Feasibility of an Accurate Dynamic Standard for Water Flow

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Abstract

We used NIST's primary water flow standard to study the feasibility of accurately determining mass flow rates $\dot{m}$ of water "dynamically," that is from the time derivative of the weight *W* of the collection tank: $\dot{m}_{\mathrm{D}} = (dW/dt)/g$. When data for a constant flow in the range 10 kg/s < $\dot{m}_{\mathrm{S}}$ < 60 kg/s was averaged over 40 seconds, the average dynamic flow rate $\langle \dot{m}_{\mathrm{D}} \rangle$, agreed with the static standard $\dot{m}_{\mathrm{S}}$ within the noise, $\left(\langle \dot{m}_{\mathrm{D}} \rangle / \dot{m}_{\mathrm{S}} - 1\right) = 0.00015 \pm 0.00033$. (The uncertainty is the standard deviation of one measurement). These results are consistent with arguments that dW/dt is only weakly sensitive to jet entering the collection tank and to the turbulence inside the tank. We conclude that further study of a dynamic flow standard for larger flows is justified. A dynamic standard can use a conventional diverter that is much simpler than the uni-directional diverter with collector/bypass unit that was designed and built for NIST's primary, static standard.

Keywords: Dynamic gravitational standard; Liquid flow calibration; Water flow standard

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Introduction

In this work, we demonstrate the feasibility of measuring the mass flow rate $\dot{m}$ of water with standard uncertainties on the order of 0.015 % by "dynamic" weighing, *i.e*. by continuously weighing a collection tank while water is flowing into the tank. In contrast, conventional determinations of $\dot{m}$ rely on two, static weighings: first the collection tank is weighed just before a flow of water is diverted from a bypass into the tank and, second, the tank is weighed just after the flow is diverted from the collection tank back into the bypass. In the dynamic method, the timing for determining $\dot{m}$ is controlled by the electronics of the weigh scale and the computer that records the weighing; in the static method, the timing is determined by the motion of a mechanical diverter. The dynamic method can achieve accurate timing using either ordinary valves or a simple diverter; in contrast, NIST had to develop a complicated, traveling collection/bypass (C/B) unit to make equally accurate static measurements. The simplicity of the dynamic timing is advantageous for measuring much larger flows than we consider here.

Our primary experimental result is: within the noise of the dynamic weighing, the dynamic and the static weighing are equivalent. Specifically, for steady flows in the range 10 kg/s < $\dot{m}_{\rm S}$ < 60 kg/s, the dynamic mass flow rate $\langle \dot{m}_{\rm D} \rangle$ differed from the static standard $\dot{m}_{\rm S}$ by the fraction: $\left(\langle \dot{m}_{\rm D} \rangle / \dot{m}_{\rm S} - 1\right) = 0.00015 \pm 0.00033$, where the uncertainty is the standard deviation of one measurement of $\langle \dot{m}_{\rm D} \rangle / \dot{m}_{\rm S}$ and the brackets "$\langle \; \rangle$" denote averaging over a 40 s collection interval. During our measurements, we noticed that the uncertainty of the dynamic mass flow rate measurements had an unexpected dependence on the flow rate. For example, when averaged over 40 s intervals, dynamic flow measurements at 10 kg/s and at 60 kg/s had a relative standard uncertainty of $u_r(\langle \dot{m}_D \rangle) = 0.0002$. At 20 kg/s the relatively uncertainty was anomalously large: $u_r(\langle \dot{m}_D \rangle) = 0.0007$. Most likely, the anomalously large uncertainty at 20 kg/s resulted from an instability of the pump-driven flow rate at frequencies below 1 Hz. If the noise had originated in the non-equilibrium conditions in the collection tank, we would expect it to increase monotonically with flow rate. If the noise originated in the weigh scale, it would have been independent of flow rate.

