THE NEW NIST WATER FLOW CALIBRATION FACILITY

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Abstract

A static-gravimetric liquid flow calibration facility is under construction at the NIST Gaithersburg Campus. The facility is designed to calibrate flow meters from 25 mm to 400 mm in diameter, at flow rates from 8 L/min to 38,000 L/min. It incorporates a diverter valve design which greatly reduces the uncertainty associated with the flow diversion into the collection tank. This paper details design and construction novelties of the system and outlines the expected uncertainty budget for the calibration facility.

Introduction

The new NIST Water Calibration Facility is under construction at the Gaithersburg Campus. When completed, it will have three parallel pipelines of 100 mm, 200 mm and 400 mm in diameter, with the capability of calibrating flow meters from 25 mm to 400 mm at flow rates ranging from 8 L/min to 38,000 L/min. The facility incorporates a diverter valve design [1, 2] (hereafter referred as a uni-diverter), which reduces the uncertainty (error) associated with traditional diverter mechanisms. With the use of the uni-diverter and improved control over flow parameters, the projected expanded uncertainty $(k = 2)$ of the system is expected to be 0.086% – a significant reduction from 0.12% for the prior NIST Water Calibration Facility.

In this paper, we describe the facility in detail and explore its expected uncertainty budget.

Description of the Flow Facility

The NIST Water Calibration Facility is a closed loop flow system; Fig. 1 shows a detailed layout of it. The entire facility is located over a water reservoir containing about 227,000 L of water. Four constant velocity pumps – three at 112 kW (150 hp) and one at 75 kW (100 hp) – can be operated individually to pump water from the reservoir into the flow loop through a customized manifold. The manifold splits the flow into three separate pipelines of 100 mm, 200 mm and 400 mm in diameter, and a bypass of 200 mm in diameter; only one pipeline is operated at any given time. The bypass contains a throttle valve that is used, in conjunction with the fine and coarse control valves on each pipeline, to control the flow and working pressure within the test loop. The throttle valve is controlled by a pneumatic actuator equipped with a 4-20 mA position sensor.

Each pipeline is fitted with a flow conditioner, located downstream of the manifold, which helps remove asymmetries from the flow before it enters the pipeline straight section prior to the meter under test. The straight section provides an upstream straight length of about 24 diameters for the 400 mm pipeline. Straight lengths of 76 and 174 diameters, respectively, are available for the smaller pipelines. Once the flow in each pipeline passes through the meter under test, it is split into two lines, each equipped with throttle valves as shown in Fig. 2. Splitting the flow allows for coarse and fine throttle control of the flow passing through the meter under test. Downstream of the throttling valves, the flow is combined and sent through two valves in series before exiting through the fishtail and nozzle into the uni-diverter mechanism. The section of pipe between the two valves houses a leak detection system to ensure that no leakage occurs into or out of unused sections of the flow system during testing. The fishtail transitions the flow from the circular cross section in the test section to the rectangular cross section of the nozzle. All three pipelines are inter-connected, as shown in Fig. 2, to allow the fluid to collect in larger tanks if longer collection times are needed.

