A Measurement Assurance Program for Low Flow Calibration by the Transfer Method – CS80

— Jeff Peery Sept. 16, 2010

This document outlines the Measurement Assurance Program (MAP) for *Seametrics* CS80 flow measurement system – a liquid flow measurement system used to calibrate liquid flow meters. It consists of four elements: 1) calibration of measurement devices, 2) statistical process control of measurement devices, 3) a measurement uncertainty analysis, and 4) a proficiency test. This MAP is responsible for process control, maintaining quality of measurements, and traceability to National Institute of Standards and Technology (NIST) standards.

MAP's are necessary to maintain quality assurance and ties to national standards [1]. They assure quality of all measurement devices and test procedures and assure a state of statistical control of the measurement process. Upon establishing traceability to national standards a MAP may be implemented to maintain it over time.

This document outlines the MAP used to evaluate and manage *Seametrics* liquid flow calibration system. Law of propagation of error is used to predict measurement uncertainty [2]. A proficiency test is used to validate the system's measurements. Process control is maintained by Statistical Process Control (SPC) [3]. Under this MAP liquid flow rate, volume, and k-factor measurements are traced to NIST and measurement quality is maintained.

METHODS

Liquid flow meter calibrations are performed by driving liquid water at constant flow rate through a system of closed conduit and referencing a primary flow meter (meter under test) to a secondary flow meter (flow standard). The calibration system is composed of a storage tank, pump, and two secondary flow meters. All components are connected by stainless steel 304 tube. The pump is used to drive fluid from the storage tank to the primary and secondary flow meters; maximum flow rate is approximately $5.04\text{x}10^{-3}$ m^3/s and minimum flow rate is approximately $3.15\text{x}10^{-4}$ m^3/s. Upstream of the primary and secondary meters are sections of straight pipe that are sufficient in length to fully develop flow. Pump motor speed is used to regulate flow rates.

Prior to collecting measurements a thermal steady state, hydrodynamic steady state, and test meter output steady state are obtained. After all steady states are obtained volume, time, temperature, and primary and secondary meter output are measured.

K-factor and flow rate measurements are traced to NIST through an unbroken chain of comparisons. Comparisons are created annually by calibrating all measurement devices at an accredited laboratory. Traceability is maintained through SPC. Measurement uncertainty was evaluated by an uncertainty analysis. The entire system was validated by a proficiency test.

STATISTICAL PROCESS CONTROL

Statistical control of the calibration system is assessed using SPC. The system is calibrated regularly against a check standard. Check standard calibrations include two flow rates. Measurements are grouped and plotted using control charts. Control limits are calculated from Shewhart's control limit factors [3; Table A.5].

A proficiency test is performed annually using an accredited laboratory, and establishes measurement traceability at that point in time. For all other points in time, SPC maintains confidence in the measurement processes.

UNCERTAINTY ANALYSIS

Law of Propagation of Uncertainty [2] was used to determine uncertainty in flow rate, volume, and K-factor measurements. The result was second order accurate (Eq. 1).

$$w_R = \left[\left(\frac{\partial S}{\partial \eta_1} w_1\right)^2 + \left(\frac{\partial S}{\partial \eta_2} w_2\right)^2 + \dots + \left(\frac{\partial S}{\partial \eta_n} w_n\right)^2\right]^{\frac{1}{2}} \qquad (1)$$

where δ was partial differential operator, η was component of measurement process, w was uncertainty of η, S was measurand, and w_R was measurement uncertainty.

The uncertainty analysis was simplified by assuming that liquid temperature was equal to pipe temperature. This assumption was valid because Biot number was much less than unity.

Conservation of mass was used to derive a function for flow rate (the method is similar to that given by T. T, Yeh *et. al* [4]). The calibration system was modeled as a completely closed system (no leaks) and was broken into three components: 1) storage mass, 2) primary mass and 3) secondary mass. Storage mass was mass contained between the secondary and primary meters, secondary mass was total mass seen by the secondary meter (flow standard), and primary mass was total mass seen by the primary meter (meter under test). Assuming that mass was conserved, the difference in mass passing through the primary meter from test start to test end was obtained by equating the total mass at each time. Differences were expanded by taking the total derivative (Eq. 2).

$$\Delta M_{\mathrm{Pr}\,i} = + \Delta V_S \rho_S + \Delta \rho_S V_S + \Delta V_{Sec} \rho_{Sec} + \Delta \rho_{Sec} V_{Sec} \qquad (2)$$

where ρ was density kg/m^3, V was volume m^3, Δ was the difference operator. Subscripts *S*, *Sec*, and *Pri* refer to Storage volume, Secondary flow meter, and Primary flow meter respectively. Sign of primary and secondary mass depends upon whether the primary flow meter was upstream or downstream of secondary flow meter. Volume and density were assumed to change with temperature (Eq. 3-4):

$$\Delta V = 3 \cdot \alpha \cdot \Delta T \cdot V \qquad (3)$$

$$\Delta \rho = \alpha \cdot \Delta T \cdot \rho \qquad (4)$$

where T was temperature K, and α was coefficient of thermal expansion 1/K. Equations 3 and 4 were substituted into equation 2 to obtain an expression for the change in primary mass (Eq. 5). Note that if the primary meter is upstream of the secondary meter, equation 5a is used. If the primary meter is downstream of the secondary meter then equation 5b is used.

