National Institute of Standards and Technology
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NIST Measurement Services:

NIST Calibration Services for Water Flowmeters
Water Flow Calibration Facility

NIST Special Publication 250

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Abstract

This document describes the Water Flow Measurement Standards at the National Institute of Standards and Technology (NIST). These primary standards are disseminated using calibration services offered by NIST's Fluid Metrology Group using its Water Flow Calibration Facility (WFCF). This facility has three parallel pipelines with diameters of 100, 200 and 400 mm and three weighing systems with capacities of 1100 kg, 3700 kg and 22500 kg. Part of the WFCF which includes a 3700 kg collection tank and a 100 mm pipeline (for the sake of simplicity hereafter referred to as WFCF 3700/100) is now complete and operated by the Fluid Metrology Group. The WFCF 3700/100 is used to provide water flowmeter calibration services as reported in [1] for the Calibration Service ID Number 18020C. The WFCF 3700/100 uses the static gravimetric method [2] and an error-free uni-directional diverter with a collection/bypass unit (CB unit) to perform water flowmeter calibrations between 40 L/min and 1600 L/min. The WFCF measures flow using the static gravimetric method that employs weighing the water collected in the 3700 kg tank during a measured time interval [3]. The expanded uncertainty of the flow measurement is 0.033 % when a full tank (3700 kg) is weighed (k = 2 or approximately 95 % confidence level).

Key words: calibration, correlated uncertainty, flow, flowmeter, water flow standard, diverter, mass calibration, meter, uncertainty.

1 Introduction

We provide an overview of the water flow calibration service and the procedures for customers to submit their flowmeters to NIST for calibration. We describe the significant and novel features of the standard, in particular, the uni-diverter with CB unit, and analyze its uncertainty. We demonstrate theoretically and experimentally that the newly developed uni-directional diverter with CB unit leads to virtually zero time correction and low uncertainty contributions from the diverter performance. The largest source of uncertainty is the measurement of the mass of water collected. Procedures and periodicities for calibration of reference masses, the weigh scale, density, temperature, time, and humidity sensors, are described together with their uncertainty and stability.

Calibrations of liquid flowmeters are performed with primary standards [2-4] that are based on measurements of the more fundamental quantities: length, mass, time. Primary flow calibrations are accomplished by timed collection of the measured mass of water flowing through the meter under test (MUT) during approximately steady conditions of flow, pressure, and temperature. All of the quantities measured in connection with the calibration standard (i.e., temperature, mass, time, etc.) are traceable to established U.S. national standards. The flow measured by the primary standard is computed along with the average of the flow indicated by the MUT during the collection interval. An additional flowmeter is normally used to set the test flows and to monitor the flow stability.

NIST's Water Flow Calibration Facility consists of the 3 fundamental component parts:

- *flow generation system*: comprised of storage tank, pumping system, and a flow control system which actuates the control valves. The *flow generation system* produces the water flow through the test section at the constant rate required for test point series necessary for a calibration.
- *test section*: piping system producing the required flow conditions for the MUT. The main purpose of this piping system is to implement ideal flow for flowmeter operation, i.e. the appropriate, fully developed pipe flow for the conditions. Therefore, an axisymmetric filter and two flow conditioners (tube-bundle and perforated plate) are installed upstream of the flowmeter 15 meters (or 150 diameters of the pipe) away the MUT to avoid any flow disturbance that might affect the meter performance.
- *gravimetric reference system*: weigh system with collection tank and a flow diverting device. This device is the part of the calibration system that directs the flowing water into the collection tank while triggering a clock to determine the collection time. The water collected can be determined in terms of volumetric or gravimetric units.

NIST offers calibration services for water flowmeters in order to provide traceability for flowmeter manufacturers, secondary flow calibration laboratories, and flowmeter users. For a calibration fee, NIST calibrates a customer's flowmeter and delivers a calibration report that documents the calibration procedure and the calibration results, with their uncertainty. The flowmeter and its calibration results may be used in different ways by the customer. The flowmeter is often used as a transfer standard to perform a comparison of the customer's primary water flow standards to NIST's primary water flow standards to establish the customer's traceability, to validate their uncertainty analysis, and to demonstrate the proficiency of their testing process. Customers without primary standards can use their NIST calibrated flowmeters as working or reference standards in their laboratory to calibrate other flowmeters.

The Fluid Metrology Group of the Process Measurements Division (part of the Chemical Science and Technology Laboratory) at NIST now provides water flow calibration services over a range of 40 kg/min to 1600 kg/min. After completion of 200 mm and 400 mm pipelines with 1100 kg and 22500 kg collection tanks, NIST will be able to provide water flow calibration services in the range of 8 kg/min to 38,000 kg/min.

Table 1 presents the flow ranges covered by the present and planned primary water flow standards available from the Fluid Metrology Group.

Table 1. Primary water flow calibration capabilities within the NIST Fluid Metrology Group. Green regions represent operational systems, white regions represent those under construction.

Feature	Tank 1	Tank 2		Tank 3
Tank Volume, L	22000	3700		900
Tank Material	Steel	Fiberglass		Fiberglass
Scale Type	Load Cell	Weigh Scale		Weigh Scale
Scale Capacity, kg	22500	4500		1100
Scale Resolution, kg	2	0.2		0.04
Pipe Size, mm	200 to 400	100 to 200		25 to 100
Flow Range, L/min	880 to 38,000	40 - 1,600 (100mm)		8-1500
		200-4,900 (200mm)		
Working Pressure, kPa	100-1000	100-1000		100-1000
Expanded Uncertainty	0.086% (projected)	3000 kg	600 kg	0.075% (projected)
		0.033%	0.051%	

This document describes the theory, methods of operation, and uncertainty of the 100 mm pipeline with the 3700 kg collection tank primary standard that covers the flow range from 40 L/min to 1600 L/min.

2 Description of Measurement Services

Customers should consult the web address www.nist.gov/fluid_flow to find current information regarding NIST's calibration services, fees, technical contacts, and flowmeter submittal procedures.

NIST uses the WFCF 3700/100 primary standard described herein to provide water flowmeter calibrations for flows between 40 L/min and 1600 L/min. The facility can be used at flows as low as 10 L/min and as high as 1800 L/min, but calibrations below 40 L/min and above 1600 L/min should be discussed with NIST flow calibration staff before a flowmeter is submitted for calibration.

The WFCF does not have a temperature control system and, therefore, only room temperature calibrations are available. Since pump heating occurs, the temperature increases during the test procedure at a rate of about 0.2 K/hour. Typically, flowmeter calibration results will produce unique curves when appropriate compensation is made for the viscosity and density of the water and thermal expansion effects in the meter.

Meters can be calibrated at NIST if the flow range and piping connections are suitable, and if the system to be tested is judged to have the precision appropriate for the WFCF flow measurement uncertainty. Typical flowmeters calibrated in the WFCF are high quality turbine, ultrasonic, Coriolis, and magnetic flowmeters. The precision, repeatability, and reproducibility (see [8, 9]) of these flowmeters are generally considered appropriate for the WFCF. However, other flowmeters can be tested as well, where customers feel they need the cost-benefits of having a NIST calibration of their meter. Flowmeter types with significant imprecision (instabilities significantly larger than the WFCF uncertainty) should probably not be calibrated in the WFCF for economic reasons.

A normal flow calibration performed by the NIST Fluid Metrology Group is intended to quantify meter performance and its stability or precision. This is done by making multiple measurements in the desired test conditions to produce meter factor averages and standard deviations. Calibrations generally consist of two sets of measurements, with increasing and decreasing flow adjustments, where 5 successive measurements are made at each flow set point. The scatter in each set of 5 can produce a standard deviation that can be termed a Repeatability. Repeatability can quantify the short-term stability of the meter. Longer-term stability is usually quantified by changing the conditions to include typical usage patterns for the meter, such as turning it off and then turning it back on. The two sets of 5 measurements determined at essentially the same set point, but after the system is turned off and then turned back on can produce a standard deviation that can be termed a TOTO (Turn-Off-Turn-On) Reproducibility. Typical calibration set points might be chosen at nominal rates, such as: 40 L/min, 200 L/min, 500 L/min, 1000 L/min, and 1600 L/min. Therefore, the final data set consists of 50 (or more) primary flow measurements with corresponding meter outputs made at five flow set points. The sets of five measurements can be used to assess meter performance in terms of averages and repeatability (short term stability or the closeness of agreement among a number of consecutive measurements), while the sets of ten can be used to assess reproducibility (long term stability or the closeness of agreement among a number of repeated measurements when conditions change). For further explanation, see the sample calibration report in Appendix. Variations on the number of flow set points, spacing of the set points, and the number of replicated measurements can be discussed with the NIST technical contacts. However, for data quality assurance reasons, NIST rarely conducts calibrations involving fewer than three flow set points and two sets of three flow measurements at each set point.

Whenever it is possible, the Fluid Metrology Group presents flowmeter calibration results in a dimensionless format that takes into account the physical model for the flowmeter type. The dimensionless parameter approach usually facilitates accurate flow measurement performance when the conditions of use (temperature, viscosity, and dimensional changes) differ from the conditions used for the calibration.

Hence, for a turbine flowmeter calibration, the calibration report will present Strouhal number versus Reynolds or Roshko number.

3 Procedures for Submitting a Flowmeter for Calibration

The Fluid Metrology Group follows the policies and procedures described in Chapters 1, 2, and 3 of the NIST Calibration Services Users Guide [7]. These chapters can be found on the internet at the following addresses:
http://ts.nist.gov/ts/htdocs/230/233/calibrations/Policies/policy.htm,
http://ts.nist.gov/ts/htdocs/230/233/calibrations/Policies/domestic.htm, and
http://ts.nist.gov/ts/htdocs/230/233/calibrations/Policies/foreign.htm.

Chapter 2 gives instructions for ordering a calibration for domestic customers and has the sub-headings: A.) Customer Inquiries, B.) Pre-arrangements and Scheduling, C.) Purchase Orders, D.) Shipping, Insurance, and Risk of Loss, E.) Turnaround Time, and F.) Customer Checklist. Chapter 3 gives special instructions for foreign customers. NIST contact information can be found www.nist.gov/fluid_flow .

4 The NIST Water Flow Primary Standard

The static gravimetric liquid flow measurement method is used by the WFCF 3700/100. The WFCF 3700/100 is designed to have uncertainty levels that are lower than high-performance flowmeters or secondary standards for which it provides flow traceability. The main features of the WFCF 3700/100 are a well established theory, a complete and detailed uncertainty analysis, and traceability to the NIST mass, time, temperature standards. The WFCF is a highly automated facility. It uses the National Instruments LabView environment and custom designed virtual instruments to operate mechanical and electronic equipment of the standard during calibration and to store data (see section 6 for details).

4.1 Fundamentals of the Static Gravimetric Method

Static gravimetric liquid flow calibration systems are widely used as primary liquid flow standards by NIST and other laboratories. Primary static weigh flow calibrations are arranged by collecting a measured mass of the fluid flowing through the meter being calibrated over a measured time interval under approximately steady conditions of flow, pressure, and temperature at the meter under test. All of the quantities measured in connection with the calibration standard (i.e., temperature, mass, time, and density) are traceable to established national standards. The flow measured by the primary standard is computed along with the average of the flow indicated by the meter under test during the collection interval. The calibration result, in the form of a meter factor, is the ratio of the computed flow result from the standard to the averaged meter indication, or the reciprocal of this ratio. An additional flowmeter is normally used in the test pipe to set flow, to check the flow stability, and possibly to assist in processing final results.

One can derive an equation for the average mass flow through the meter being calibrated during the collection time by writing a mass balance for the control volume composed of the inventory and tank volumes:

$$\dot{m} = \frac{M}{\Delta t} + (\rho_2 - \rho_1)V_I, \qquad (1)$$

where M is collected mass and Δt is collection time. The inventory volume, V_I is the volume of piping between the meter under test and the standard used, at the end of the pipe, to measure the flow. The densities ρ_1 and ρ_2 are those in the inventory volume at the beginning and end of the collection interval. This equation applies to an idealized set of conditions: (1) the flow velocity profile exiting the pipe and entering the standard is symmetric with respect to the middle of the fishtail, and (2) the motion of diverter in the middle of the water jet is horizontal. Under these conditions, the start and stop time signals provide the proper collection time. More information about Static Gravimetric Method can be found in the Refs. [2, 3].

4.2 Equipment Arrangement, Schematic and Operation Sequence

The layout of the WFCF is shown below (Figure 1).

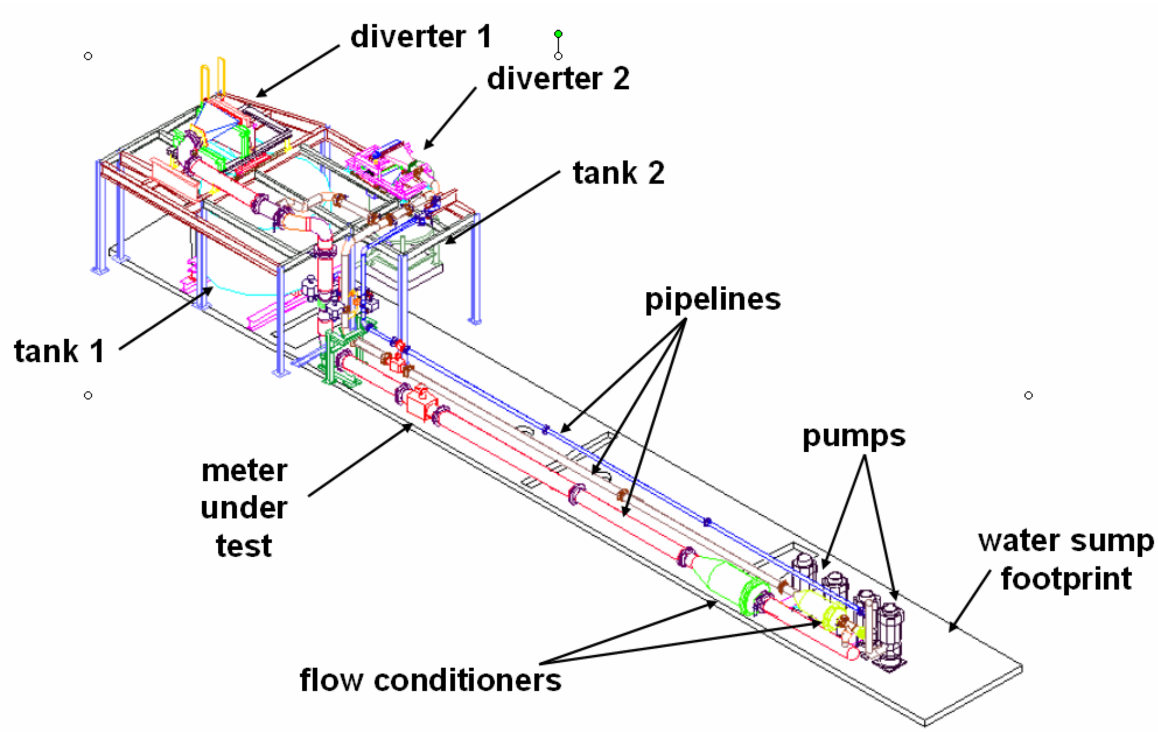

Figure 1. A Perspective Drawing of NIST's Water Flow Calibration Facility.

