DIVERTER UNCERTAINTY LESS THAN 0.01% FOR WATER FLOW CALIBRATIONS

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Abstract: We describe the primary water flow standard at NIST and tests that determined the uncertainty of a new diverter design called a “uni-diverter”. The tests compared the flow measurement results for the uni-diverter (operated with the collection / bypass unit) and the diverter operated in the traditional manner with a time correction (as described in ISO 4185). The uni-diverter introduces less than 0.01% into the total flow uncertainty.

1. INTRODUCTION

Static gravimetric liquid flow calibration facilities determine flow by measuring the time required to accumulate a measured mass of liquid in a collection tank. Liquid diverters are used to switch the liquid flow into the collection tank when starting a measurement and to switch it back to the bypass loop at the end of the measurement by cutting a liquid jet from a rectangular nozzle. A diverter mechanism is also necessary for a static volumetric approach. These calibration methods are the most commonly used for low uncertainty liquid flow measurements, such as those made at national standards [1-4] and commercial calibration laboratories.

At the NIST Gaithersburg Campus, a new Water Flow Calibration Facility (WFCF) is under construction. The facility will have three parallel test sections with diameters of 100 mm, 200 mm, and 400 mm and three weighing systems with capacities of 1100 kg, 4500 kg and 22500 kg. The WFCF will calibrate flow meters from 25 mm to 400 mm in diameter at flows from 40 L/min to 38,000 L/min [3].

A schematic of the NIST WFCF is shown in Fig. 1. The facility is located above a water reservoir that has a capacity of approximately 230 m^3. Water flow is maintained in the system by four constant velocity pumps, three at 112 kW (150 hp) and one at 75 kW (100 hp). The 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 manifold 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.

Flow at the test section is controlled by two sets of valves. One set is located near the pump (a main valve for each pipeline and a bypass throttle valve) and controls the amount of water returned to the reservoir without passing through the meter test sections. The other valves on each pipeline (located downstream of the test section) are the fine and coarse controls of water flow and pressure in the test section of the WFCF. Once the flow passes through the meter under test and the fine and course control valves, it goes through two valves in series (a leak detection system) and then a fishtail and rectangular nozzle into a diverter mechanism.

The nozzle and diverter are designed to 1) rapidly switch the flow from the bypass to the collection tank and back again without disturbing the flow conditions in the test section and 2) generate trigger 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).