This work was conducted using NIST's water-flow calibration facility (WFCF) that is sketched in Fig. 1 [1]. The WFCF uses the relation:

$$\dot{m} = \frac{W_f - W_i}{g(1 - \rho_{air} / \rho_{water})} + \frac{(\rho_f - \rho_i)V_I}{(t_f - t_i)} \tag{1}$$

to determine the average mass flow $\dot{m}$ through the meter being calibrated. In Eq. (1), $\Delta W \equiv W_f - W_i$, is the change in the weight of the collection tank during the collection time interval $\Delta t \equiv t_f - t_i$, V_I is the inventory volume, *i.e*. the volume piping between the meter under test and the end of the pipe used to measure the flow, ρ_f and ρ_i are the densities of the initial and final states in the inventory volume at the beginning and the end of the collection interval, and the term $(1-\rho_{air}/\rho_{water})$ is a buoyancy correction. The WFCF achieves a standard relative uncertainty $0.00016 < u_r(\dot{m}_S) = 0.00026$ for mass flows in the range 0.7 kg/s to 60 kg/s [1]. These low uncertainties are achieved, in part, because the WFCF uses a carefully engineered bypass/collector unit (i.e. a uni-directional diverter that always travels in the same direction when it cuts the flow) to determine the collection time interval Δt with a standard uncertainty smaller than 0.005 %. However, at flows above 60 kg/s, water splashes out of the diverter and greatly increases the uncertainty of calibrations. To avoid the expense of building a larger uni-directional diverter, we investigated the dynamic method.

In Section 2, we obtain a remarkably simple equation to compute the mass flow from the dynamic weighings:

$$\dot{m}_{\text{D}} = \frac{\langle dW/dt \rangle}{g(1-\rho_{\text{air}}/\rho_{\text{water}})} \tag{2}$$

Here g is the acceleration of gravity and $(1-\rho_{\text{air}}/\rho_{\text{water}})$ is the buoyancy correction. In practice, the weigh scale was read at intervals of 49.1517 ms and the results were averaged over intervals ranging from 40 s to 300 s to compute $\langle dW/dt \rangle$. In these tests, the WFCF was used in the configuration that was optimized for the static calibration of customers' meters. The WFCF was not designed for dynamic flow measurements; therefore, we expect that its performance as a dynamic standard could be significant improved.

Recently, Aguilera et al. [2] discussed liquid flow calibration system based on dynamic weighing. They noted that the water jet filling the collection delivers vertical and transverse momentum to the water already in the tank thereby driving complex flows. They consider the submerged water jet and its penetration depth, impact energy dissipated in the tank, and fluid structure interaction. In Section 2, below, we adopt an alternative point of view. We consider the collection tank to be a black box operating under nearly steady-state conditions. We argue that most of the complexities of the flow within the tank are irrelevant to the dynamic weighing, provided that the mass flow rate $\dot{m}$ remains constant. Although our arguments are not rigorous, they make Eq. (2) plausible. The measurements support these arguments.

For completeness, we note that gas flow calibration systems based on dynamic weighing have been described in the recent literature [3].

2.1 Two Assumptions Yield a Simple Model for the Dynamic Flow Standard

We consider a highly simplified model of WFCF operating in a dynamic weighing mode. (See Fig. 2.) With two assumptions, this model leads directly to Eq. (2). We then discuss why many complications might not affect Eq. (2).

In Fig. 2, the distributor/collector unit is represented by a funnel that directs the water flow from the pump into the collection tank. Near the top of the funnel, the free air-water surface establishes a flow-dependent reference height where the water pressure equals the ambient pressure and the vertical velocity of the water is zero, on average. The water emerges from the bottom of the funnel in a jet that falls freely through an imaginary "control" surface (dashed red box) into the collection tank. The dashed line inside the collection tank near the middle of the tank represents a horizontal fiberglass grid fixed inside the tank. This grid damps waves (sloshing) and breaks up the jet into many smaller, slowly falling streams, thereby reducing splashing and turbulence.