The NIST WFCF is a closed loop flow system that consists of a flow source (centrifugal pumps), flow conditioners, pipe lines, test section for the MUT installation, valves for changing the flow, a diverter with CB unit (see below), collection tanks, weigh scales, and a timer (see also Figure 2 and 3). The facility is located above a water reservoir that has a capacity of approximately 230 m^3. Water flow is produced and maintained in the system by four constant velocity pumps, three driven by 112 kW electric motors (pumps P-1 to P-3, in Fig 2) and one driven by a 75 kW electric motor (pump P-4). A manifold splits the flow into three separate test section pipelines and a bypass of 200 mm diameter. The three pipelines are coupled to facilitate flow comparisons between the tanks and to permit tests with long collection times by collecting low flows in the larger tanks. Downstream of the manifold, each pipeline has a flow conditioner that delivers a symmetric, fully developed turbulent velocity profile to the flow meter in the test section. Upstream of the meter under test, the facility has straight lengths of 24 diameters for the 400 mm pipeline, 76 diameters for the 200 mm pipeline and 174 diameters for the 100 mm pipeline.

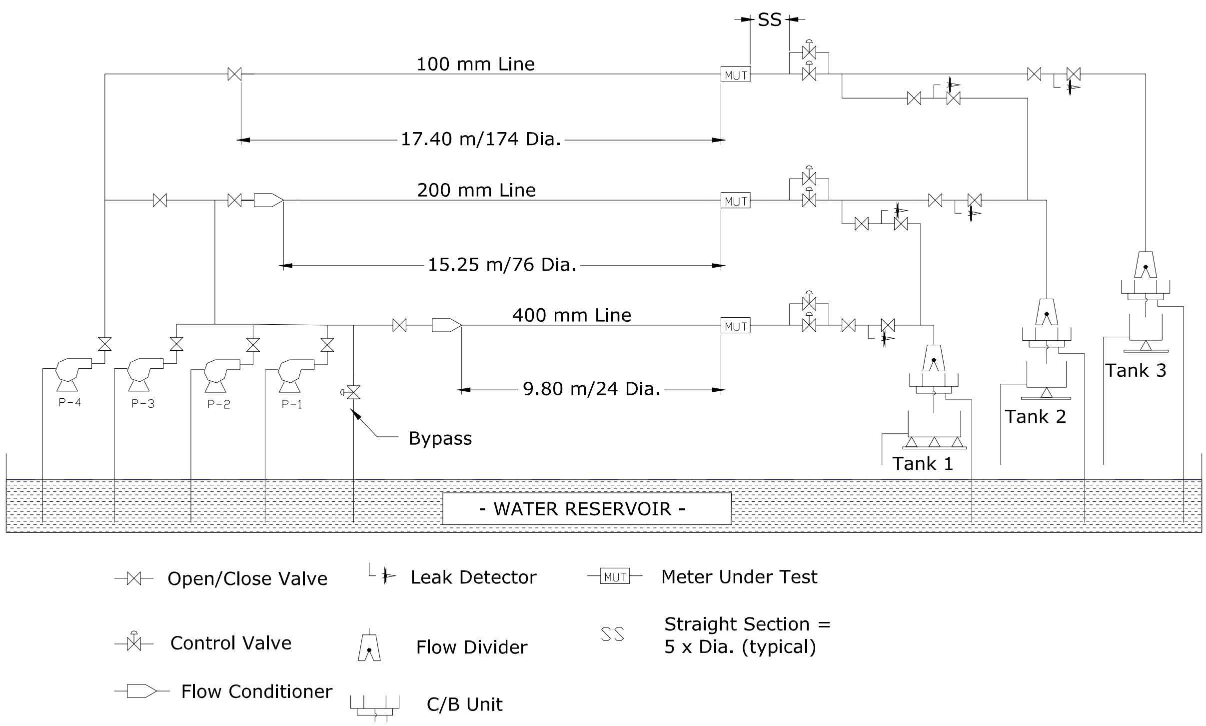

Figure 2. A Sketch of the Flow Paths of the Water Flow Calibration Facility.

Flow at the test section is controlled by two sets of valves. One set is located upstream near the pump, a main valve for each pipeline and a bypass throttle valve that controls the amount of water returned to the reservoir without passing through the meter test section, see Fig 2. The other valves on each pipeline (located downstream of the test section) are the fine and coarse controls for setting the water flow rate and the pressure in the test section of the WFCF. Once the flow passes through the meter under test and the control valves, it goes through two valves in series (a leak detection system) and then a fishtail which produces the rectangular jet flow for the diverter mechanism, see Fig 3. See also Ref. 5 for details.

The process of making a gravimetric flow measurement normally consists of the following steps:

1. Close the tank valve, open the bypass valve, and establish a stable flow through the pipeline and the meter under test.
2. Zero the weigh scale or measure the initial mass of water in the collection tank.
3. Switch the diverter to the position to collect water in the collection tank and start the timer to initiate the collection time measurement. At the same time, record the initial water temperature in the pipeline between the MUT and the collection tank and the room air temperature, pressure, and humidity (for buoyancy corrections to the collected mass measurement.).
4. Collect the water passing through the MUT during the measured collection time (time should be long enough to collect >600 kg of water).
5. Reverse the diverter position and trigger the stop time.
6. Measure the final mass of water in the collection tank, and, after this, drain the collection tank.

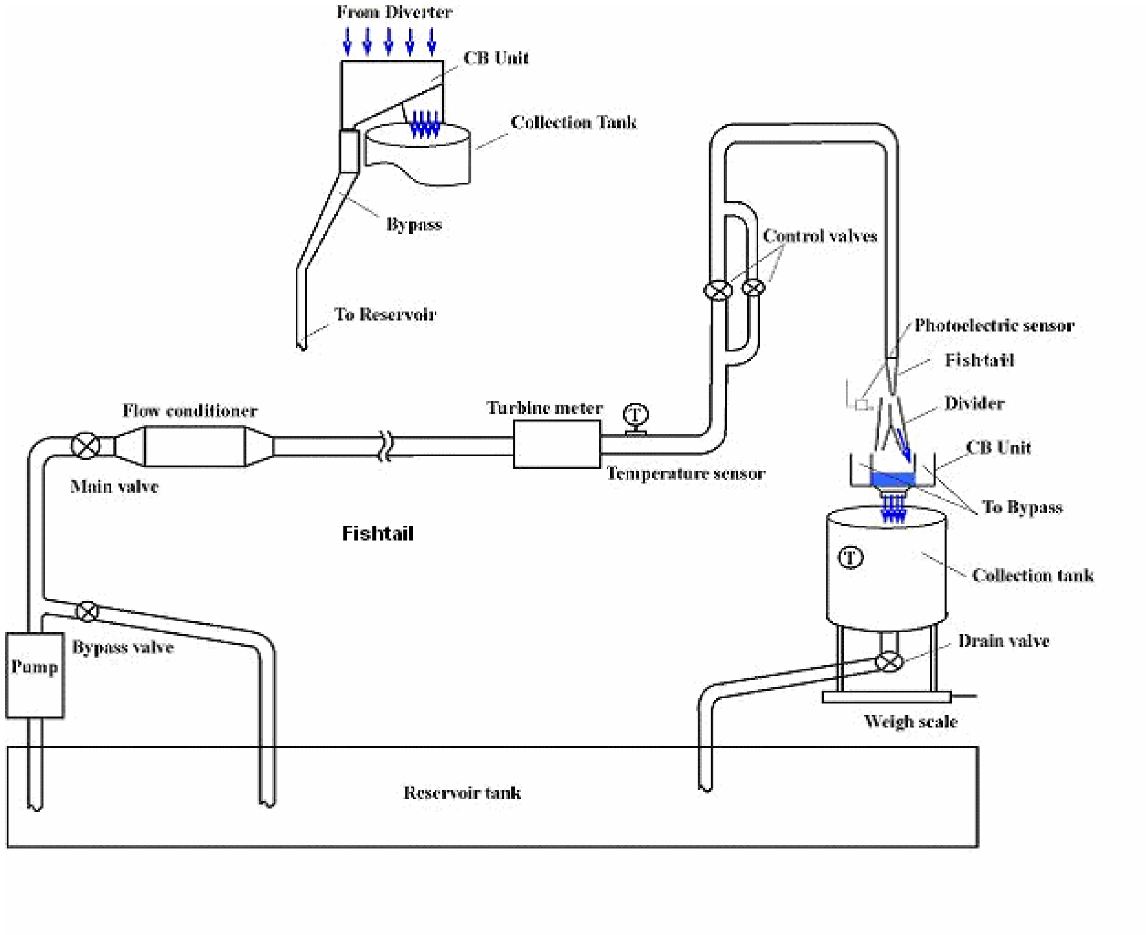

Figure 3. Sketch of the Arrangement of Equipment in the WFCF 3700/100 System.

4.3 Error-Free Uni-directional Diverter: Theory and Design

The nozzle and diverter are designed to 1) rapidly switch the flow from the collection tank bypass to the collection tank and back again without disturbing the flow conditions in the test section and 2) generate the timing signals for accurate measurement of the collection time. During a normal calibration cycle, two diverter traverses are required: a first traverse to switch flow from the bypass loop into the collection tank (starting a timer), and a second one to switch flow back to the bypass (stopping the timer).

The WFCF 3700/100 uses a uni-directional diverter that is immune to certain sources of uncertainty found in traditional diverters. In the traditional diverter design, a dividing plate is moved through a rectangular jet flowing out of the fishtail, see Fig 3. At the start of the collection, the dividing plate switches the flow from the bypass channel into the collection tank. At the end of the collection interval, the diverter traverses the jet in the opposite direction returning the flow to the bypass. The traditional diverter usually requires a correction time resulting from any asymmetry of the distribution of the flow exiting the fishtail and any asymmetry of the diverter motions through the rectangular jet exiting the fishtail. The procedure for conventional diverter correction, which is usually a function of liquid flow rate, is given in many flow measurement standards, see Refs. [2, 5, 6].

The basic concept of the new diverter system developed for the NIST WFCF by the Fluid Metrology Group makes use of repeated unidirectional motions of the diverter valve in order to reduce errors associated with asymmetry in the diverter valve motion and in the liquid jet velocity profile. A theoretical consideration and supporting experimental data of the uni-directional diverter performance are given in [5, 6]. Here only a brief description will be given. The uni-directional diverter exploits the idea of error self cancellation under condition A+D = B+C or A=C & B=D or A=B and C=D (see Figure 4).

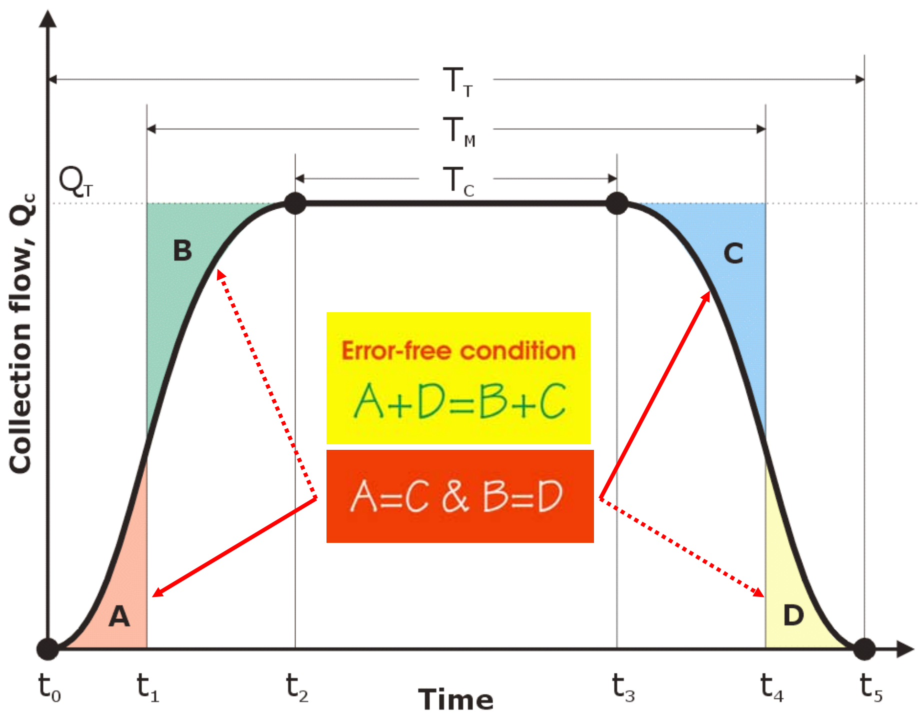

Figure 4. Collection Flow Diagram and Error-free Conditions.