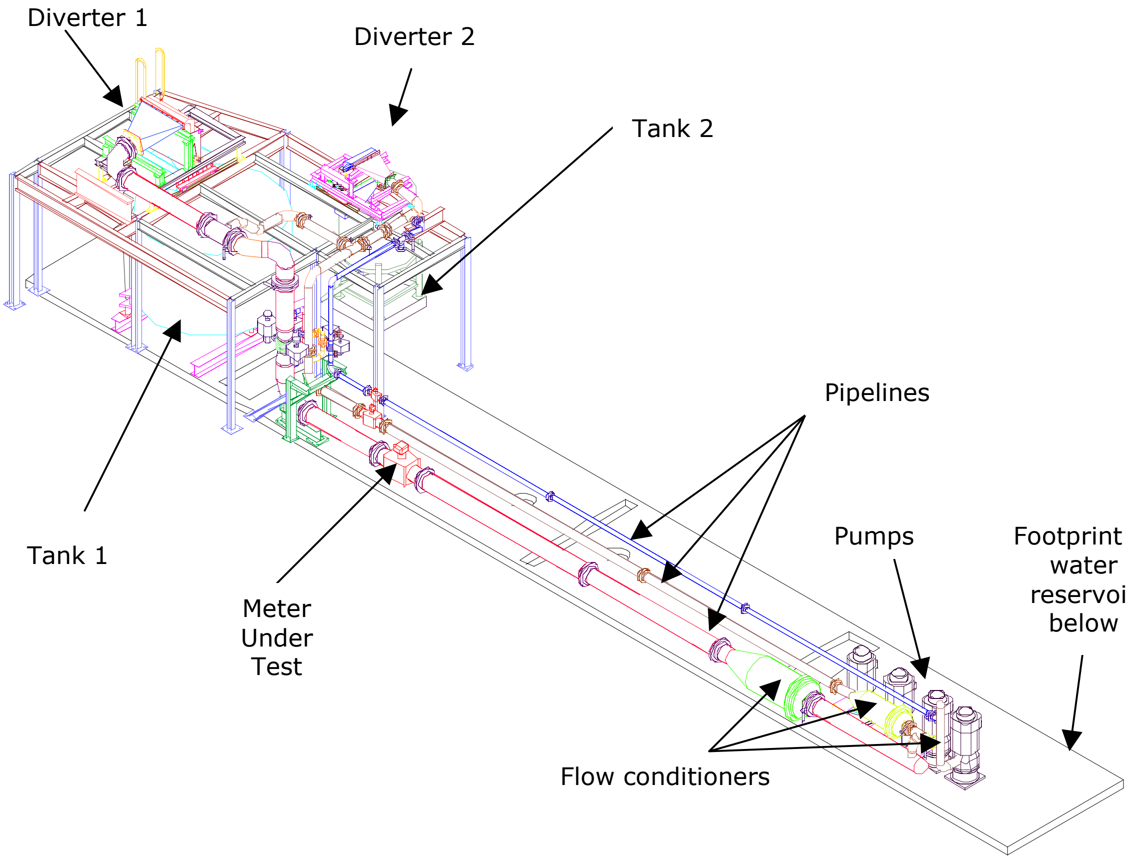

Figure 1. Sketch showing the layout of the facility (Tank 3 and Diverter 3 not shown).

The nozzle for Tank 1 has a length-width aspect ratio of 12.75. ISO guidelines suggest that the liquid sheet formed by the nozzle generally has an aspect ratio of 15 – 50 in the direction of divider travel. However, the performance of the uni-diverter is essentially independent of the geometry of the nozzle and the corresponding liquid sheet [1, 2] and its small aspect ratio does not affect the performance of the facility.

Table 1. Facility Specifications.

Feature	**Tank 1**	**Tank 2**	**Tank 3**
Tank Volume, L	22,000	3,700	900
Tank Material	Steel	Fiberglass	Fiberglass
Scale Type	Load Cell	Scale	Scale
Scale Capacity, kg	22,500	4,500	1,100
Scale Resolution	2.3 kg (0.01%)	0.23 kg (0.005%)	0.045kg (0.004%)
Pipe Size, mm	200 to 400	100 to 200	25 to 100
Flow Range, L/min	880 to 38,000	110 to 4,900	8 to 1,500
Working Pressure, kPa	100 - 1000	100 - 1000	100 - 1000
Projected Expanded Uncertainty	0.086%	0.075%	0.075%