We make two assumptions: (1) the flow from the pump is constant, and (2) there is no mechanism inside the control surface that can store significant vertical momentum for times that are comparable to the collection time. The first assumption implies that the jet delivers a vertical component of momentum across the control surface at the constant rate $\dot{p}_\mathrm{c} = \dot{m}V_\mathrm{c}$ and second assumption implies that the momentum p_c is delivered to the weigh scale quickly. Under these assumptions, an ideal weigh scale reads the sum of three terms: W = tare + $\dot{p}_\mathrm{c}$ + $w(1-\rho_\mathrm{air}/\rho_\mathrm{water})$, where w is the weight of collected water. Under these assumptions, an ideal weigh scale reads the sum of three terms: W = tare + $\dot{p}_\mathrm{c}$ + $w(1-\rho_\mathrm{air}/\rho_\mathrm{water})$, where w is the weight of collected water. By assumption, the only time-dependent term in W is the weight of the collected water;

therefore, differentiating the readings of the weigh scale with respect to time yields an "instantaneous" version of Eq. (2). In practice, the average time derivative $\langle dW/dt \rangle$ is be obtained by recording several thousand values of *W* and fitting them to a linear function of time.

To estimate the effect of the jet on the weighing, we consider the dimensionless ratio

$$\frac{\dot{p}}{W_f - W_i} = \frac{\dot{m}\sqrt{2gh}}{W_f - W_i} \qquad (3)$$

In Eq. (3), $\dot{p}_\mathrm{c}$ is force (rate of momentum delivery) transmitted by the jet to the weigh scale as the jet falls from the reference height $h = 0$ to the control surface at h, and $(W_\mathrm{f} - W_\mathrm{i})$ is the weight of the water collected. In this work, the reference height $h = 0$ was air-water free surface in the C/B unit functioning as a funnel. Depending upon the flow, the reference surface was located between 1.0 m and 1.2 m above the top of the collection tank. We collected up to 3000 kg of water at flow rates in the range 10 kg/s < $\dot{m}$ < 60 kg/s. Under these conditions, the ratio in Eq. (3) was $0.0015 < \dot{p}_\mathrm{c}/(W_\mathrm{f} - W_\mathrm{i}) < 0.009$. To obtain relative uncertainties of flow less than $u_\mathrm{r}(\dot{m})$, the fractional variation of $\dot{p}_\mathrm{c}$ must be less than $u_\mathrm{r}(\dot{m})/0.009$. For example, to obtain $u_\mathrm{r}(\dot{m}) < 0.0001$, $\dot{p}_\mathrm{c}$ may vary up to 1.1 %. Because $(W_\mathrm{f} - W_\mathrm{i})$ is fixed by the size of the collection tank, the allowable variation of $\dot{p}_\mathrm{c}$ decreases as $\dot{m}^{-1}$.

2.2 Alternative Accounting for the Momentum in the Jet.

Figure 3 displays a simplified dynamic calibration system at the start time t_i and the end time t_f of a collection interval. During the interval $(t_\mathrm{f} - t_\mathrm{i})$ the mass of water collected increases by $(m_\mathrm{f} - m_\mathrm{i})$. The mass $(m_\mathrm{f} - m_\mathrm{i})$ is larger than the mass of water that flowed through an upstream meter (not shown) during the same time interval by the mass of the jet between the heights h_f and h_i which we denote m_j: $m_j = \dot{m}\left(\sqrt{2gh_i} - \sqrt{2gh_f}\right)$. At t_i and t_f, the weigh scale indicates the sum of three terms: (1) tare, (2) the momentum transferred to the water in the collection tank, and (3) the mass of the collected water, corrected for buoyancy. At t_i, the rate of momentum transferred to the collected water is $\dot{p}_i = \dot{m}\sqrt{2gh_i}$; at t_f, the rate of moment transferred is $\dot{p}_f = \dot{m}\sqrt{2gh_f}$. The rate of momentum transferred to the collected water decreases because the jet falls more slowly at h_f than at h_i. In fact, $\dot{p}_i - \dot{p}_f = \dot{m}(V_i - V_f)$ is exactly equal to m_j, as expected from the discussion in Section 2.1. This equality was noticed by Shafer and Ruegg in 1958 [4].