The uni-diverter is made to move in the same direction through the liquid jet both at the beginning and the end of the water collection. Its design has two separate active elements (See Fig. 5): 1) a traditional divider (which cuts the flow) is operated by a pneumatic angular actuator and 2) a Collection/Bypass (CB) unit that directs the flow to the bypass or the collection tank regardless of the divider position. The CB unit is mounted below the divider on linear bearings and can be moved horizontally under computer control. Three proximity sensors detect the location of CB unit and transmit it to the computer. The CB unit consists of three separate channels and coordination of the position of the CB unit with the position of the divider allows cutting the water jet in the same direction for both the start and stop of the collection. The uni-directional travel of the divider dramatically reduces errors due to asymmetry in 1) the divider actuated motion, 2) the liquid jet velocity profile, and 3) the position of the diverter trigger [6]. The full operation sequence of the uni-diverter system is shown in Figure 6.

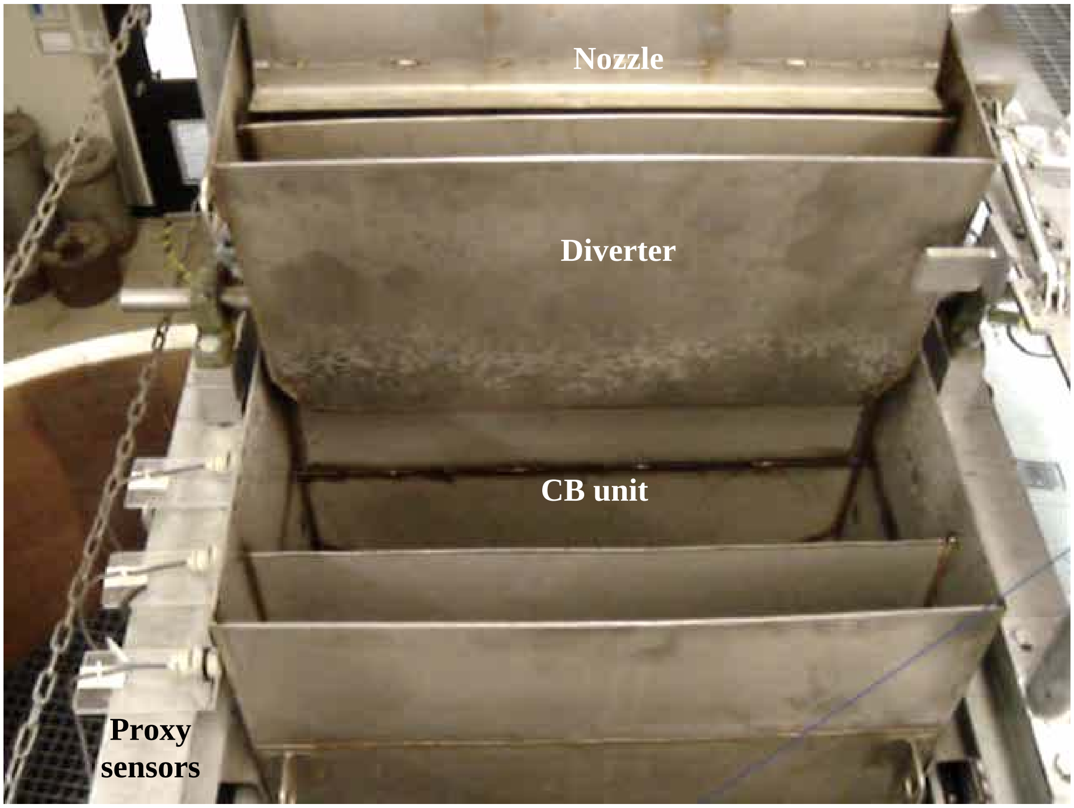

Figure 5. Photograph of the Uni-diverter

Thus uncertainties due to jet profile asymmetry and any asymmetries in the divider velocity versus time as it moves through the jet are negligible. Hence, time uncertainties of the uni-directional diverter arise only from temporal instabilities of the flow, instabilities in the water jet profile, and any irreproducibility of the divider motion in a single direction. The freedom to choose the locations of the start and stop switches is a valuable feature of the uni-directional diverter. Performance tests of the uni-directional diverter are given below.

A comprehensive analysis of the uni-directional diverter can be found in [6].

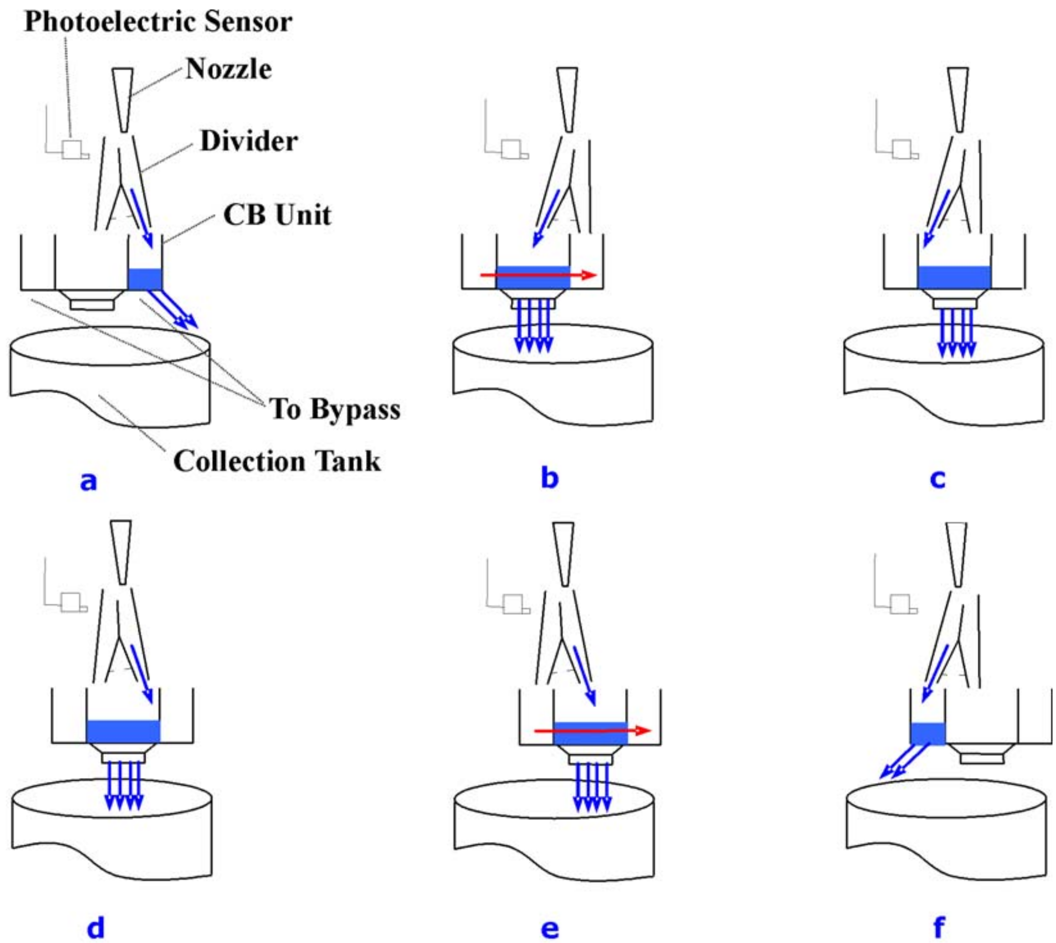

Figure 6. Collection-bypass Cycle.

5 Uncertainty Analysis for NIST's Water Flow Calibration Facility

In this section, we will analyze summarized in the Table 2 the uncertainties of the WFCF 3700/100. Firstly, we will briefly describe the subject of uncertainty analysis itself, together with the current conventions that apply. Next, we will give the results of the uncertainty analysis for mass flow. We will give uncertainties of the sub-components such as those for collected mass, the density of the fluid flowing through the meter during the collection, and the collection time which must be combined to obtain the mass and volume flow rate uncertainties. The comprehensive graphical representation of the measurement equation that serves as the basis for the uncertainty analysis and explanation of notations is given in Ref.1. An additional uncertainty source (beyond those listed in Ref. 1) is the water evaporation M_E, shown in the diagram in Figure 7.

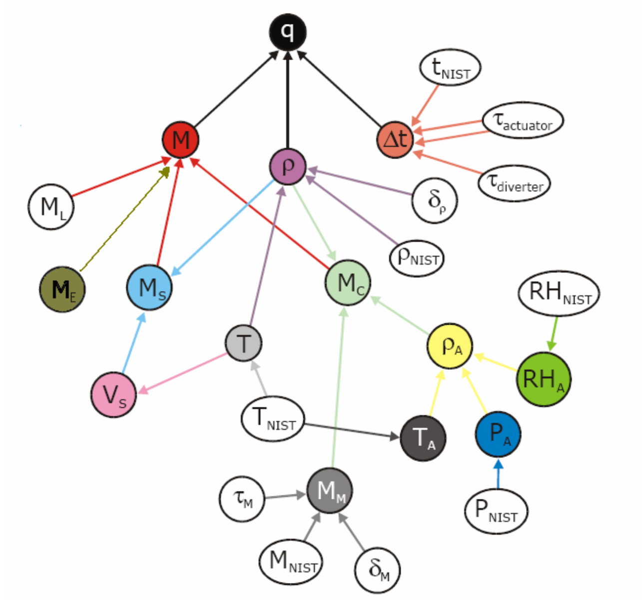

Figure 7. Uncertainty Diagram (Ref.1).

Table 2. Uncertainty Budget of the WFCF 3700/100 for Mass Collections of 3000 kg and 600 kg.

	Reference	Value	Uncertainty, %	Uncertainty, %
Collected Mass			3000 kg	600 kg
1. *Mass uncertainty*				
Scale indication, 0.2 kg	5.2.1.1	0.2 kg	0.004	0.02
Scale drift	5.2.1.1		0	0
Scale calibration	5.2.1.1		0.01	0.01
Buoyancy correction	5.2.1.2		0.0005	0.0005
Leaks and splashes	5.2.1.3		0	0
Storage effects	5.2.1.4		0.003	0.003
Evaporation	5.2.1.5		0.004	0.004
Total mass uncertainty			**0.012**	**0.023**
2. *Collection time uncertainty*				
Timer calibration	5.2.2.2	0.0001 s	0.0004	0.0004
Timer actuation and diverter	5.2.2.1		0.01	0.01
Total time uncertainty			**0.010**	**0.010**
3. *Water density uncertainty*	5.2.3		0.0053	0.0053
Combined uncertainty for Q			**0.016**	**0.026**
Expanded uncertainty for Q (95% confidence level)			**0.033**	**0.051**

5.1 Techniques for Uncertainty Analysis

The uncertainty of a mass flow measurement with the WFCF 3700/100 is based on the techniques described in Refs.[8, 9] The process identifies the equations involved in the flow measurement so that the sensitivity of the final result to uncertainties in the input quantities can be evaluated. The uncertainty of each of the input quantities is determined, weighted by its sensitivity coefficient, and combined with the other uncertainty components to arrive at the combined uncertainty, using the root-sum-squared technique.

As described in [8, 9], consider a process that has an output, y, based on N input quantities, x_i. For the generic basis equation:

$$y = y(x_1, x_2, \ldots, x_N)\,, \tag{2}$$

if all the uncertainty components are uncorrelated, the standard uncertainties can be combined using the root-sum-squares (RSS) technique to give:

$$u_c(y) = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial y}{\partial x_i} \right)^2 u^2(x_i)}\,, \tag{3}$$

where $u(x_i)$ is the standard uncertainty for each of the inputs, and $u_c(y)$ is the combined standard uncertainty of the measurand. The partial derivatives in Eq. 3 represent the sensitivity of the measurand to the uncertainty of each input quantity.

5.2 Volumetric Flow

Volumetric flow, Q, is derived from the mass flow knowing the average liquid density, ρ, at the MUT location during the collection interval, i.e.,

$$Q = \frac{\dot{m}}{\rho} = \frac{M}{\Delta t \rho} \tag{4}$$

The combined uncertainty of the volumetric flow rate is calculated using the propagation of component uncertainties and then using the root-sum-square (RSS) method to combine the results. The three main uncertainty components are those that arise from the collected mass, collection time, and water density, and their combination gives:

$$u = \sqrt{u_M^2 + u_{\Delta t}^2 + u_\rho^2} \tag{5}$$

where u_M, $u_{\Delta t}$, and u_ρ are the standard uncertainties of the collected mass, collection time, and liquid density, respectively. The confidence interval given by this equation is 68%. A coverage factor of $k = 2$, will be used to convert the combined standard uncertainty to the expanded uncertainty with approximately 95% confidence level.

5.2.1 Collected Mass Uncertainty

5.2.1.1 Scale Calibration, Mass Standards Calibration, Long-term Stability, and Sensitivity

The first component of mass uncertainty we will consider is the weigh scale resolution. For a collection mass M the weigh scale resolution of 0.2 kg leads to an uncertainty of $\frac{0.2}{M\sqrt{3}}$ or 0.004% for fully filled tank (3000 kg) and for 20% filled tank 0.02% (the square root of 3 takes into account Rectangular to Normal Probability Distribution conversion).

Another part of the mass uncertainty is scale calibration. Calibration of the weighing scale uses a sequential, incremental loading method based on a set of 45 kg weights calibrated at NIST using the 65 kg weight set and 60 kg mass comparator from NIST's Volume calibration service. The traceability of water flow measurements to the national standards of mass is through a 65 kg set of stainless steel weights calibrated by the NIST Mass and Force Group, http://www.mel.nist.gov/div822/groups.htm. Weights from the 65 kg set are used to calibrate the 60 kg mass comparator. The weighing system is composed of 12 mass standards of 45 kg each and used for calibration and checking of the operation of the weighing scale (See Fig. 8).