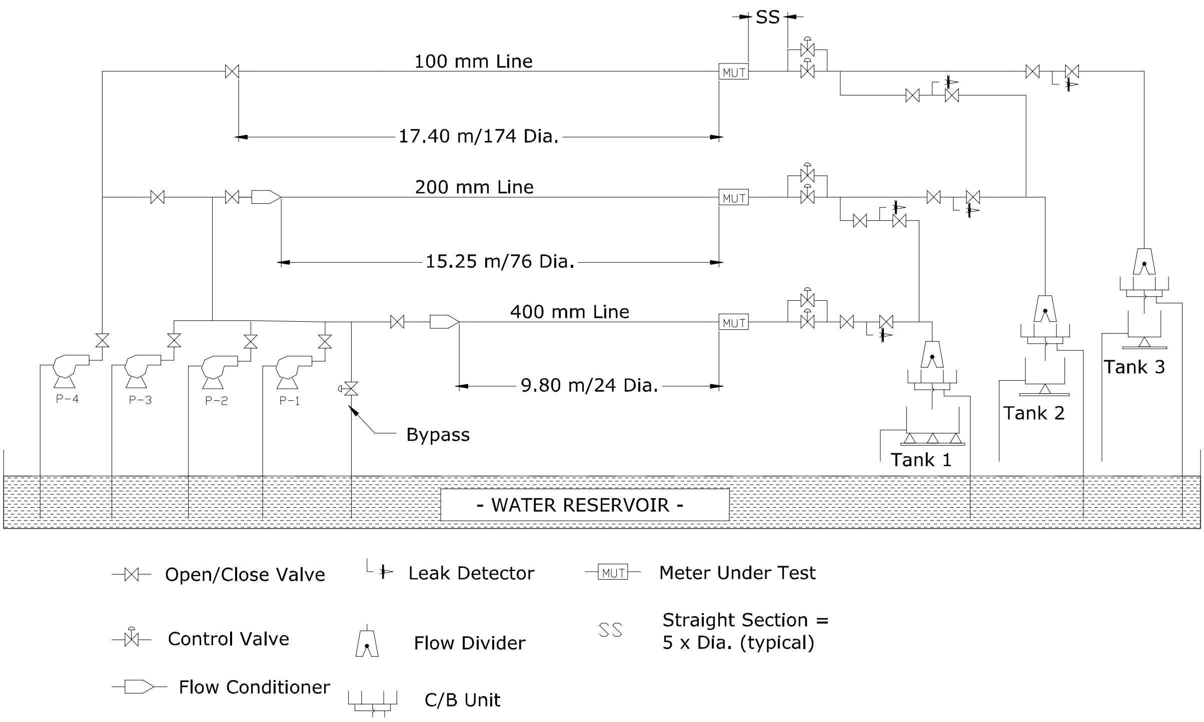

Figure 2. Schematic of the facility.

The Uni-Diverter

A typical static-gravimetric liquid flow calibration system uses a diverter valve, which, during the calibration cycle directs the calibration flow to either a bypass or a collection tank. The diverter error can be considered to be an uncertainty in the calibration time, and its error is an unknown bias that cannot be reduced statistically by increasing the number of calibrations considered. Previous investigations [3, 4] have evaluated the performance of traditional diverter valve designs to reduce the error associated with the determination of the liquid flow calibration time. Fast diverter actuation, longer collection time (i.e., larger collection tank), and symmetric timer actuation are techniques commonly used for reducing the diverter error. While these traditional techniques have attempted to minimize the diverter error, the approach described here seeks to eliminate the diverter error altogether using a new diverter design.

The uni-diverter, which has been incorporated into the NIST flow facility, uses a unidirectional diverter valve, which eliminates the bulk of the diverter error. Fig. 3 shows the diagram of the uni-diverter assembly. The uni-diverter consists of two separate components, the traditional divider (which cuts the flow) and a translating collection bypass (C/B) unit (which directs the flow between the collection tank and the bypass to the reservoir). The divider is mounted on a pair of axial bearings and pivots about its axis to cut the flow from one side to the other. The movement of the divider is limited to a maximum angle of 7.5 degrees from vertical on each side in order to minimize liquid splashing. The C/B unit is mounted below the divider on linear bearings and is comprised of three separate channels; the center channel directs the flow into the collection tank while the outer channels direct the flow into the bypass back to the reservoir. Traversing the C/B unit on the linear bearings facilitates the redirection of flow from the collection tank to the bypass and vice versa. The operation of the uni-diverter is described in detail in [2].

Since the flow diversion during both collection and bypass processes is propagated in the same direction (i.e., identical diverter velocity profile), the components of the diverter valve error are correlated and self-canceling, provided the flow remains steady during the calibration. The uncertainty associated with the uni-diverter has been shown not to exceed 0.031% even for abnormal biases in diverter conditions tested. For conventional calibration conditions, the uncertainty is expected to be smaller.