Engel [5] noted that $\dot{p}$, the rate of momentum transfer, decreases during the collection interval because of the height-dependence of $\dot{p}$. He predicted that dW/dt has a term that varies as the square-root of the time during the collection interval; however he did not discuss the mass of the jet between h_i and h_f. We believe that when m_j is considered, the square-root term does not occur and this interpretation is consistent with our measurements.

2.3. Is There Significant Momentum Storage?

We used Eq. (2) to compute the average flow from dynamic weighings. This equation will not be accurate if water flowing within the control volume has a time-dependent net component of vertical momentum. Figure 4 contains sketches of hypothetical, simple flows in the collection tank driven by a jet. (We imagine the true, complex flow to be a superposition of many such flows.) Many flows do not have net vertical motions of the center of mass of the water; such flows cannot affect the readings of the weigh scale. Examples of such flows include internal flows beneath a quiescent interface 4(a), symmetrical waves 4 (b), and rigid body rotation 4 (c). Figure 4(d) contains a sketch of bubbles entrained by the jet. As the bubbles rise towards the surface, the center of mass (C.M.) of the water beneath the surface falls; therefore such a flow has a net vertical component of momentum. We can think of the bubbles as storing part of the vertical component of momentum. If this component has a net change during the collection interval, Eq. (2) will fail. Initially, there are no bubbles; at the end of a collection interval, momentum stored in the bubbles' motion is on the order of

$$p_{\text{stored}} = M \frac{V_{\text{bubbles}}}{V_{\text{water}}} \frac{D_{\text{tank}}}{t_{\text{rise}}} \qquad (4)$$

where $M \equiv \dot{m} t_{\text{collection}}$ is the collected mass, D_{tank} is the depth of the water collected, and t_{rise} is a typical time required for the bubbles to rise to the surface. The average rate of change of stored momentum, $\dot{p}_{\text{stored}} = p_{\text{stored}} / t_{\text{collection}}$, can be compared to the typical rate of momentum transfer across the control surface $\dot{p}_{\text{c}} = \dot{m}\sqrt{2gh}$:

$$\frac{\dot{p}_{\text{stored}}}{\dot{p}_{\text{c}}} = \frac{0.3\, V_{\text{bubble}}}{V_{\text{water}}\; t_{\text{rise}}} \qquad (5)$$

We estimated $V_{\text{bubble}}/V_{\text{water}} < 0.05$ by looking for a drop in the level of the collected water immediately after the flow was stopped. We detected no drop, with an estimated uncertainty of 10 cm. If the dynamic weighings are averaged over most of the collection interval and if a typical time for a bubble to rise to the surface is 4 s or more, $\dot{p}_{\text{stored}} / \dot{p}_{\text{c}} < 0.01$ and the momentum stored in bubbles is negligible. If a typical bubble rise time is less than 4 s, it is likely that the bubbles are concentrated in a frothy "head" near the surface of the collection time and that this head forms early in the collection interval. In this case, the determination of

$\langle dW/dt \rangle$ should be started after the head has formed. Typically, we began the determination of $\langle dW/dt \rangle$ approximately 10 seconds after the flow started. The discussion of bubbles can be repeated to make an order-of-magnitude estimate for the momentum stored in breaking waves in the collection tank and a similar conclusion will be reached. We acknowledge that this discussion is not rigorous; however, the conclusions are consistent with the measurements reported below.

3. Apparatus and Measurement Procedures

In this work, we used the 10 cm diameter flow line of the water flow calibration facility (WFCF). The flow rates, 10 kg/s to 60 kg/s, correspond to Reynolds' numbers of 130,000 to 800,000, referred to the pipe's diameter. For comparing static and dynamic flow measurements, the key components of the WFCF are the collector/bypass (C/B) unit, the collection tank, the weigh scale, and check standards. We describe these in turn. Then, we outline the measurement procedures.