The calibration procedure requires replacing the steel weight of the mass standards using water and then adding mass standards to sequentially progress across the scale range to calibrate the full capacity of the weighing scale. This is done because a sufficient number of mass standards are not available to complete the calibration without partial water fills. The procedure with using mass standards and water load equivalents leads to a higher uncertainty. Figure 9 illustrates the scale calibration procedure, and the following steps describe the tasks.

1) Close the drain valve of the weigh tank. At the initial position of the calibration process, the masses lie on a stand attached to the floor (See Fig. 8). When the calibration starts, the system sets 0 kg, at this point the balance bears the tare weight of residual liquid in the tank. Record the scale indication.
2) Place the set of 45 kg mass standards on the scale. These masses are raised by a pneumatic system of pistons that grab the 3-stacked masses in 4 sets. The load cells read the corresponding nominal mass of 540 kg. Record the scale indication.
3) Remove the set of 45 kg mass standards from the scale and fill the tank until the scale indicator value is identical to that obtained in the last iteration of step 2. Care must be exercised to match the value indicated when loaded with the mass standards.
4) Repeat steps 2 and 3.

Buoyancy corrections are taken into account for both water and steel weights (see paragraph 5.2.1.2).

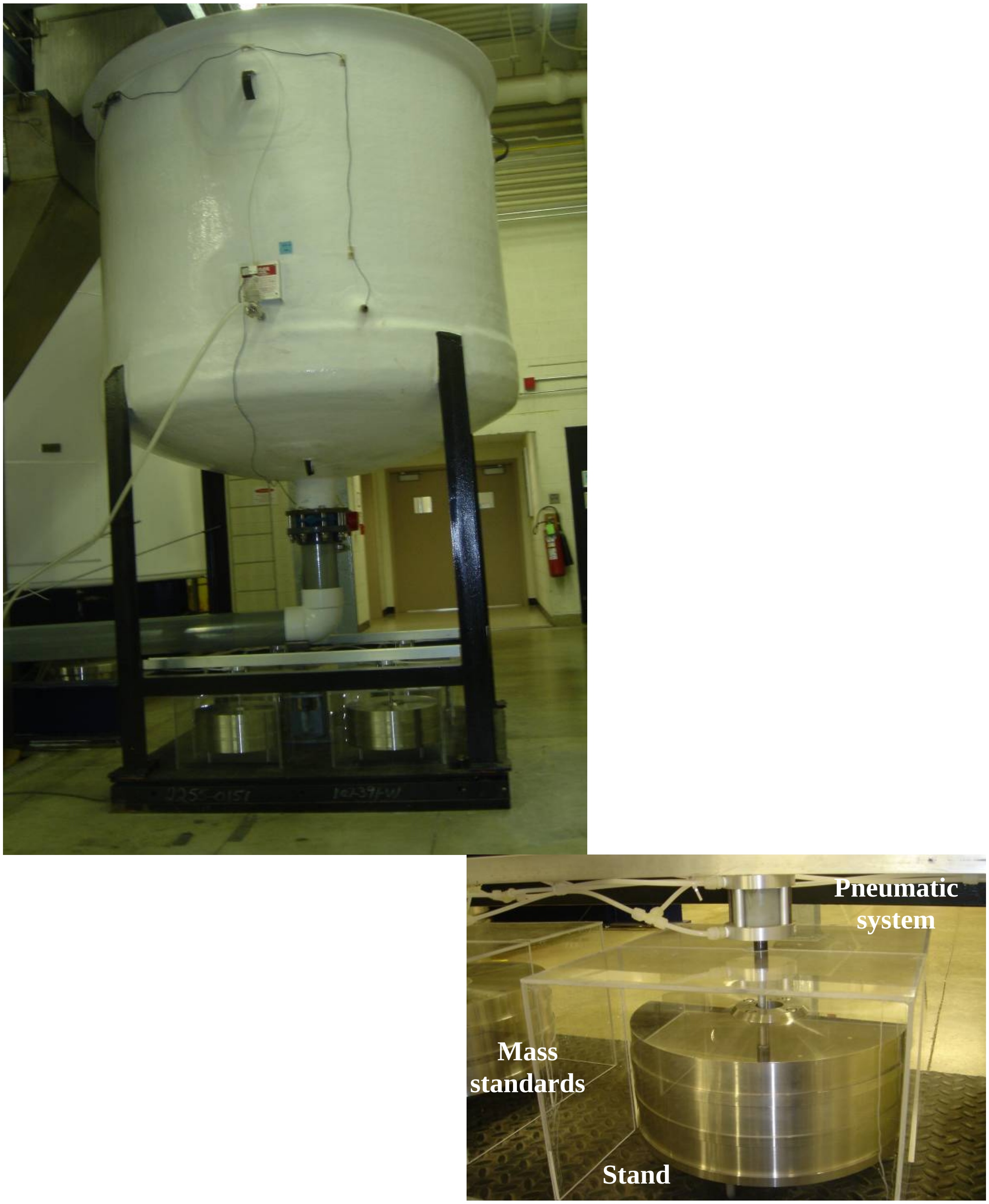

Figure 8. Weighing System for WFCF 3700/100 and Mass Standards

The maximum tank load is about 3700 kg, the reference mass is approximately 540 kg so the number of mass increments necessary to fully load the scale is 6 or 7.

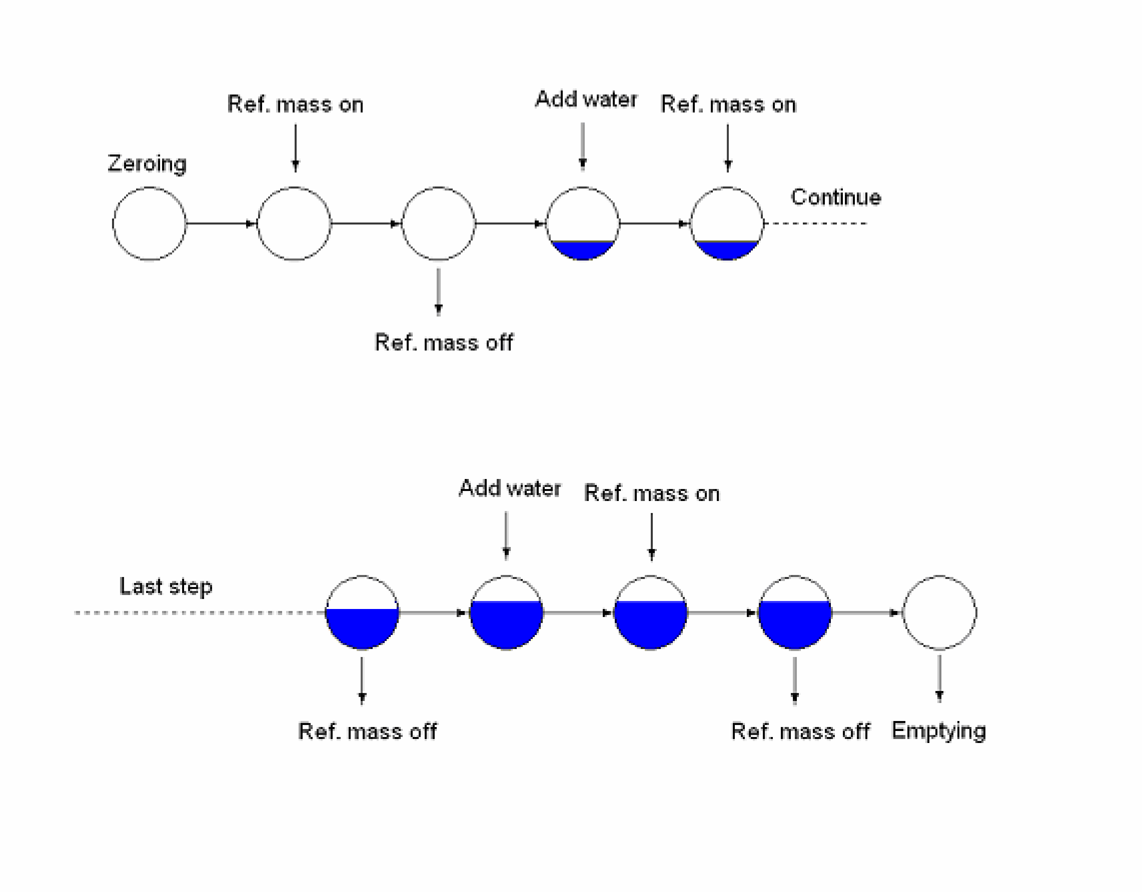

Figure 9. The Scale Calibration Sequence

The following system of equations is used to describe the data reduction procedure.

$$m_i^{on} = M(m_i^{off}) + M_{ref} , \quad (6)$$

where m_i, $M(m_i)$ are scale indications and corrected masses for each step and M_{ref} is the mass of the reference weights. Superscripts *on* and *off* indicate the position of the weights. The task of the fitting procedure is to find a minimum by the least square method of the value:

$$\sum_{n}^{i=0} \left(M_{i,fit} - M\left(m_i^{on}\right)\right)^2 , \quad (7)$$

where $M_{i,fit}$ - fitted value. Three different functional forms for the corrected mass dependence were chosen: linear dependence, quadratic dependence and linear dependence which crosses the origin. It was found that the last form was sufficient to fit all data. In the procedure described above the actual parameter which is being calibrated is the slope $K = \frac{\Delta M}{\Delta m}$, for different scale loads.

The value of the scale coefficient averaged over the two year period (2004-2005, see Fig.10) is 0.99881 ± 0.00007. In 2006 the scale coefficient was found to be 0.99884 ± 0.00010 (or $\pm$ 0.01%) and this value is included in the uncertainty budget, Table 2.

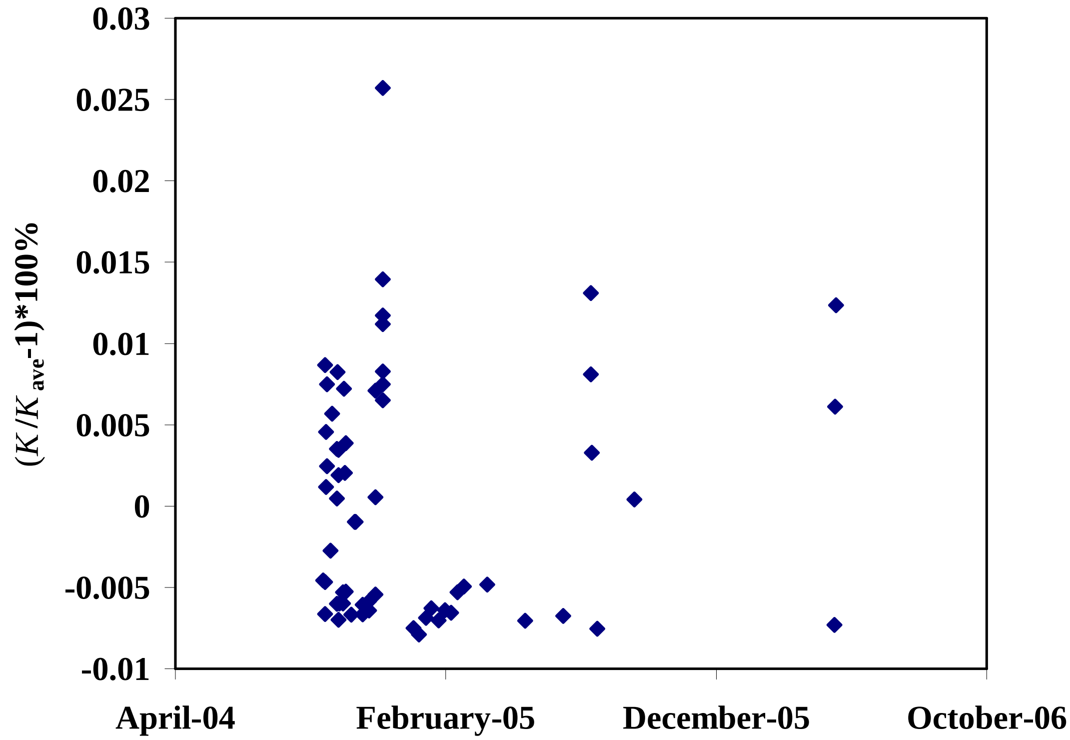

Figure 10. Residuals from Linear Fit

The calibration results for the weigh scale over the past two years show that the pressure and temperature dependencies of the weigh scale and any other sources of drift in the scale calibration are much smaller than the uncertainty in scale calibration, 0.01%, and, therefore can be neglected.

The pneumatic weight handling system has improved the efficiency of the scale calibration technique to enable a scale calibration prior to each flowmeter calibration if necessary.

The scale performance is checked periodically by placing a weight stack of known mass from NIST’s Volume calibration service on the scale.

The set of 45 kg weights is used for calibration and checking the operation of the weighing scale. These 45 kg weights are calibrated by a double substitution weighing method using the 65 kg set and 60 kg mass comparator from NIST’s Volume calibration service. The uncertainty of NIST’s Mass Standards calibrations are less than 3 parts per million and are negligible in comparison with the other types of scale uncertainties mentioned here.

5.2.1.2 Buoyancy Correction

The mass values observed by the weigh scales in the static weighing system are subject to buoyancy forces. According to Archimedes' Law, to obtain the true mass of the water collected, the air and water densities are required. The true mass can be found using the following relationship:

$$M_T = \frac{M_M}{\left(1 - \frac{\rho_A}{\rho_W}\right)} \qquad (8)$$

where M_M is the apparent mass indicated by the scale, ρ_A the air density, and ρ_W is the water density. The buoyancy uncertainty for the WFCF was estimated in [1] and it is less than 0.0005%.

5.2.1.3 Splashes and Leaks

Liquid splashing from the diverter and weigh system and minor leaks from the pipework are usually apparent and are eliminated before calibrations start. Therefore, uncertainties for splashes or leaks are neglected.

5.2.1.4 Storage effects

Storage effects due to changes in the density of the water and dimensions of the pipes for the volume between the MUT and the outlet of the fishtail (the inventory volume) must be considered. For the WFCF, this effect is estimated to be less than 0.003% [1].