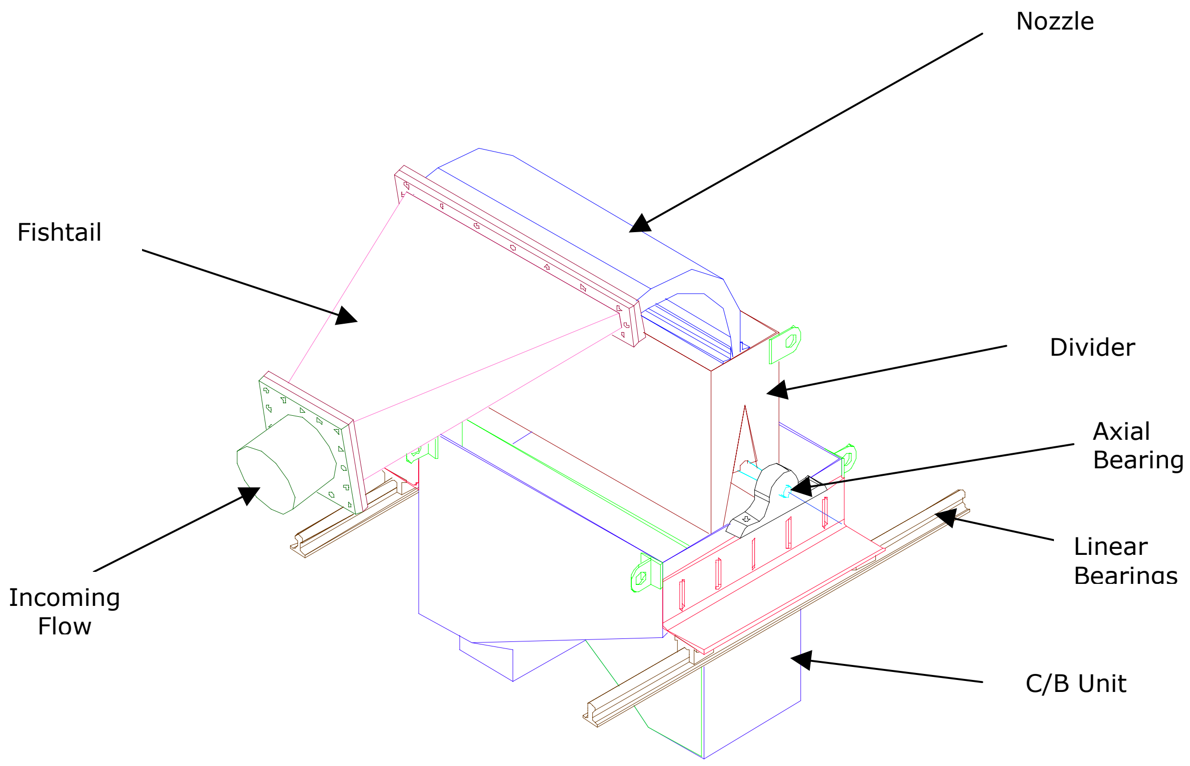

Figure 3. Sketch showing the fishtail, divider & C/B unit (uni-diverter) and some of its structural mountings.

The Measurement Principle

A conventional static-gravimetric liquid flow calibration facility is composed of a liquid reservoir, a pumping system, a pipeline to the meter under test, the meter under test, piping connecting the meter under test to a timed collection system, a diverter valve, and a fluid weighing collection system. The diverter valve is used to direct flow either into the collection system or into a bypass, which returns the flow to the reservoir. The calibration flow is determined by collecting a prescribed mass of steadily flowing fluid over a measured time interval. During the calibration, other quantities (e.g., fluid temperature and pressure) are measured as needed to determine pertinent fluid properties.

Such static-gravimetric systems are, in fact, mass flow measurement facilities. The mass flow, $\dot{m}$, is defined by

$$\dot{m} \equiv \frac{M}{\Delta t} \tag{1}$$

where M is the liquid mass through the tested meter during the time interval Δt. The volumetric flow, q, is derived from the mass flow knowing the liquid density, ρ, at the tested meter location.

$$q = \frac{\dot{m}}{\rho} = \frac{M}{\Delta t \ \rho} \tag{2}$$

The Uncertainty Analysis

The combined uncertainty of the volumetric flow is calculated by using the root-sum-square (RSS) method to couple the uncertainty components that arise from the collected mass, collection time, and liquid density

$$u_q = \sqrt{u_M^2 + u_{\Delta t}^2 + u_\rho^2} \tag{3}$$

where u_q is the combined standard uncertainty of the volume flow rate, and u_M, $u_{\Delta t}$, and u_ρ are the standard uncertainties of the collected liquid mass, collection time, and liquid density, respectively. The definition for measurement uncertainty is given in [5], and the expected uncertainties are discussed in the following sections and summarized in Table 2. The confidence level given by equation (3) is 68.27%, and a coverage factor of k=2 is used to convert the combined standard uncertainty to the expanded uncertainty with a 95% approximate level of confidence:

$$U_q = k \cdot u_q \tag{4}$$

The uncertainty components of the NIST static-gravimetric water flow measurement system are discussed below. As seen in equation (3), they include the uncertainty of the collected water mass, the collection time and the water density. Figure 4 provides a graphic representation of the uncertainty analysis and Table 2 shows the summary of the expected measurement uncertainty.