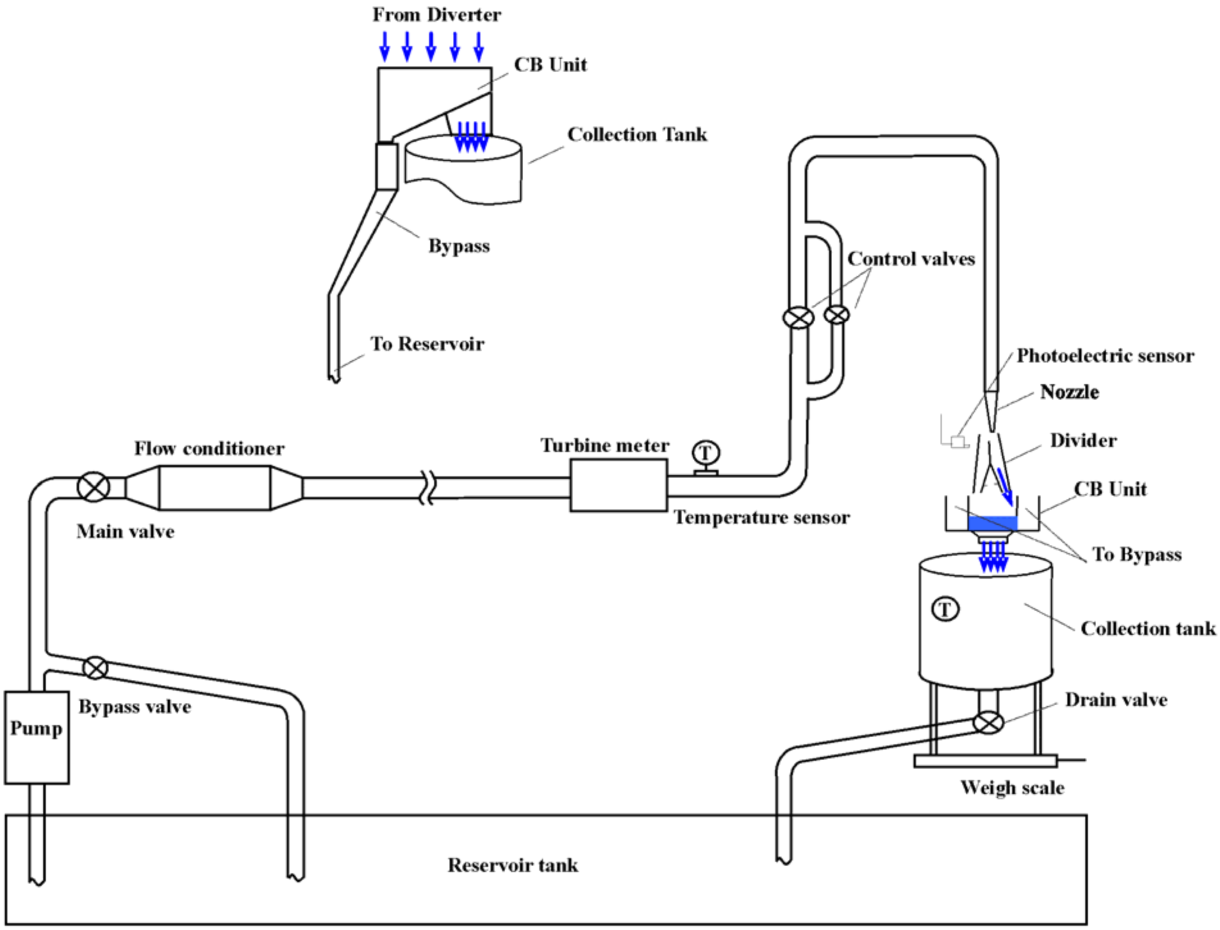

Fig. 1 *Schematic of the test facility (with side view of the collection / bypass (CB) unit).*

Uncertainties in the diversion process originate from several sources: 1) the finite time required for the divider to traverse the jet, 2) asymmetries in the velocity profile of the jet, 3) differences in the acceleration and velocity of the divider between the two directions that the divider travels, and 4) the positioning of the timer trigger for the divider with respect to the jet. These uncertainties related to the diversion can be attributed to either the mass or the time measurements; normally they are attributed to a "diverter time error".

Previous publications described a new design for a diverter called the uni-diverter because the divider moves in one direction for both the start and stop. The uni-diverter is immune to many of the uncertainties that plague traditional diverters [5, 6]. This paper describes tests that use the WFCF to compare the uni-diverter to a traditional diverter with a diverter time correction. The uni-diverter introduces less than 0.01% into the total flow uncertainty.

2. OPERATION OF THE UNI-DIVERTER

The traditional diverter mechanism has one active element: a flow divider that directs the flow from the nozzle to either the bypass or the collection tank. In this mechanism, the divider cuts through the jet in one direction at the beginning of the measurement and in the opposite direction at the end of the measurement.

The new diverter system developed for the NIST WFCF adds an extra element: a collection / bypass or CB unit located below the traditional divider so that the divider can travel through the jet in the same direction for both the start and stop of the flow diversion. The full operation sequence of the uni-diverter system is shown in Fig 2.