5.2.1.5 Water Evaporation

In the case of low flows, the collection time required to obtain an acceptably large mass change in the collection time can be quite long. For example, a calibration of a flowmeter at the rate 40 L/min takes about 15 min to fill the tank completely. Tests show that for the normal air conditions of 100 kPa, 22°C, and 50% humidity the uncertainty due to the evaporation is about 0.0004% (k=1).

5.2.2 Collection Time Uncertainty

5.2.2.1 Uni-directional Diverter Tests

The diverter is one the of critical elements in the design of a liquid flow primary standard. A complete flow diverter system provides four important functions:

1. It changes the direction of the flow stream without splashing or leaking,
2. It channels the desired flow direction to the collection tank,
3. It starts the timer, and
4. It stops the timer.

Diverting the flow and starting the timer can cause a timing error related to the specific transition point for the flow into the weighing tank. Similarly, the return diversion of the flow to the by-pass channel and stopping the timer can cause timing error. Therefore, the determination of the uncertainty of the collection period is crucial.

Uncertainties in the diversion process originate from several sources:

1. The finite time required for the dividing plate to traverse through the rectangular jet,
2. Asymmetries in the velocity profile of the rectangular jet flow from the fishtail,
3. Differences in the divider motions in the two directions, and
4. The positioning of the timer triggers for the dividing plate positions in the rectangular jet.

Tests designed to evaluate uncertainties related to the diverter vary the collection time at nominally constant flow. Timing errors due to the diverter will be more significant for smaller collection times, thus leading to differences in flow results (or flowmeter calibration factors) that are dependent on collection time. Three validation tests of this type have been applied to the uni-directional diverter and are described here.

1. The uni-directional diverter was compared with a traditional diverter.

To compare performances of the traditional diverter to the uni-diverter over a range of flows, we gathered data in the following sequence:

1. Traditional diverter (single step, long diversion)
2. Traditional diverter (n-steps, short diversions)
3. Uni-diverter (single step, long diversion).

The derivation of the diverter timing correction assumes constant flow (or compensates for flow differences) and therefore to avoid having to compensate, the test flow was maintained as stable as possible while gathering data from the three methods. To minimize the effects of small flow changes during the course of the test, flow indications from a turbine meter in the 100 mm test section were used to monitor the constancy of the flow. The measured values of collected mass for the multiple diversions and uni-diverter tests were adjusted based on the ratio of the turbine meter frequency, using the traditional long diversion frequency as the reference. The data acquisition program was automated to perform all three test runs in sequence and without interruption.

Figure 11 shows the performance of the traditional diverter for 30 and 50 sec. collection times if no correction was taken into account. The linear dependence of the differences between uni-directional diverter and traditional diverter suggests that time correction for traditional diverter must be included to calculate true flow rate. Using the theoretical approach the correction to the collection time can be calculated. See Ref [5, 6] for detailed information

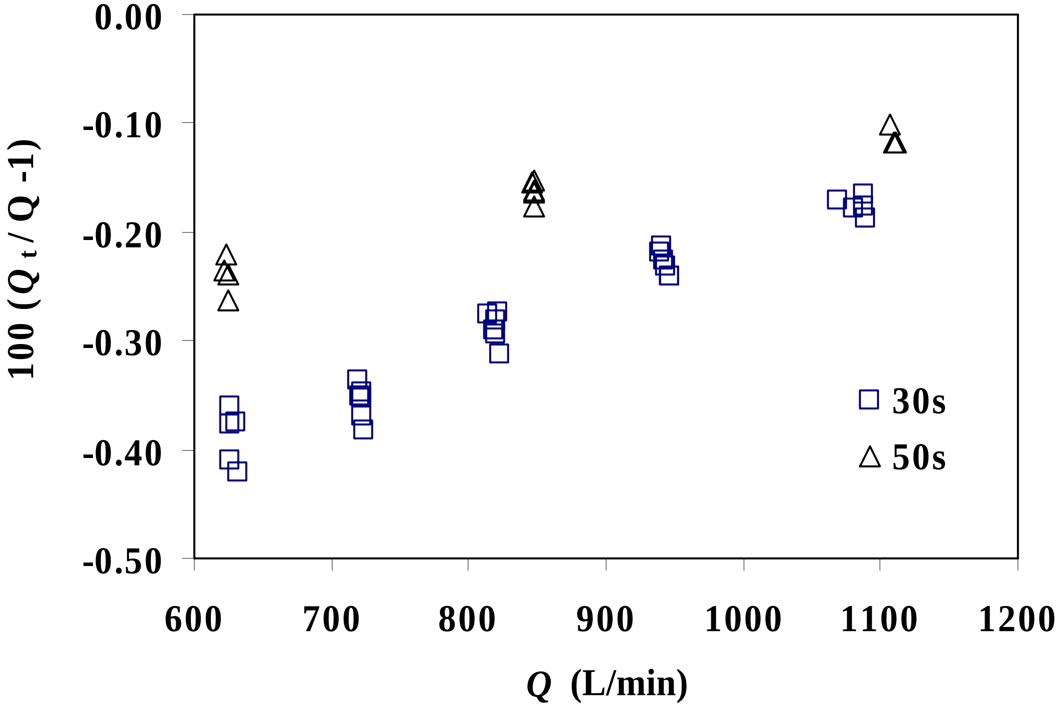

Figure 11. Differences between Traditional and Uni-directional Diverters, where No Correction is Made

Figure 12 shows a comparison between corrected collection time for the traditional diverter and uni-directional diverter. Each point is the average of 5 measurements. For the tested flow the difference is smaller than 0.005%.

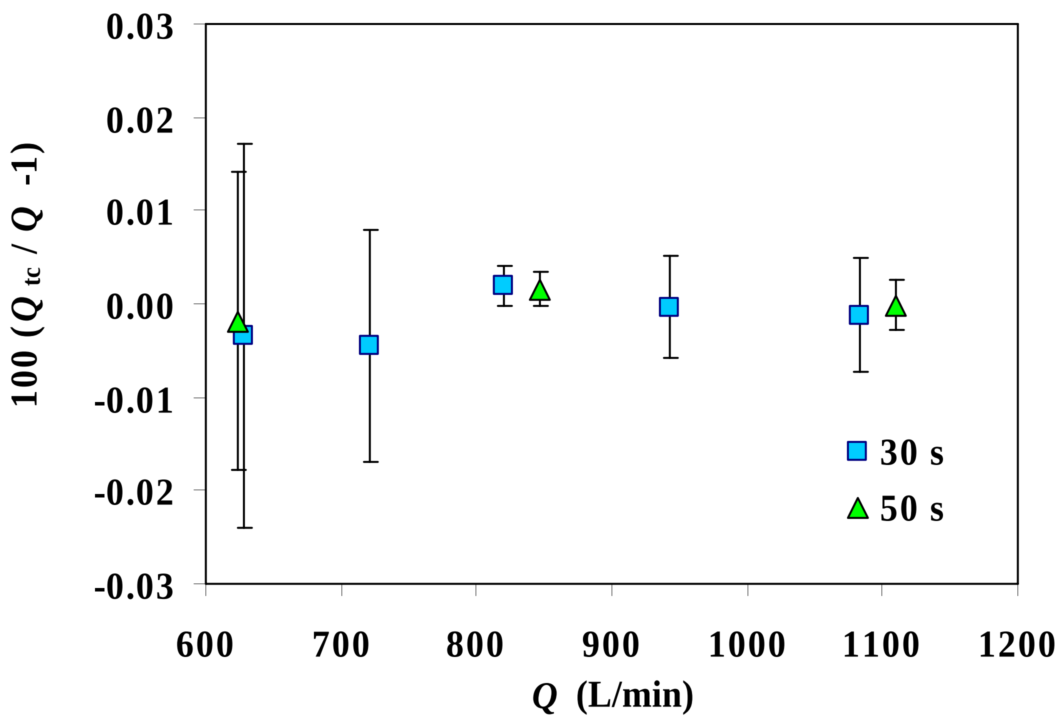

Figure12. Difference between Traditional and Uni-directional Diverter, where Time Correction is Included

2. The uni- directional diverter was also tested based purely on statistical analysis. In this experiment, two different collection times for each flow were chosen to measure the flow over a large number of sequential collections. In order to increase the sensitivity of the experiment, a maximum flow of 1800 L/min and a minimum collection time of 20 sec. were chosen (instead of the maximum 1100 L/min and of 30 sec. in the previously described experiment). Maximum collection time for the 1800 L/min flow rate was 100 sec. These two collection times were used alternately to measure flow during the experiment, which ran continuously for 10 hours.

It can be seen from the Figure 13 that the 20 s and 100 s curves almost coincide. The difference in flow measurement between the 20 s and 100 s collection times can be estimated as a ratio of the areas under the curves. It was found that this ratio is 1.00016; therefore the differences between 20 s and 100 s collection times is about 0.016%.

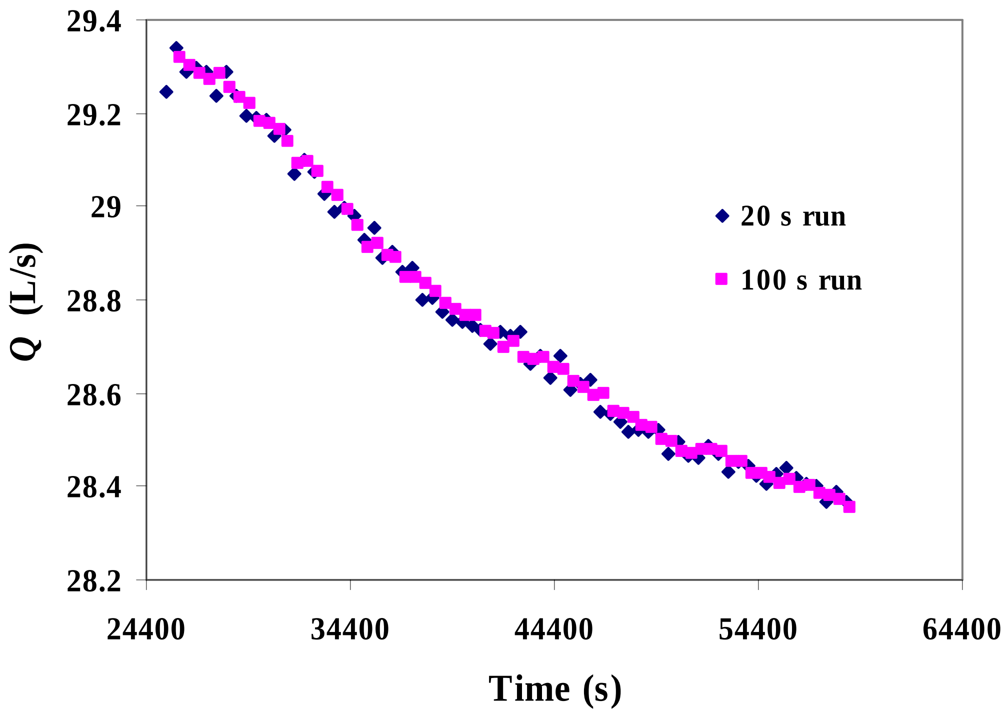

Figure 13. Ten Hour Run with 20 and 100 s Collection Times

3. Performance of the uni-directional diverter was assessed by calibrating a very stable dual rotor flowmeter which has a repeatability of better than 0.02%. The calibration result for this meter (Strouhal number) for 5 collection times spanning the range from 40 s to 200 s (See Fig. 14) was measured at a flow rate of 15 L/s (tank was filled from 600 kg to 3000 kg).

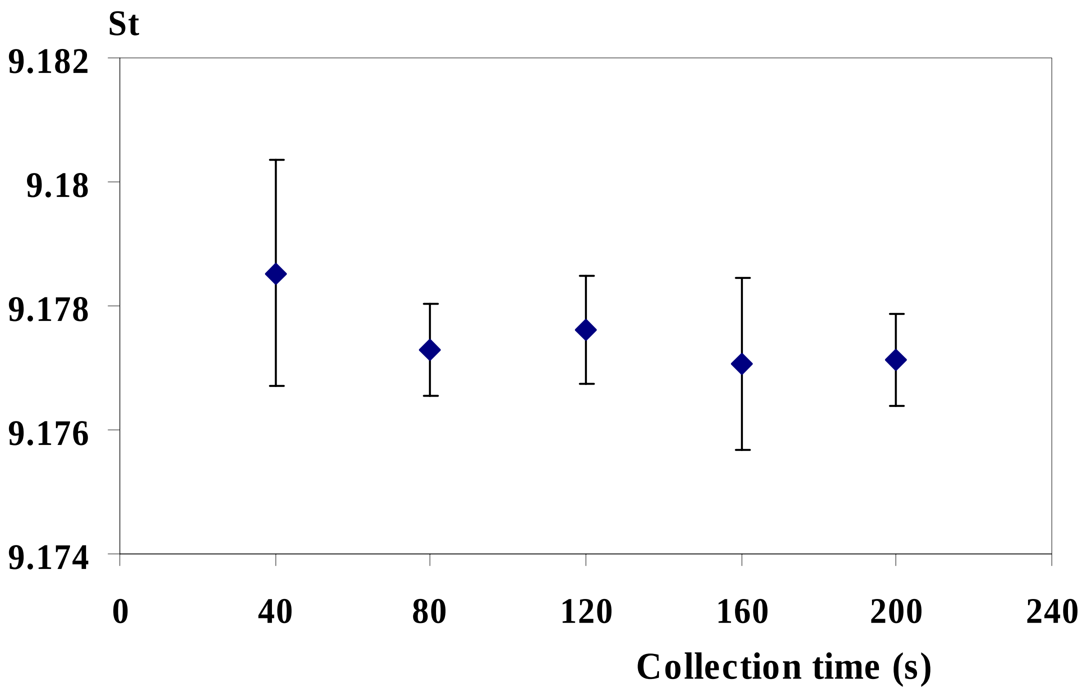

Figure 14. Measured Strouhal Number for Different Collection Times

Each point represents 7 measurements. Maximum difference between points is about 0.001 units and corresponds to 0.01%. The averaged value for all collection times is $9.17753 \pm 0.006\%$. Based on the evaluation tests described above, we are therefore using a conservative value of 0.01% for the uni-directional diverter with zero time correction.