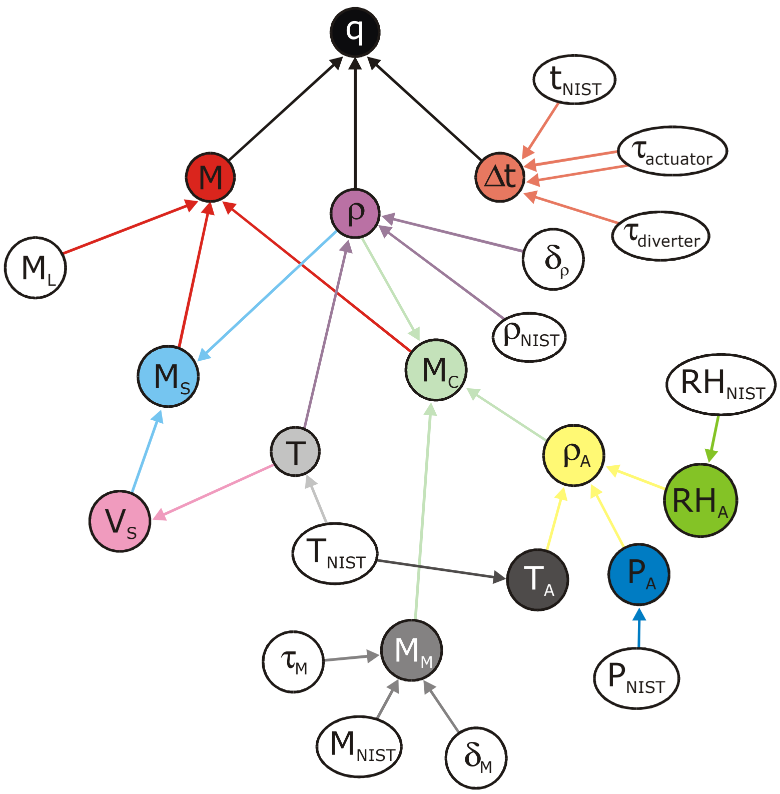

Figure 4. Graphic representation of the uncertainty analysis.

1. Collected Water Mass Measurement

For this calibration system, a statement of conservation of mass yields

$$M = M_C + M_S + M_L \quad (5)$$

where M is the water mass through the meter under test, M_C is the water mass collected in the static weighing system, M_S is the net water mass increase in the pipe connecting the meter under test to the static weighing system (i.e., the inventory volume), and M_L is the water mass leaked out of the system. All quantities in (5) represent time integrals over the collection time interval Δt.

a) The Collected Water Mass

The mass values observed by the scales in the static weighing system are apparent values that must be adjusted for buoyancy. To obtain the true mass of the water collected, the air and water densities are required. The relationship between the apparent mass and the true mass is given by

$$M_C = \frac{M_M}{\left(1 - \frac{\rho_A}{\rho}\right)} \quad (6)$$

where M_M is the apparent mass indicated by the scale, ρ_A is the air density, and ρ is the water density. The uncertainty in the buoyancy correction applied to the collection mass arises from uncertainties in the apparent mass, and the densities of air and water.

The Apparent Mass

The NIST facility uses three weighing tanks to cover its flow range. Each tank is associated with a diverter system sized according to the flow rate expected. The uncertainty of the apparent mass includes the uncertainty in the scale indication, the mass standards used to calibrate the scale, and the scale calibration drift. The uncertainty contributions from these factors are explained below and their contributions are listed in Table 2.

The scale indication uncertainty, δ_M, is estimated to be the scale resolution divided by $\sqrt{3}$; this value corresponds to the standard deviation of a rectangular distribution. It is worth noting that only 80% of the scales' capacities are used for the uncertainty estimation shown in Table 2.

The scales are calibrated using reference masses, M_{NIST}, traceable to the NIST Mass and Force Group. The scales for Tank 2 and Tank 3 are small enough to be calibrated using reference masses only, however, the load cells in Tank 1 have to be calibrated using reference masses and water load equivalents, which leads to a higher uncertainty. (see Table 2)

Although the scales will be calibrated on a regular basis (as required by the quality system), they will not be calibrated prior to each observation. Thus, there is an uncertainty associated with the temporal drift experienced the scales between calibrations, τ_M. Based on the performance of similar scales used by some of our systems, we anticipate a scale drift uncertainty no larger than 0.015%.