3.1. Collector/Bypass unit.

During normal static calibrations, the flow divider and the collection/bypass (C/B) unit direct the jet exiting from the "fishtail" into either the bypass pipe or the collection tank. In NIST's WFCF, the diverter moves 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: 1) a divider (which cuts the flow) is operated by a pneumatic angular actuator and 2) a unit C/B that directs the flow to the bypass or the collection tank regardless of the divider position. The C/B unit is mounted below the divider on linear bearings and can be moved horizontally under computer control. Three proximity sensors detect the location of C/B unit and transmit it to the computer. The C/B unit consists of three separate channels and coordination of the position of the C/B 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 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]. However, uni-directional travel of the divider cannot compensate for situations when the flow at the end of the collection is not equal to the flow at the start of the collection.

During dynamic calibrations, the C/B unit functioned as a funnel that intercepted the jet from the fishtail and directed it into the collection tank. During steady operation, the top surface of the water in this funnel defines a reference height h at which the vertical velocity is approximately zero. At a flow of 10 kg/s, this reference surface was at the bottom of the C/B unit; at 60 kg/s, this reference surface was 20 cm above the bottom of the C/B unit. The outlet of the C/B unit had a rectangular cross section 28 cm long and 33 cm wide. The outlet was 2 cm above the entrance to the collection tank and 90 cm above the grid in the collection tank. The WFCF uses optical switch to measure the collection time. The total standard uncertainty of time measurement which includes uni-directional diverter uncertainty is 0.005 %. [1, 6]

3.2. Collection tank.

The collection tank had a diameter of 1.80 m and a height of 1.66 m. A horizontal fiberglass grid was fastened inside the collection tank 90 cm below its top. The grid had square openings arranged in a square array. Each opening was approximately 3 cm on a side, 2 cm deep, and separated by 1 cm of fiberglass from the neighboring openings. When the jet from the diverter struck the grid it broke up into many smaller jets with a modest amount of splashing. During some of the measurements, water level in the collection tank rose through the grid, thereby changing the flow patterns inside the tank. However, these changes could not be detected by the dynamic weighings.

3.3. Weigh Scale

The collection tank was supported on a commercially manufactured weigh scale (Mettler-Toledo, Model 2255-0151) [†]. The scale has a capacity of 4500 kg and a resolution of 10 gm. To calibrate the scale, we used a set of twelve, 45 kg steel masses calibrated at NIST and traceable to the United States national standards of mass calibrated by the NIST Mass and Force Group. Two methods were used to calibrate the scale over its full range. The first method is described in detail in [1]. For this method, the scale was read while it supported the empty collection tank. Then, the 12 masses (540 kg) were loaded onto the scale and it was read again.

[†] In order to describe materials and procedures adequately, it is occasionally necessary to identify commercial products by manufacturer's name or label. In no instance does such identification imply endorsement by the National Institute of Standards and Technology, nor does it imply that the particular product or equipment is necessarily the best available for the purpose.

Then the masses were unloaded, approximately 540 kg of water was added to the collection tank, and the scale was read a third time. This sequence was repeated until the capacity of the scale was reached.

The second method of calibrating the scale used two commercially-manufactured water flow meters that had acceptable short-term stability (repeatability). The calibration factors for each of the flow meters were measured by flowing approximately 540 kg of water into the collection tank at a flow rate of 10 kg/s for a collection time of approximately 54 s. Then, these calibration factors were used with longer collection times to check the scale readings at intervals of approximately 500 kg. During these checks, the flow rate was maintained near 10 kg/s. Thus, this calibration relies on the short-term stability and linearity of the flow meters. The meters were a 4″ electromagnetic flow meter (manufacturer: Krohne, model Optiflux 5000) and dual rotor flowmeter (4″ ExactFlow). Both calibration methods produced the same result; the weigh scale readout was a linear function of the load with the calibration coefficient $K = 0.998789 + 4.57\times10^{-5}(t\,/^{\circ}\,\mathrm{C} - 20.3)$. The standard uncertainty of K was 0.005 %.