5.2.2.2 Counters and Timers

Liquid collection time is measured with a Hewlett Packard Model 53131A counter. The uncertainty of this timer is 0.0001 s. During a typical high flow calibration, which has 20 s to 30 s collection time, this uncertainty leads to a value of 0.0004% or less.

5.2.3 Density

The Static Gravimetric Method for measuring liquid flow rate determines the (mass)/(time) value, averaged over the collection interval. There are volumetric type flow meters and there are mass flow rate meters. For example turbine flowmeters measure the flow in (volume)/(time), ultrasonic and magnetic flowmeters measure the flow in terms of (averaged fluid velocity*area)/(time), Coriolis flowmeters measure in (mass)/(time). In order to perform necessary conversion from mass to volumetric flow the fluid density must be known. Density of the liquid flowing through the meter being calibrated is required for both types of meters.

For liquid density measurement, the Fluid Metrology Group uses a DMA 602 External Measuring Cell with Density Meter - DMA 60 manufactured by Anton Paar Corp. The density determination is based on measuring the period of oscillation of a vibrating U-shaped sample tube, which is filled with liquid. This system is equivalent to a spring-mass system, where the mass contains the sample liquid. The natural frequency of such a system will be

$$f = \frac{1}{2\pi}\sqrt{\frac{c}{M + \rho V}}$$

where *c* is an elastic constant, *M* is the mass of the body, *V* is the filled volume, and ρ is the density of the sample liquid. Therefore the period, T, can be calculated as

$$T = 2\pi\sqrt{\frac{M + \rho V}{c}}$$

or

$$T^2 = A\rho + B$$

where *A* and *B* are temperature dependent coefficients to be calibrated using reference liquids. At the same temperature, the density difference between two fluids is

$$\rho_1 - \rho_2 = \frac{T_1^2 - T_2^2}{A}.$$

The densimeter manufacturer claims that the fractional uncertainty for the density of the water at room temperature is $5 \cdot 10^{-6}$, provided that the temperature instability is less than 0.01 K. This uncertainty includes $2 \cdot 10^{-6}$ due to the temperature instability and $3 \cdot 10^{-6}$ due to deviation of the oscillator.

In order to estimate the performance of the Anton Paar densimeter and to find coefficients *A* and *B*, four fluids were used: distilled water, Standard Reference Material 211d (Toluene), Standard Reference Material 2214 (Isooctane) and air. Certificates for SRM 221d and SRM 2214 can be found via: https://srmors.nist.gov/pricerpt.cfm. Measurements were performed at 20°C. Water density was calculated using the Patterson and Morris polynomial [10]. Density of the air was calculated using the temperature, atmospheric pressure, relative humidity and corresponding equation [11]. Relative humidity of the air inside the vibrating tube was re-calculated for the tube temperature assuming that the partial pressure of the water vapor is the same for the room and tube. First, the water vapor pressure was calculated for the room temperature and after this value was divided by the saturated water pressure at the tube temperature to get the relative humidity of the air in the tube.

Figure 15 shows that experimental data can be fitted with a linear dependence between square of the period of vibrating tube versus the density. Fitted values for *A* and *B* are 0.024029(4) ± 0.000002 m^3s^2/kg and 25.994(0) ± 0.001(5) s^2 respectively.

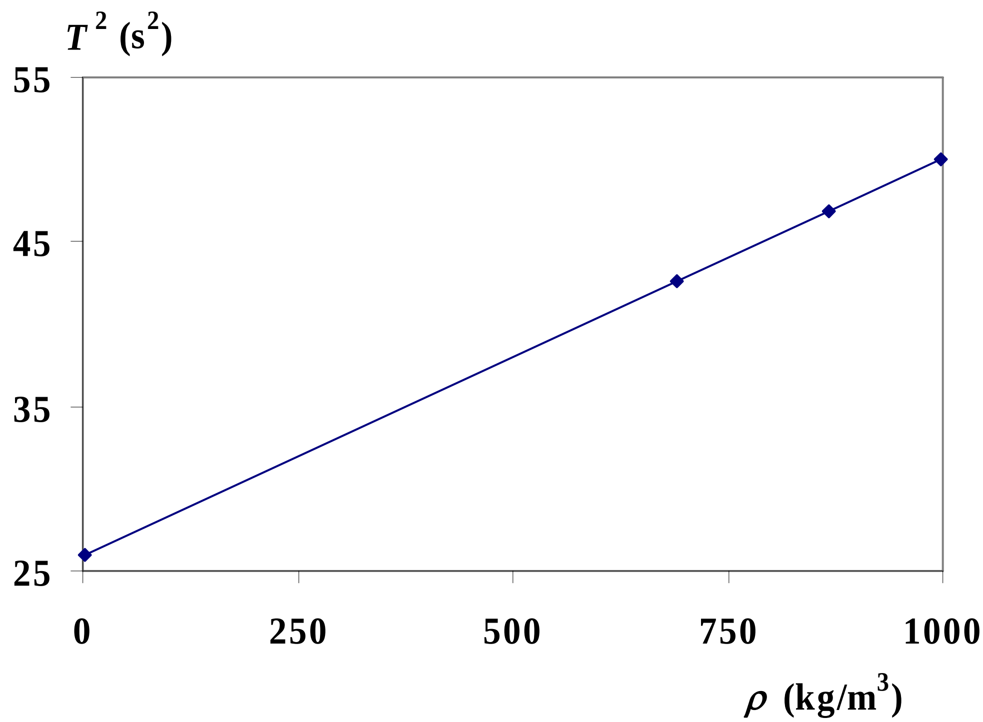

Figure 15. Densimeter Results Using the Four Fluids

The standard deviation for four fluids (Figure16) is 0.053 kg/m^3 or 0.0053%. This is considered a good result when one takes into account that this value is only about twice as large as the claimed uncertainties for the Standard Reference Materials (0.025 kg/m^3 for Toluene and 0.035 kg/m^3 for Isooctane).

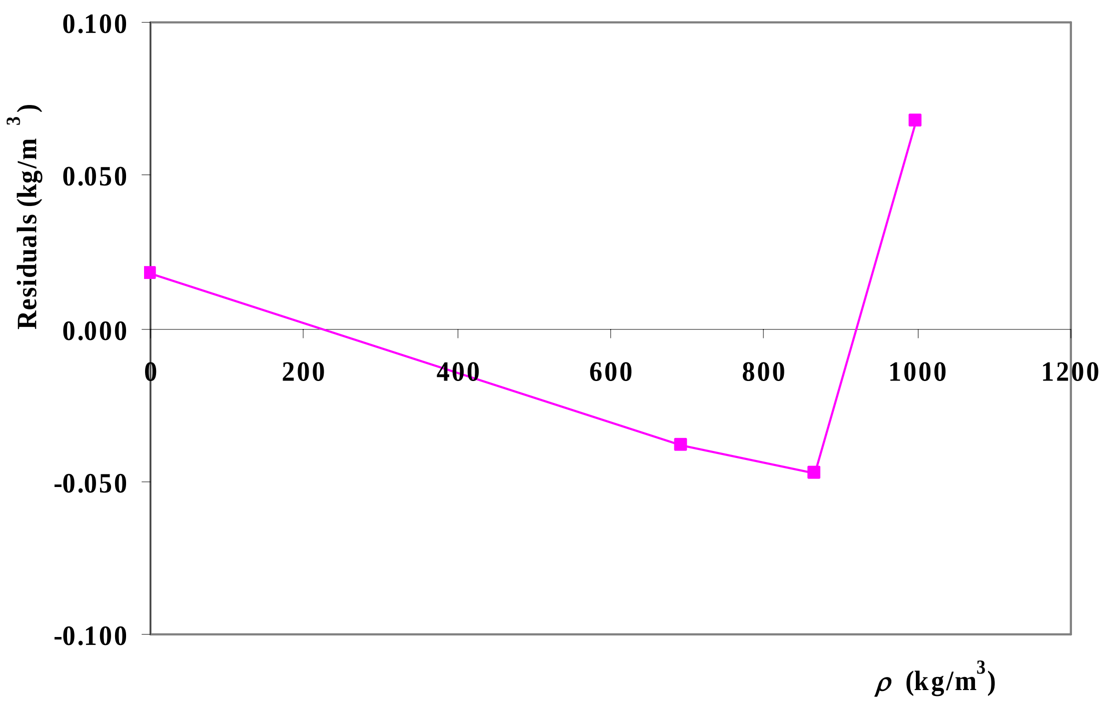

Figure 16. Residuals from the Densimeter Tests.

As mentioned before, the coefficients *A* and *B* are temperature dependent. In order to find these dependencies, the Anton Paar Densimeter was calibrated using air and water in the temperature range 18 °C to 36 °C in 2 °C steps.

It was found that both *A* and *B* can be approximated with linear dependence with

$$A = 2.40900 \times 10^{-2} - 2.97018 \times 10^{-6}\ (T/°C) \text{ and}$$
$$B = 26.06049 - 3.519921 \times 10^{-3}\ (T/°C),$$

where *T* is the tube temperature in °C (see Figs 17 and 18).

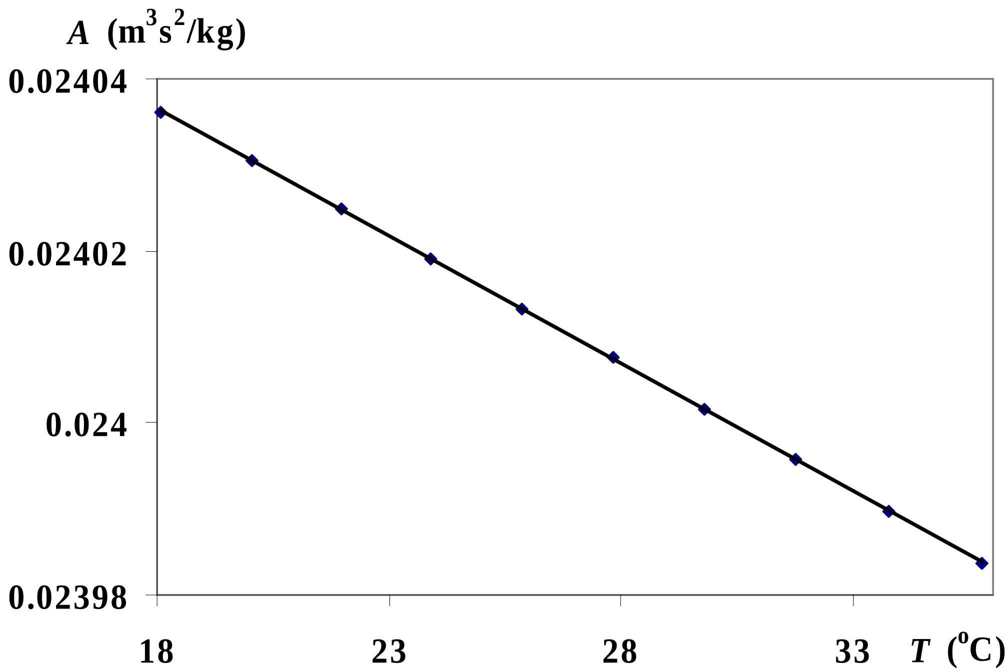

Figure 17. Temperature Dependence of the Coefficient, *A*

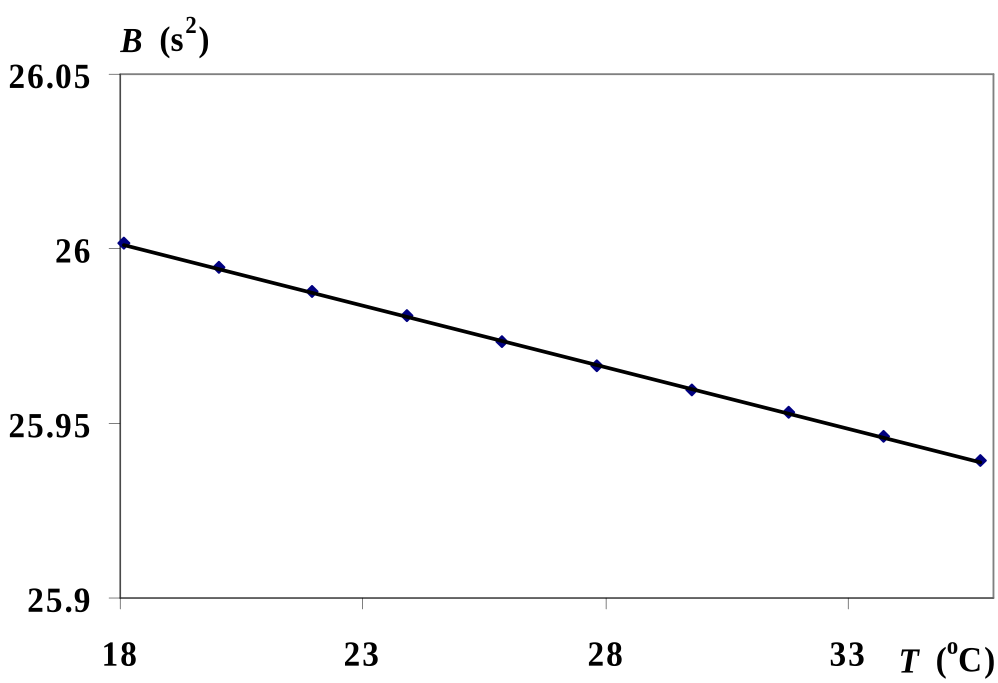

Figure 18. Temperature Dependence of the Densitometer Coefficient, *B*

The density of the flume water was measured in the same temperature range. It was found that the difference between distilled water and flume water density has weak temperature dependence (Figure 19).