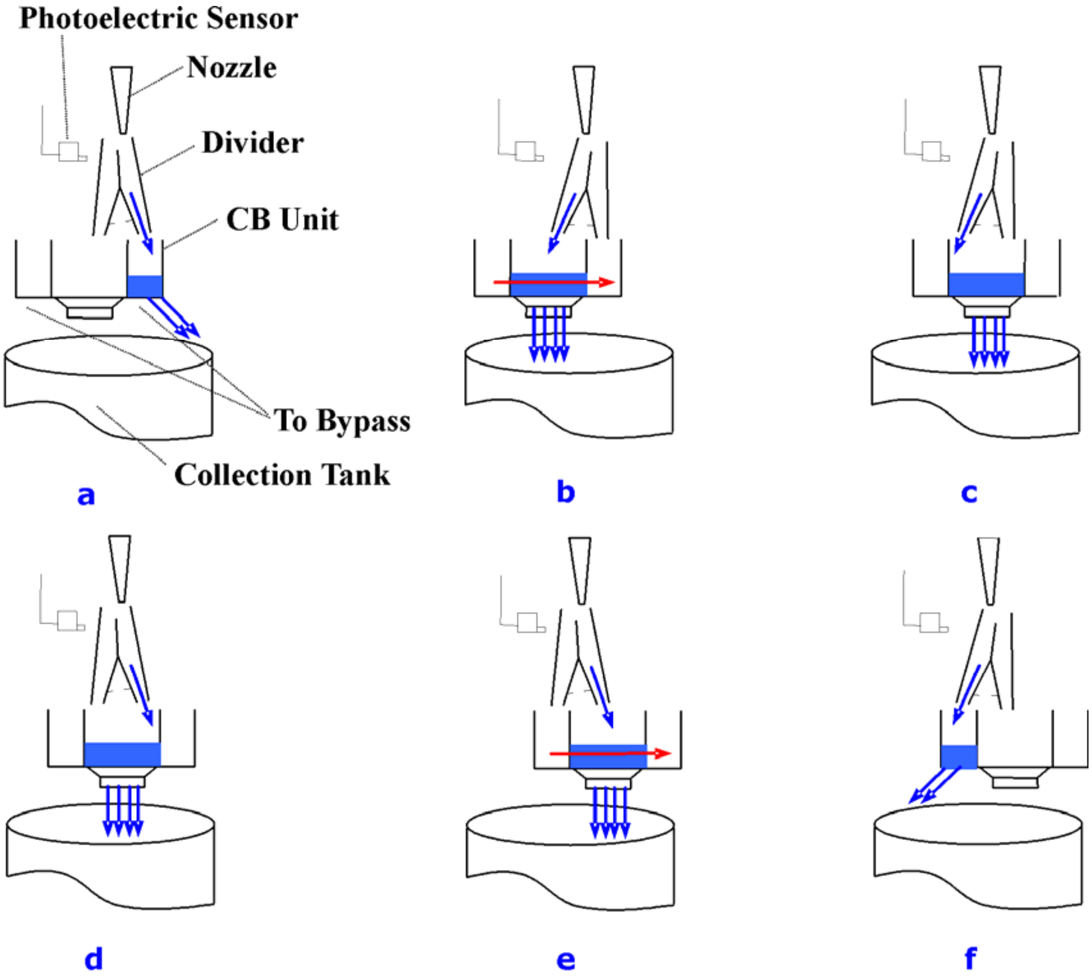

Fig. 2 *Sequential operation of the uni-diverter.*

Its design has two separate active elements: 1) a traditional divider (which cuts the flow) is operated by a pneumatic angular actuator and 2) a 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 the blade of the divider to travel through 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.

3. EXPERIMENTAL DETAILS

3.1. Experimental apparatus

The present evaluation of the uni-diverter was performed in the 100 mm pipeline of the WFCF which provides a maximum flow up to 1500 L/min using a 3700 L collection tank on a 4500 kg weigh scale. A prototype of the uni-diverter was evaluated previously [5, 6]; here, we check the latest implementation of the design in the WFCF.

Both the new and traditional diverter methods can be carried out with the uni-diverter. The system functions as a traditional diverter when the CB unit is stationary at the position shown in Fig. 2a or 2f. Hence, the two designs were easily compared, since the same equipment and flow conditions are used.

The time of diversion of the water flow into the collection tank is measured with a photoelectric sensor and interrupter flag mechanism that generate a trigger signal for a timer / counter. The photoelectric sensor is mounted on the stationary framework and a metal flag is mounted on the movable portion of the divider. Estimates of the diverter valve correction value at one flow are obtained from a combination of observations using a reference flow meter (in this case a turbine meter) with good short-term flow measurement stability. A data acquisition and control program was written to automate the data collection and capture data in a spreadsheet.

3.2. Analysis of diverter time correction

The measurement of volumetric flow, Q, at a meter under test by the static gravimetric method is expressed by the equation

$$Q = \frac{M}{t\,\rho_w} \tag{1}$$

where M is total mass collected, t represents collection time measured between starting and stopping the collection, and ρ_w is the density of the water.

The flow measured with a traditional diverter, Q_t and the flow measured with the uni-diverter, Q_u are calculated from Eqn. 1 by using their respective collected masses and times.