The Air and Water Density

The primary contributors to the air density uncertainty are the measurements of air temperature, pressure, and relative humidity. The air temperature measurement in the flow laboratory is made with an ensemble of thermistors. Due to the discretized nature of this measurement, the uncertainty in the air temperature measurement, T_A, is estimated to be 1 K. This estimate leads to a relative uncertainty in the air density of 0.4%. A hygrometer is used to measure the relative humidity of the air, RH_A, in the flow laboratory. The estimated uncertainty for the relative humidity is 6% and this results in an uncertainty no greater than 0.2% in the air density. The uncertainty of air density, due to a barometric pressure uncertainty, P_A, of 0.07 kPa, is 0.07%. Thus, the combination of the uncertainty in the measurements of air temperature, pressure, and relative humidity mentioned above, is no greater than 0.5% in the air density. In this analysis, the uncertainty contribution due to the equation of state for humid air has been neglected due to its small relative contribution.

Due to the magnitude of the density ratio of water to air (1000:1), the effect on the total uncertainty of buoyancy correction may be acceptably small for the requirements of this system with only modest efforts applied to the determination of the air and water densities. The relative uncertainty in the air density given above is 0.5%, which results in a relative mass uncertainty of 0.0005%. Here we claim a water density uncertainty of 0.01% (see Water Density Measurement section below), which results in a relative mass uncertainty of 0.00001%. The combined relative uncertainty in the buoyancy correction for the collected water mass is $5\times10^{-6}\ M_C$, or 0.0005%.

b) The Mass Correction due to Storage Effects

The time integral of the change in water mass in the inventory volume during the collection time interval is given by

$$M_S = \Delta(\rho V_S) = V_S\Delta\rho + \rho\Delta V_S \tag{7}$$

Here, Δ denotes the net change during the collection time interval Δt, ρ is the water density, and V_S is the inventory volume. The uncertainties due to storage effects result from the unsteady state conditions. Thus, it should be noted that for this analysis, changes in temperature refer to temporal variations and not to spatial variations, which naturally occur in a calibration system like the one described here.

When fluid temperature is in a steady state condition, both $\Delta\rho$ and ΔV_S are zero. Thus, allowing the fluid temperature to stabilize throughout the system before flow collection is initiated helps minimize inventory volume storage effects. In our system, temperature measurements are monitored to determine whether the temperature is steady to within 0.05 K/min prior to any flow determination. Under these conditions, the storage effects due to inventory volume changes, $\rho\Delta V_S$, are negligible. The relative volume change, $3\alpha\Delta T$, is $51\times10^{-6}\ V_S$ for $\alpha = 17\times10^{-6}$/K (i.e., stainless steel) and $\Delta T = 0.1$ K. This corresponds to an uncertainty of 0.00051% in the water mass due to storage effects when the inventory volume equals the collected water volume and the collection period does not exceed 2 minutes. Similarly, the storage effects due to water density changes, $V_S\Delta\rho$, are small. The change in water density is $3\times10^{-5}\rho$ for $\Delta T = 0.1$ K, which corresponds to an uncertainty of 0.003% in the water mass due to storage effects when the connecting volume is equal to the collected water volume and the collection period does not exceed 2 minutes.

In reality, the inventory volume is typically smaller than the collected water volume and the collection periods fluctuate from 25 seconds to 2 minutes. For the uncertainties shown in Table 2, the inventory volumes leading to Tank 1, Tank 2 and Tank 3 are 1630 L, 330 L, and 170 L respectively.

c) The Mass Correction due to Leaks

Leaks throughout the system are usually apparent and are fixed before calibrations are initiated. In addition, the leak detection system will shut the calibration down if a leak occurs into, or out of, unused sections of pipe during the calibration. Thus in this uncertainty analysis, we have assumed the water mass leaking out of the system to be negligible.