The weigh scale was used with a commercially-manufactured (Toledo-Mettler, model "Jagxtreme") signal-conditioning unit with digital outputs. For all the measurements reported here, the low-pass filter was set at 2 Hz. For dynamic flow calibrations, the weight on the scale must be determined at precisely defined intervals. This was accomplished by utilizing the continuous output of the signal-conditioning unit, synchronized with its internal clock. Every 49.1517 ms, the scale delivered a digital output that we recorded. In separate measurements, we verified that the weigh scale's clock was stable, fractionally to 5×10^{-6}.

3.4. Auxiliary Measurements

Three thermistors were used to monitor temperatures in the WFCF. One was placed in the pipeline between the check standards and the fishtail; the other two were in the collection tank. The uncertainty of thermistors calibration is 5 mK.

Periodically, water samples are taken from the flow loop for density measurements. The density was measured with an uncertainty of 0.005% using a vibrating tube densimeter (Anton Paar Corp, DMA 602 External Measuring Cell with Density Meter - DMA 60). The water pressure was monitored between the flow conditioner and the fishtail. Typically, the pressure was 400 kPa to 500 kPa. The temperature, pressure, and humidity of the air were monitored (Vaisala model PTU200 environmental monitor). The density, temperature, and pressure of the air and of the water were the essentially the same during the static and dynamic measurements; thus, these properties do not play a role in comparisons.

3.5. Check Standards

Throughout this work, we used two check standards: a dual rotor turbine meter (4” Exact-Flow) and an electromagnetic flow meter (4” Krohne, model Optiflux 5000). Both check standards were located upstream from the fishtail (See Fig. 1.) The check standards confirmed that the average flow varied less than 0.1 % during a typical collection interval. On several occasions, we manually changed the flow rate by several percent during a collection interval. In every case, the dynamic weighing and the check standards tracked the flow changes within their combined uncertainties. These check standards confirmed that the excess noise for flows near 20 kg/s was flow-related and not scale-related.

3.6. Measurement Procedures

Figure 5 displays the qualitative features of the data. This plot shows the differences $\Delta W \equiv W_{n+1} - W_n$ between successive readings of the weigh scale at intervals of 49.1517 ms during a 60-second long interval for a flow of 60 kg/s. Near time zero, the diverter redirected the flow from the bypass into the collection tank. Approximately 1.1 s later, ΔW reaches a peak of 3.8 kg. Within the following 2 seconds, ΔW settles down to an average value of 2.844 kg. At 40 s, the C/B unit disturbs the flow and after 50 s (not shown), the flow is redirected into the bypass. The dynamic flow rate was calculated by fitting a linear function of time to the values of $W(t)$ for times in the range 4 s < t < 40 s. (The same result was obtained by averaging between 10 s and 40 s.)

During all our tests, the readings of the electromagnetic and dual rotor flow meters were recorded as well the data required for the static calibration (initial scale reading, start diversion time, stop diversion time, water temperature, pressure) as described in [1]

4. Results

Figure 6 compares the dynamic and static flow measurements acquired during two runs 7 days apart spanning the range 10 kg/s < $\dot{m}_S$ < 60 kg/s. The results can be summarized by: $10^4\left(\langle\dot{m}_D\rangle/\dot{m}_S - 1\right) = 1.5 \pm 3.3$, where the uncertainty here and below is the standard deviation of one measurement from the mean. If the noisy data at 20 kg/s are excluded, the results are: $10^4\left(\langle \dot{m}_\mathrm{D}\rangle / \dot{m}_\mathrm{S} - 1\right) = 1.6 \pm 2.0$. We excluded the noisy data at 20 kg/s and fit $\langle \dot{m}_\mathrm{D}\rangle / \dot{m}_\mathrm{S}$ to a linear function of $\dot{m}_\mathrm{S}$. The result is the dashed line in Fig. 6, which has the equation: $10^4\left(\langle \dot{m}_\mathrm{D}\rangle / \dot{m}_\mathrm{S} - 1\right) = 0.0 \pm 0.6 + (2.2 \pm 0.8)\dot{m}/(50\ \mathrm{kg/s})$. The coefficient of $\dot{m}_\mathrm{S}$ is so small that future measurements at higher flow rates are warranted.

