to the rising level relative to the falling column, 3) the effects of waves in the collection tank, and 4) changes in the actuation time of the balance due to differences in mass between the start and stop conditions.[10] An analysis of the NIST hydrocarbon flow standard gives a volumetric flow uncertainty of 0.12%.

The hydrocarbon flow standard uses two collection tanks to cover the flow range of 3.5×10^{-2} L/min to 1500 L/min. The flow standard uses a hydrocarbon liquid known as MIL-C-7024C or Stoddard solvent as a surrogate liquid due to the similarity of its density and viscosity to JP-4 and JP-5 jet fuels. Typical meter types calibrated in this facility are turbine meters, nozzles, positive displacement meters, and coriolis meters. Pipe sizes from 1.25 cm (0.5 in) to 7.6 cm (3 in) with A/N fittings, ASA 150 lb flanges, National Pipe Threads and other common fittings can be accommodated. Pressures at the test section are maintained at approximately 110 kPa to prevent cavitation at the meter under test. The hydrocarbon temperature is normally maintained at approximately 296 K, but heat exchangers allow testing at temperatures about 5 K above or below room temperature.

Conclusions

The NIST Fluid Flow Group maintains standards for the measurement of gas, water, and hydrocarbon liquid flows. These flow standards are used to conduct comparisons with other national metrology institutes and to disseminate flow traceability and proficiency[4] to laboratories within the United States. The methods of operations of these flow standards have been described as well as information pertinent to customers of these facilities, such as pipe sizes, flow ranges and measurement uncertainties. Other calibration services offered within the Fluid Flow Group have not been discussed herein, such as air speed, density, and volume and more information on these calibrations can be found in the references.[1]

References

[1] Marshall, J. L., editor, NIST Calibration Services Users Guide, NIST Special Publication 250, January 1998, http://ts.nist.gov/ts/htdocs/230/233/calibration/index1.html.

[2] *International Vocabulary of Basic and General Terms in Metrology*, 2nd edition, International Organization for Standardization, 1993.

[3] Wright, J. D., *Validating Uncertainty Analyses for Gas Flow Standards Via Intra- and Inter-Laboratory Comparisons*, NCSL Conference Proceedings, Charlotte, NC, 1999.

[4] Mattingly, G. E., Flow Metrology: *Standards, Calibrations, and Traceabilities*, in Flow Measurement, Spitzer, D. W., editor, Instrument Society of America, Research Triangle Park, NC, pp. 575-587.

[5] Wright, J. D. and *NIST Calibration Services for Gas Flow Meters: Piston Prover and Bell Prover Gas Flow Facilities*, NIST Special Publication 250-49, August 1998.

[6] Caron, R. W., Kegel, T. M., and Britton, C. L., *A Measurement Assurance Program (MAP) Using Critical Flow Venturis*, 4th International Symposium of Fluid Flow Measurement, Denver, Colorado, June, 1999.

[7] Wright, J. D., *Flowmeter Calibration Facility for Heated Gas Mixtures*, NCSL Conference Proceedings, Atlanta, GA, 1997.

[8] *Measurement of Liquid Flow in Closed Conduits- Method by Collection of the Liquid in a Volumetric Tank*, ISO 8316 : 1987 (E), International Organization for Standardization.

[9] *Measurement of Liquid Flow in Closed Conduits by Weighing Method*, ASME/ANSI MFC-9M-1988, American Society of Mechanical Engineers, New York.

[10] Shafer, M. R. and Ruegg, F. W., *Liquid Flowmeter Calibration Techniques*, Transactions ASME, October, 1958, pp. 1369 – 1379.