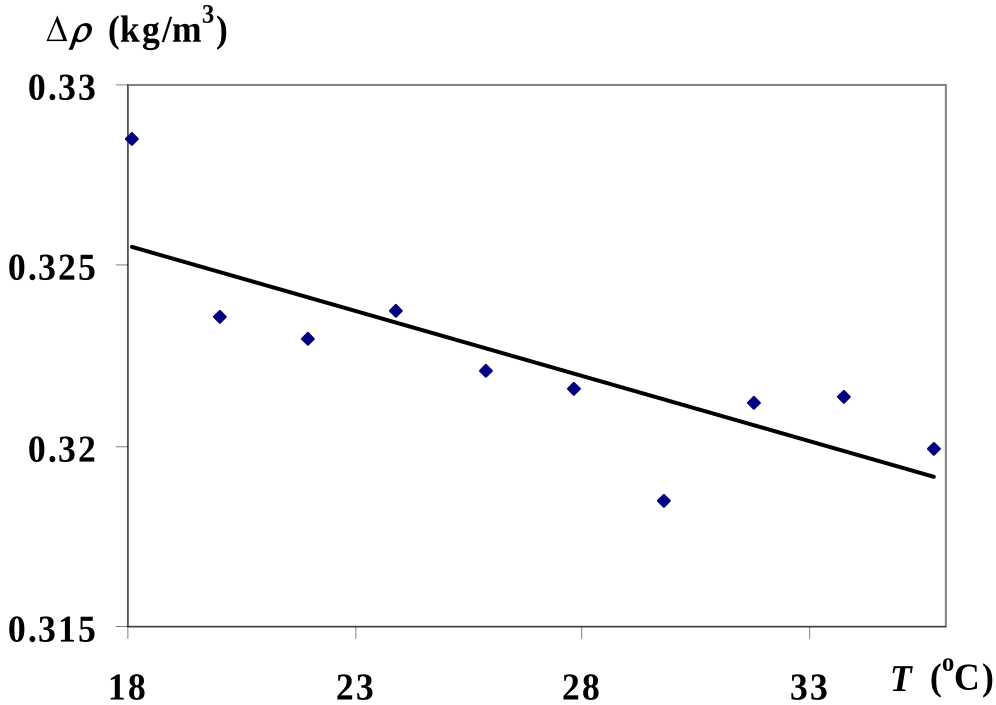

Figure 19. The density difference between flume and distilled water

The density of the flume water can be found by adding an additional linear term

$$\Delta\rho = 0.3321 - 3.631 \cdot 10^{-4} T,\ kg/m^3,$$

to the distilled water polynomial (where T is in °C) . The maximum uncertainty for the density difference is about 0.004 kg/m^3 which is negligible compared to the uncertainty (0.05 kg/m^3) for the 4 fluids previously described. . The expanded uncertainty is about 100 parts in 10^6. The density of the flume water is checked once a month or after adding water to the reservoir.

5.2.4 Viscosity

Practice indicates and current experiment confirms that universal calibration curves for turbine flowmeters can be constructed if calibration data are expressed dimensionlessly as:

$$Ro = \frac{fD^2}{\nu}$$

$$St = \frac{\pi f D^3}{\dot{Q}}$$

where Ro is the Roshko number, and St is the Strouhal number, where f is the meter frequency, D is the flowmeter diameter, ν is the kinematic viscosity and $\dot{Q}$ is the volumetric flow rate. The kinematic viscosity of the flume water must be measured to calculate the Roshko number.

The Fluid Metrology Group uses a capillary Micro-Ubbelohne Viscometer with Schott Gerate AVS 440 measuring system to measure the kinematic viscosity of liquids. The manufacturer claims that the uncertainty of the viscosity measurement is 0.1 % with temperature stability 0.01 K.

The kinematic viscosity can be calculated using expression:

$$\nu = K_\nu (t - \Delta t_{HC})$$

where K is the calibration constant of the capillary viscometer, t is the flow time, Δt_{HC} is the Hagenbach correction. The calibration constant was found using distilled water as a reference liquid. The constant $K_\nu = 0.002734$ (cm^2/s^2) was found by the Fluid Metrology Group with 0.1% uncertainty. The fractional residuals from fitting the kinematic viscosity as a function of temperature is shown in Figure 20. There was no noticeable temperature dependence of the constant found.

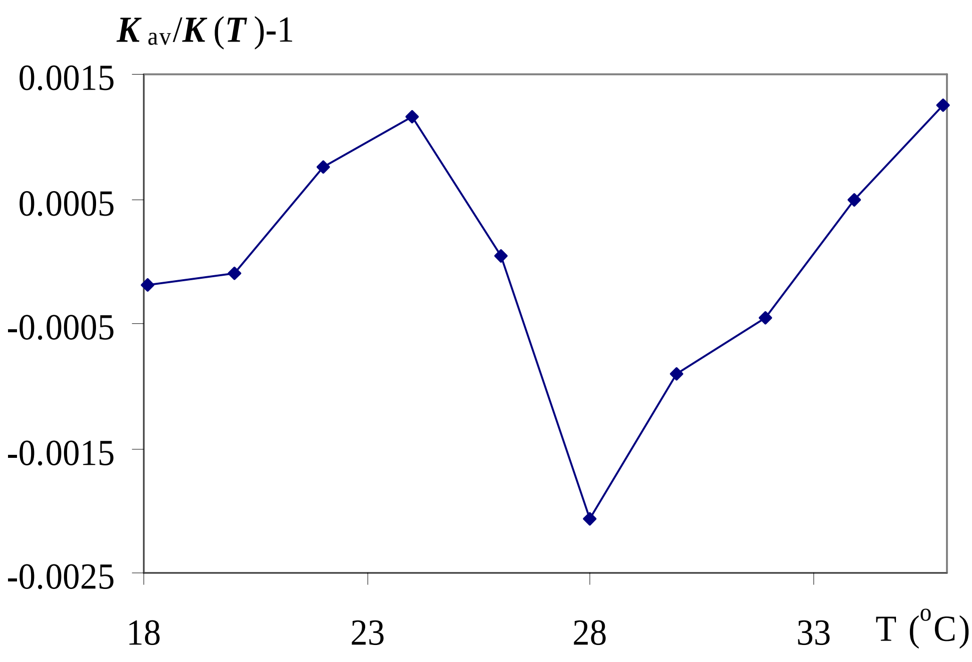

Figure 20. Residuals for Calibration Constant Fitting

These results show that the flume water kinematic viscosity is very close to the viscosity of distilled water. The difference between viscosities of the flume water and distilled water is shown below (Fig. 21).

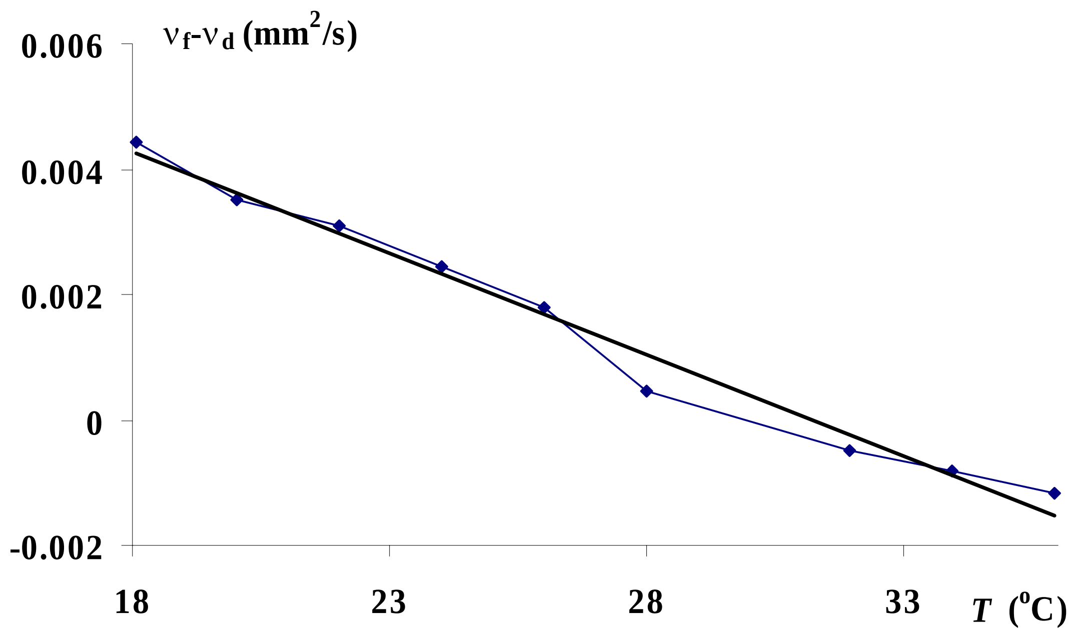

Figure 21. Difference Between Viscosities of the Flume and Distilled Water

The kinematic viscosity of the distilled water [12] can be fitted with an uncertainty of 0.001% using a rational polynomial

$$\nu = (a + cT + eT^2)/(1 + bT + dT^2)$$

with coefficients: a=1.794345 cm^2/s, b=0.034252 $cm^2/s/K$, c=-0.00172 $cm^2/s/K$, d=0.000201$cm^2/s/K^2$ and e=2.86·$10^{-5}$$cm^2/s/K^2$. In order to obtain viscosity the difference $-3.241\cdot10^{-4}T + 1.011\cdot10^{-2}$ between flume and distilled water should be added. The viscosity of the flume water is measured periodically, once every 3-4 months.

5.2.5 Temperature Measurement

In order to obtain the true mass of water collected and the desired value of the volumetric flow, buoyancy effects are needed. This means that temperatures of the water and the pressure and temperature and humidity of the room air is required for density computations.

Temperature measurements are made of the flowing liquid and of the atmospheric conditions surrounding the weighing system. These measurements are made using calibrated thermistors placed at various locations along the water flow path and a Keithley Model 224 current source, a Keithley Model 7001 switch system, and a Keithley Model 2002 Multimeter . One sensor is located immediately upstream of the MUT and two are inside of the weigh tank.

The thermistors are calibrated using an isothermal bath (Hart Scientific Model 5003) by comparing their responses to those of a four-wire platinum resistance transfer standard thermometer (Thermometrics Model TS8901) that is periodically calibrated by the NIST Thermometry Group. The four calibration coefficients and the temperature uncertainty for each thermistor are obtained using a linear regression method. All sensors are calibrated over the range 15 to 40 ºC. This range represents the expected range of temperatures during use of the WFCF 3700/100. The calibration of the thermistors is performed once per year.

Each thermistor is physically removed from the indicator by as much as 15 m. Extension cables are used to connect the sensors to the indicator. The temperature differences for the extension cables do not exceed 0.01 K.

Uncertainty in Measured Temperature Values

The components of uncertainty in the temperature values measured by each thermistor are:

- the uncertainty of the transfer standard which is taken as 0.0012 K
- the effect of the extension cable connection which is taken as 0.01 K
- the residuals after a best fit of the thermistor calibration results.

6 Data Acquisition and Control System

The NIST WFCF is a fully automated system. The automatic control of the measurement process, the data collection and the calculation of final results are done by computer. The data acquisition and control system consists of a NI terminal block integrated by a (I/O) NI PCI-MIO-16XE-10 board, an IEEE-488 interface board and a RS-232 communication port.

An IEEE-488 interface is used to interface counters and temperature measurement devices to the data acquisition system. This interface functions as defined in ANSI/IEEE 488-1975 and ANSI/IEEE 488.1-1987.

An RS-232 communication port is used to acquire readings from the weigh scale, the flow check standard and the data for the room conditions via the temperature, pressure and humidity sensors.

Figure 22 shows the data acquisition flow diagram.

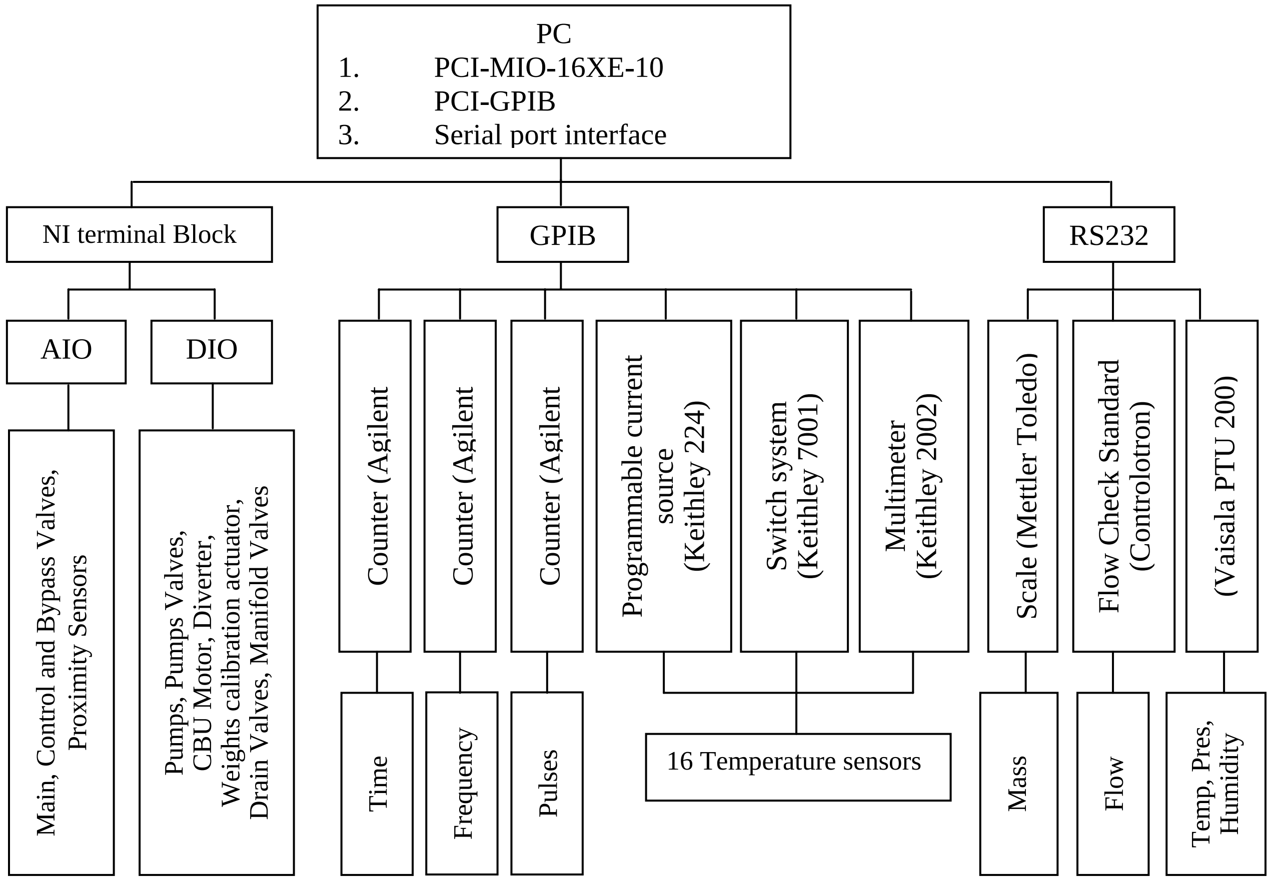

Figure 22. Data Acquisition Chart for the Facility

LabView software is utilized to control the system and to put data into spreadsheet format. The data acquisition software is designed to minimize operator intervention, thereby reducing or eliminating the number of entry errors. Moreover, the software provides specific instructions displayed on the screen to inform the operator of current and next calibration steps. The software panel allows the user to visualize and to manipulate different functions and devices in the facility.