Using flows of 10 kg/s, we searched for systematic variations of $\langle \dot{m}_\mathrm{D}\rangle / \dot{m}_\mathrm{S}$ with collection time. We found no trend, as shown in Fig 7. We also searched for systematic variations of $\langle \dot{m}_\mathrm{D}\rangle / \dot{m}_\mathrm{S}$ with the initial load in the collection tank. For these measurements, we also used flows of 10 kg/s; however, we started the flow after the collection tank had been partially filled with water that had been allowed to come to equilibrium. The results are shown in Fig. 8 for collection times of 50 s and 100 s. We did not expect $\langle \dot{m}_\mathrm{D}\rangle / \dot{m}_\mathrm{S}$ to depend upon the initial filling. However, the lines in Fig. 8 suggest that a weak dependence on the initial filling was present. The slope of the dashed line (100 s collection time) is 40 % of the slope of the solid line (50 s collection time.) When the initial load was 2000 kg or higher, the grid in the collection tank was already submerged when the collection began. This distinction is not obvious in Figure 8.

Figure 9 displays typical, 10-second-long, records of successive weight differences $\Delta W \equiv W_{i+1} - W_i$, divided by their average values +ΔW〉 to display the fractional noise in the weighings. The fractional noise in ΔW/+ΔW〉 depends on the flow rate and, unexpectedly, it has a maximum near 20 kg/s. We observed that the exit aperture of fishtail is never completely filled for flows well below 20 kg/s and it is always completely filled for flows well above 20 kg/s. Near 20 kg/s, we suspect that the flow randomly switches between filled and not-filled states and that the switching generates excess fluctuations in $\Delta W/\langle\Delta W\rangle$. To test this unexpected behavior of NIST's WFCF, (and, hopefully, to reduce the flow noise), we are designing a fishtail with a variable aperture that will always be filled. (The exit aperture of the existing fishtail is a rectangle, 2.5 cm × 75 cm.)

5. Conclusions

As described in [1], the timer actuation and diverter contribute a fractional uncertainty of 0.00005 (with coverage factor k =1) to uncertainty of NIST's WFCF static flow standard. Thus, the differences between the dynamic and static flow measurements (Figures 6, 7, and 8) are, typically, a factor of 4 larger that this component of the uncertainty of NIST's standard. The small flow-rate dependence of the comparison (Figure 6) implies that the dynamic standard could be used at much larger flows than we could study with the existing WFCF. (When the flow exceeds 60 kg/s, water splashes out of the existing C/B unit.).

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Figure Captions

Figure 1. Schematic diagram of water-flow calibration facility.

Figure 2. WFCF operating in dynamic mode. The flow velocity V is approximately zero at the reference height $h = 0$; the velocity is V_c at the control surface.

Figure 3. Simplified dynamic flow calibration system at two different times. Unlike Fig. 2, there is no grating in the collection tank.

Figure 4. Schematic flows driven by a jet. (a) internal circulation, (b) symmetric wave, (c) rigid body rotation, d) rising bubbles accompanied by a falling center of mass.

Figure 5. Weight differences during 60 kg/s flow.

Figure 6. Comparison of dynamic and static flow measurements as a function of flow rate for 50 s collection intervals. Run 2 was conducted 7 days after Run 1.

Figure 7. Comparison of dynamic and static flow measurements as a function of collection time for a flow rate of 10 kg/s. Run 2 was conducted 9 days after Run 1.

Figure 8. Comparison of dynamic and static flow measurements as a function of initial load for a flow rate of 10 kg/s.

Figure 9. Fractional differences between successive weighings, $\Delta W \equiv W_{i+1} - W_i$, divided by their average value +ΔW $\rangle$. The fractional noise is largest for flows near 20 kg/s. (The scale output was processed by the manufacturer's "2 Hz" filter.)

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