As described earlier, the measured collection time is subject to errors. Various methods have been used to calculate corrections to the total measured collection time, t_T for the traditional diverter mechanism [4]. For the present evaluation, we followed the process described in ISO 4185 Method 1 and used a combination of long and short diversions into the collection tank to determine the diverter timing error. The long observations fill the tank in a single diversion over some predetermined time interval. In our experiments, we performed the diverter correction experiment twice, once with a collection interval of 30 s and the second time with a collection interval of 50 s. Then a second set of short duration diversions were used to fill the collection tank. In this manner, the cumulative effect of several diversions may be observed in filling the tank rather than only one. The diverter error is cumulative. When the measurement results are compared to a single long diversion, the diverter time correction can be calculated.

The measured collection time plus the diverter correction time, $t_T+\delta$, is the “corrected” collection time. With this substitution, equation (1) becomes

$$Q_{tc} = \frac{M_T}{(t_T + \delta)\,\rho_w} \tag{2}$$

where Q_{tc} is the corrected traditional flow, and M_T and t_T are the collected mass and measured collection time in a single long diversion. Assuming that the value of δ is constant for any number of diversions (at a given flow), the flow for a collection comprised of n short diversions is also based on Egn 1:

$$Q_{tc} = \frac{\sum_{i=1}^{n} M_i}{\left(\sum_{i=1}^{n} t_i + n\delta\right)\rho_w} \tag{3}$$

where $\sum_{i=1}^{n} M_i$ is the total mass collected in a series of n-diversions without resetting the weighing scale.

Using Eqns. 2 and 3, and assuming that both Q_{tc} and ρ_w are constant, we can arrive at an equation to compute the traditional diverter error, δ,

$$\delta = \frac{t_T \sum_{i=1}^{n} M_i - M_T \sum_{i=1}^{n} t_i}{nM_T - \sum_{i=1}^{n} M_i} \tag{4}$$

and the corrected flow based on the single-repetitive method, Q_{tc} can be calculated by using this value of δ in Eqn. 2.

To compare performance of the traditional diverter and 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 assumed constant flow and therefore, 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 normalize the data. 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. The largest correction to the data for flow instability was 0.1 %. Each test was repeated 5 times at the same flow. For all tests, n was equal to ten.

The flow value for new uni-diverter flow, Q_u was computed using Eqn. 1.

4. RESULTS

Figure 3 shows the percentage difference between the flows determined via the uncorrected traditional diverter (Q_t) and the uni-diverter (Q_u). Figure 4 presents the differences measured between the corrected traditional diverter and the uni-diverter. The data are for two different total collection times (30 s and 50 s) and the flows range from 600 L/min to 1100 L/min.

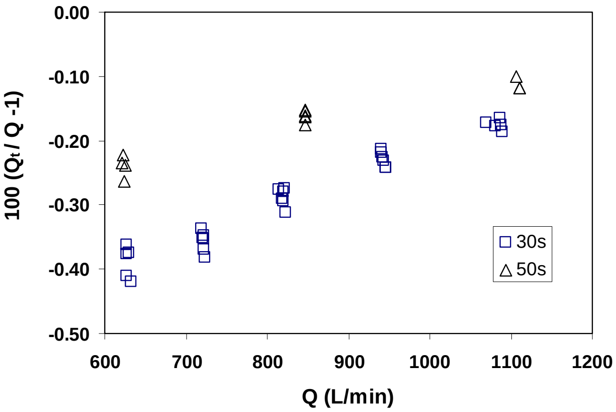

***Fig. 3** Flow difference between uncorrected traditional diverter and uni-diverter for 30 s and 50 s collections, showing 5 individual values at each flow.*

The departures from zero in Fig. 3 depend on the collection time; however, the diverter correction times are independent of the collection time (See Fig. 5). If the normal diverter correction is not made, the shorter collection time (30 s versus 50 s) leads to larger errors in flow. Probably, the rather large size of the differences in Fig. 3 were caused by an unfavorable placement of the photosensor that generated a trigger signal when the divider was near one edge of the jet instead of near the middle of the jet.

Figure 4 shows the differences between the corrected traditional diverter and the uni-diverter. We plot the averages of the five individual data points along with their standard deviation. The largest difference between the corrected traditional and uni-diverter flows (average of five measurements) is 45 parts in 10^6 with standard deviation of < 0.02%.