2. Collection Time Measurement

Contributors to the collection time uncertainty include the uncertainties arising from the calibration of the timer, the mechanism used to actuate the timer, and the diverter itself. These factors are discussed below and their contributions are listed in Table 2.

a) The Timer Calibration

The uncertainty of the timers, τ_{NIST}, used to measure Δt is 0.0001 s. During a typical high flow calibration, which has a collection time of 25 s (worst case scenario), this uncertainty leads to a relative standard uncertainty of 0.0004% in the collection time.

b) The Timer Actuation

The actuation of the timer used to determine the collection time is performed by LEDs which trigger the counters. The uncertainty in the collection time due to the timer actuation, $\tau_{actuator}$, is no greater than the time required for the voltage recorded by the detector to vary from an arbitrary high value to a low value and vice versa. This value is estimated to be 0.002 s leading to an uncertainty of 0.008% for a typical high flow calibration collection time of 25 s. By combining the start and stop uncertainties, we obtain a relative standard uncertainty of 0.0113% in the collection time.

c) The Diverter Error

Since the uni-diverter, which has been incorporated into this flow facility, duplicates the cutting motion during the collection and bypass processes, the components of the diverter valve error are self-canceling, provided the flow remains steady during the calibration. Prototype testing has shown that the uni-diverter error is 0.006% with a standard deviation of 0.03% or less, for even extreme bias conditions [2]. This error includes uncertainties arising from the timer actuation. Since we have already addressed this uncertainty in the previous section, by removing this uncertainty the diverter uncertainty, $\tau_{diverter}$, is estimated to be no more than 0.029%. During prototype tests, the typical collection times were 30 s; however, for practical calibration conditions, the error is expected to be smaller due to better flow stability and a longer collection time.

3. Water Density Measurement

The water used in this facility is drawn from the municipal water supply. Due to dissolved minerals in the water, the density values are offset from those of distilled water. Historically, samples were drawn from the system reservoir and their densities were measured at temperatures near 293 K. The uncertainty of the density measurement, δ_ρ, was 0.005%. The difference between the measured density of the mineral laden water sample and the density of distilled water has been determined. The standard deviation of these values is 0.00004 g/cm^3, or 0.004% of the water density. The density difference is taken as a constant bias to the density of distilled water. This practice will continue with the new system with a sampling frequency dictated by the quality system.

The uncertainty in water temperature also contributes to the uncertainty of water density. The facility uses thermistors for all fluid temperature measurements. Using a circulating water temperature bath, these thermistors are calibrated by a PRT working standard, which has been calibrated by the NIST Thermometry Group. The standard uncertainty in the temperature measured by the PRT, T_{NIST} , is 0.0012 K in the range of 291 K to 308 K for the flow facility. The uncertainty of the thermistors is 0.03 K in the working range.

For distilled water, the density uncertainty, ρ_{NIST} , is less than 0.001% for a 0.03 K uncertainty in water temperature. The combined uncertainty in the value of the water density calculated from the observed temperature, including effects of dissolved minerals in the flowing water, is no greater than 0.01%.

Table 2. Projected Volumetric Flow Measurement Uncertainty.

	Tank 1		**Tank 2**		**Tank 3**	
	Value	%	Value	%	Value	%
1) mass:						
a) collected mass:						
buoyancy correction		0.0005		0.0005		0.0005
scale indication	2.27 kg	0.0072	0.227 kg	0.0036	0.0455 kg	0.0029
scale drift		0.0150		0.0150		0.0150
scale calibration		0.0224		0.0100		0.0100
b) storage effects:						
inventory volume		0.00032		0.00032		0.00068
c) leaks		0		0		0
total mass uncertainty		***0.0279***		***0.0184***		***0.0183***
2) collection time:						
timer calibration	0.0001 s	0.0004	0.0001 s	0.0004	0.0001 s	0.0004
timer actuation	0.002 s	0.0113	0.002 s	0.0113	0.002 s	0.0113
diverter uncertainty, %		0.0289		0.0289		0.0289
total Δt uncertainty		***0.0310***		***0.0310***		***0.0310***
3) water density uncertainty		***0.0100***		***0.0100***		***0.0100***
combined flow uncertainty, u_q		0.043		0.037		0.037
expanded uncertainty, U_q		**0.086**		**0.075**		**0.075**

Conclusions

The new NIST static-gravimetric Water Calibration Facility is under construction at the Gaithersburg Campus. The facility incorporates an uni-diverter valve design, which will significantly reduce the uncertainty associated with traditional diverter mechanisms. With the use of the uni-diverter and better control over flow parameters, the 2σ value for the uncertainty of the system is expected to be no greater than 0.086%. This represents a significant reduction from the 0.12% uncertainty claimed for the prior NIST Water Calibration Facility.

This uncertainty analysis is only an estimate for a system not yet operational. As progress is made in its construction, these estimates are bound to change.

Acknowledgements

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