7 Summary

We have given a description of NIST's Water Flowmeter Calibration Facility which is used by the Fluid Metrology Group to offer water flowmeter calibration services in the range; 40 to 1600 L/min. This standard has an uncertainty of 0.033% for liquid mass collections of 3000 kg, and 0.051% for 600 kg collections.
The intended audience for this document includes NIST's water flowmeter calibration customers, and the characteristics and uncertainties claimed are intended to reflect the concerns of this audience. This document explains the method of operation of the WFCF,

the functions of its various components, and provides details necessary for customers wanting to submit meters for calibration (i.e., pipeline sizes, costs, turnaround time, etc.), and gives a detailed analysis of the uncertainty of its mass (or volumetric) flow measurement results. Additionally, we have given a description of typical flow calibration, including a sample calibration report.

8 References

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NIST
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Technology Administration, U.S. Department of Commerce

Appendix: Sample Calibration Report

REPORT OF CALIBRATION

FOR

A TURBINE WATER FLOWMETER

May 01, 2006

Mfg.: ABCD Corporation
ABCD Serial No: 1234
Pipe Diameter: 100 mm (4 inch)

submitted by

Waterflow , Inc.
Metertown, MD

Purchase Order No. A123 dated April 01, 2006

The flowmeter identified above was calibrated by water at a constant rates through the flow meter and then into Water Flow Calibration Facility (WFCF) Standard. The water used for calibration was drawn from municipal water supply. Density and viscosity of the of the water were measured at a few temperatures near the room temperature and the result of measurement was approximated by corresponding equations. The WFCS Standard determines volume flow by measuring collected mass, collection time and density of the water.[1] The flowmeter was tested two times at five flows and at each flow three (or more) measurements were gathered at different flow rates. As a result, the tabulated data for this test are averages of six or more individual calibration measurements.

The flowmeter was installed in an assembly that meets the ISO Standard for liquid flow measurements and a photograph of the installation is shown in Figure 1. The collected mass was measured using Mettler Scale, collection time was measured using HP 15331 counter. The air properties, such as temperature, pressure, and humidity, were taken with PTU 200 at the beginning and the end of each individual test.

[1] 2. D.W. Spitzer, Editor. Flow Measurement 2nd Edition. Chapter 27, Laboratory Primery Standard, by J.D.Wright. P. 731-761.

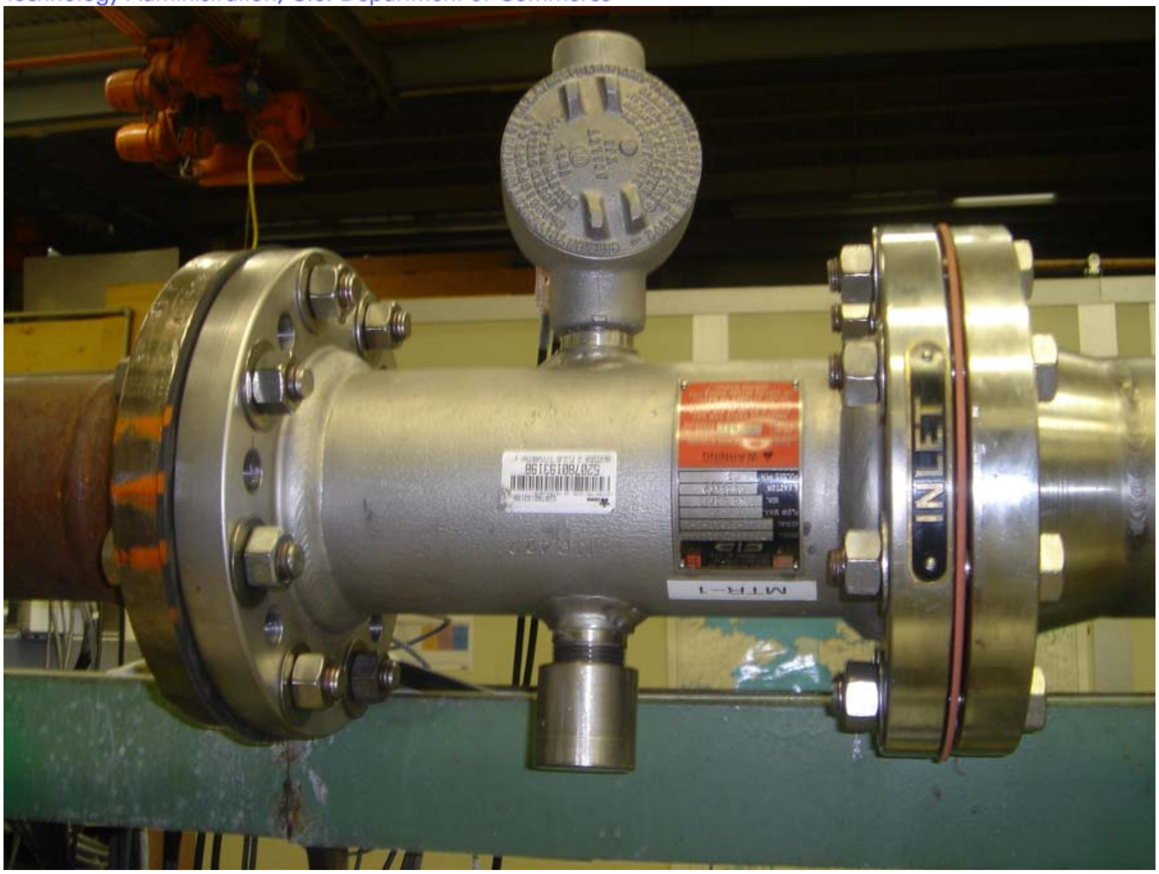

Figure 1. A photograph of the flow meter installation.

The Reynolds number is included in the tabulated data and it was calculated using the following expression:

$$Re = \frac{4 \cdot \dot{m}}{\pi \cdot d \cdot \mu} \tag{1}$$

where $\dot{m}$ is the mass flow of the water, d is the nominal diameter of the pipe, and μ is water viscosity, all in consistent units so that Re is dimensionless. The viscosity of the water was measured and approximated with quadratic equation.

$$\mu = a_0 + a_1 T_0 + a_2 T_0^{\;2} \tag{2}$$

The calibration results are presented in the following table and figure.

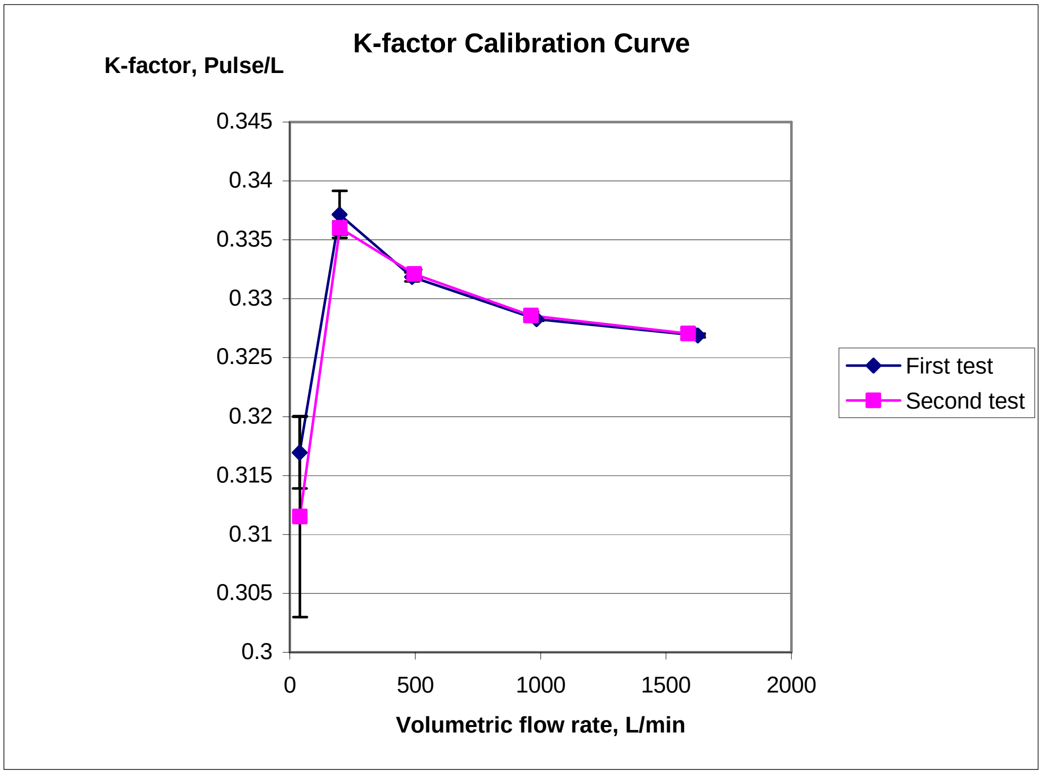

Figure 2. Calibration results for ABCD water flowmeter, SN 1234

1st Test

Flow Rate	K-factor	StDev(k=2)	StDev %(k=2)
38.90595	0.316952	0.003047	0.961393627
198.5555	0.337156	0.001996	0.592000515
488.1079	0.331855	0.000382	0.115249776
984.11	0.328268	0.000139	0.08441277
1626.398	0.326893	0.000159	0.048694467

2nd Test

Flow Rate	K-factor	StDev(k=2)	StDev %(k=2)
41.03114	0.311506	0.008526	2.737168322
199.3274	0.336018	0.000575	0.17121386
496.488	0.332102	0.000391	0.117796995
962.2345	0.328583	0.000304	0.092614897
1589.378	0.327057	0.000461	0.140951815

An analysis was performed to assess the uncertainty of the results obtained for the meter under test.[2, 3, 4] The process involves identifying the equations used in calculating the

[2] International Organization for Standardization, *Guide to the Expression of Uncertainty in Measurement*, Switzerland, 1996 edition.

[3] Taylor, B. N. and Kuyatt, C. E., *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, NIST TN 1297, 1994 edition.

calibration result (measurand) so that the sensitivity of the result to uncertainties in the input quantities can be evaluated. The 67% confidence level uncertainty of each of the input quantities is determined, weighted by its sensitivity, and combined with the other uncertainty components by the root-sum-square method to arrive at a combined uncertainty (U_c). The combined uncertainty is multiplied by a coverage factor of 2.0 to arrive at an expanded uncertainty (U_e) of the measurand with approximately 95% confidence level.

As described in the references, if one considers a generic basis equation for the measurement process, which has an output, y, based on N input quantities, x_i,

$$y = y(x_1, x_2, \ldots, x_N) \tag{3}$$

and all uncertainty components are uncorrelated, the normalized expanded uncertainty is given by,

$$\frac{U_e(y)}{y} = k\frac{U_c(y)}{y} = k\sqrt{\sum_{i=1}^{N} {s_i}^2 \left(\frac{u(x_i)}{x_i}\right)^2} \tag{4}$$

In the normalized expanded uncertainty equation, the $u(x_i)'s$ are the standard uncertainties of each input, and $s_i's$ are their associated sensitivity coefficients, given by,

$$s_i = \frac{\partial y}{\partial x_i}\frac{x_i}{y} \tag{5}$$

The normalized expanded uncertainty equation is convenient since it permits the usage of relative uncertainties (in fractional or percentage forms) and of dimensionless sensitivity coefficients. The dimensionless sensitivity coefficients can often be obtained by inspection since for a linear function they have a magnitude of unity.

For this calibration, the uncertainty of the K-factor has components due to the measurement of the mass flow by the primary standard, $u(\dot{m}) = 0.033\%$[4]. This applays to NIST's results. This performance may be expected by customer if ther meter is used in similar conditions.

To measure the reproducibility[5] of the test, the standard deviation of the K-factor at each of the nominal flows was used to calculate the relative standard uncertainty (the standard deviation divided by the mean and expressed as a percentage). The reproducibility was root-sum-squared along with the other uncertainty components to calculate the combined

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4 Water Flow Calibration Facility Standard with 100 mm pipeline and 3.700 kg collection tank for Water Flowmeter Calibrations**.**

5 Reproducibility is herein defined as the closeness of agreement between measurements with the flow changed and then returned to the same nominal value.

uncertainty. Using the values given above results for the expanded uncertainties are listed in the data table and shown as error bars in the figure.

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