For the five individual data points collected at each flow (not shown), the differences between the corrected traditional and uni-diverter flows are always less than 0.03% and at flows > 800 L/min they are less than 0.01%. The reason for the increased data scatter at the lowest flows is that for a fixed, short collection time of 30 s, rather low masses of water are collected and the scale resolution introduces variation. For example, at the lowest flows in Figs. 3 and 4, the mass collected over 30 s is about 320 kg and the 0.2 kg scale resolution amounts to 0.06% of the collected mass. The standard deviation of the 5 individual measurements falls to less than 61 parts in 10^6 for flows > 800 L/min and we believe that the performance at the higher flows is more representative of the performance of the uni-diverter. Therefore we believe that the uncertainty introduced by the uni-diverter to the mass and time measurements is less than 0.01%.

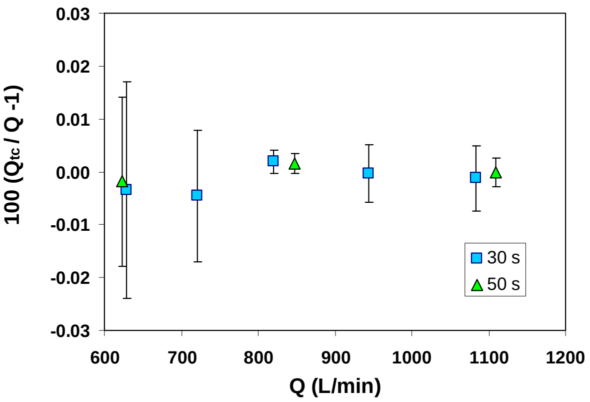

***Fig. 4** Difference between corrected traditional diverter and uni-diverter flows for 30 s and 50 s collections. Averages are plotted with error bars equal to the standard deviation of the 5 individual values.*

Figure 4 shows that the difference between the results from the corrected traditional flow and the new uni-diverter is very close to zero over the entire range of flows tested. However, in our experience, the timing corrections for the traditional diverter change over time and must be checked regularly to maintain good uncertainty performance. This is probably because of changes in the trigger sensor position or changes in the acceleration of the divider by its actuator. Our understanding of the uni-diverter leads us to believe that it will maintain its excellent performance over long periods of time, thanks to it being essentially independent of long term changes in the jet velocity profile, trigger sensor position, and changes in the actuation velocity of the divider.

Figure 5 shows diverter corrections ranging from -0.05 s to -0.13 s for both total collection times, depending on the flow. Timing errors of this size will be negligible for very long collection times, but this solution imposes undesirable limitations on the range of flows that can be measured with a single collection tank and weigh scale.

Figure 5 shows that the diverter correction was repeatable for the two sets of tests run (for different collection times) taken two weeks apart. It shows that the diverter errors are independent of the collection time. The negative diverter error indicates that the trigger location was set so that the timer started too early and / or stopped too late. The variation of the diverter correction with flow shows that the ideal trigger location (one requiring no diverter correction) will be a function of flow and therefore impractical to implement for a traditional diverter.

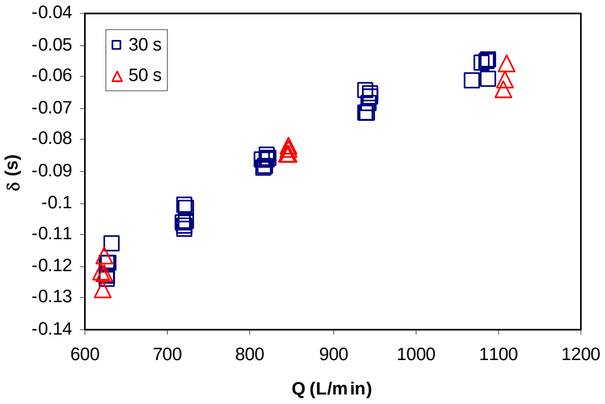

Fig. 5 *Diverter timing correction for both the individual measurements of the 30 s and 50 s data sets.*

5. CONCLUSIONS AND DISCUSSION

Based on the evaluation data presented herein, we believe the uni-diverter introduces less than 0.01% to the combined uncertainty of the flow measurement.

The use of the new diverter design can reduce the size of the required tank, increase system flow range, and reduce the uncertainty of static gravimetric and static volumetric liquid flow standards.

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