$$\Delta M_{\mathrm{Pr}\,i} = (\Delta V \rho_w)_{Sec} + (\alpha_{pi} \Delta T_{pi} V \rho_w + 3\alpha_w \Delta T_w V \rho_w)_S \qquad (5a)$$

$$\Delta M_{\mathrm{Pr}\,i} = (\Delta V \rho_w)_{Sec} - (\alpha_{pi} \Delta T_{pi} V \rho_w + 3\alpha_w \Delta T_w V \rho_w)_S \qquad (5b)$$

where subscripts *w*, and *pi* refer to water and pipe material respectively. Volumetric flow rate (Eq. 6) was obtained from equation 5.

$$\overline{Q} = \frac{\Delta M_{\mathrm{Pr}\,i}}{\Delta t \cdot \rho_w} \qquad (6)$$

where t was time s, and *Q bar* was average volumetric flow rate m^3/s.

Flow rate uncertainty was determined from equations 1 and 6. Uncertainties (table I) represented the 67% probability interval for a standard normal distribution.

RESULTS

Greatest uncertainty in k-factor measurement was approximately 0.4% (Fig. 1) with coverage factor equal to $2.0\mathrm{x}10^0$. Test time was maintained at $6.0\mathrm{x}10^1$ seconds, k-factor was $5.28\mathrm{x}10^5$ pulses per cubic meter.

Proficiency test results are listed in table III. Confidence intervals for K-factors measured by *Flow Technologies* were within the confidence interval for those measured by the *CS80*.

CONCLUSIONS

This document outlined the steps taken at *Seametrics* to establish a MAP for the CS80. Under this program all measurements performed by the transfer system are traceable to NIST. Uncertainty in flow rate, volume, and k-factor were determined by the law of propagation of error and the calibration system was validated by a proficiency test.

References

[1] B. Belanger, “Measurement Assurance Programs Part I: General Introduction,” NBS Special Publication 676-I, *U.S. Government Printing Office*, Washington, May 1984.

[2] S. J. Kline and F. A. McClintock, “Describing Uncertainties in Single-Sample Experiments,” *Mechanical Engineering*, January, 1953.

[3] D. J. Wheeler and D. S. Chambers, “Understanding Statistical Process Control,” *SPC Press*, Knoxville TN, May 1984.

[4] T. T. Yeh *et. al*., “An Uncertainty Analysis of a NIST Hydrocarbon Flow Calibration Facility,” *Proceedings of the 2004 Heat Transfer/Fluids Engineering Summer conference*, ASME 2004.

[5] ANSI/ASTM, “Measurement Uncertainty for Fluid Flow in Closed conduits” *American Society of Mechanical Engineers*, 2001.

[6] F. P. Incropera and D. P. Dewitt, “Introduction to Heat Transfer” John Wiley & Sons, Inc., 1996.

[7] Norman E. Dowling, “Mechanical Behavior of Materials.” *Prentice Hall*, 1999.

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TABLE I

THIS TABLE LISTS THE UNCERTAINTY BUDGET FOR VOLUME, K-FACTOR, AND FLOW RATE MEASUREMENTS.

Variable	Standard Uncertainty	Type	Degrees of Freedom
Temperature (%)			
ΔT[1]	$1.7\ x10^{1}$	B	
Time (s)			
PLC Loop Time	$1.70x10^{-2}$	A	1
PLC Time Resolution	$1.00x10^{-2}$	B	
Δt[2]	$1.64x10^{-2}$		
Pulse Count (counts)			
PLC[3]	$1.16x10^{0}$		
Volume (%)			
V_S	$4.95x10^{0}$	B	
Secondary Meter Volume[4]	$1.25x10^{-1}$	B	
Coefficients of thermal Expansion (K^{-1})			
Water[5]	$2.8x10^{-7}$	B	
Stainless Steel 304[6]	$1.2x10^{-9}$	B	

Combined standard uncertainty: Values were calculated using the law of propagation of uncertainty (Fig. 1)

TABLE II

THIS TABLE LISTS THE FLOW RATE PROFICIENCY TEST RESULTS.

Flow Rate (m^3/s); (gpm)	Test Time (sec)	Seametrics		Accredited Laboratory[7]	
		K_{factor} (ppg)	Expanded Uncertainty (%)	K_{factor} (ppg)	Expanded Uncertainty (%)
$2.52x10^{-3}$; 40	$6.00x10^{1}$	$1.9985x10^{3}$	$4.0x10^{-1}$	$2.000x10^{3}$	$7.5x10^{-2}$
$6.31x10^{-4}$; 10	$6.00x10^{1}$	$2.0011\ x10^{3}$	$4.0x10^{-1}$	$2.000x10^{3}$	$7.5x10^{-2}$

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[1] Temperature uncertainty was not calculated. Maximum uncertainty in temperature was estimated to be 30 degrees Celsius.

[2] RSS(PLC loop time, PLC time resolution).

[3] Assumed quantization error was two counts.

[4] Manufacturer spec.

[5] Taken as the smallest tabulated unit of precision from reference 6.

[6] Taken as the smallest tabulated unit of precision from reference 7.

[7] Colorado Experimentation and Engineering Station Inc., (CEESI).

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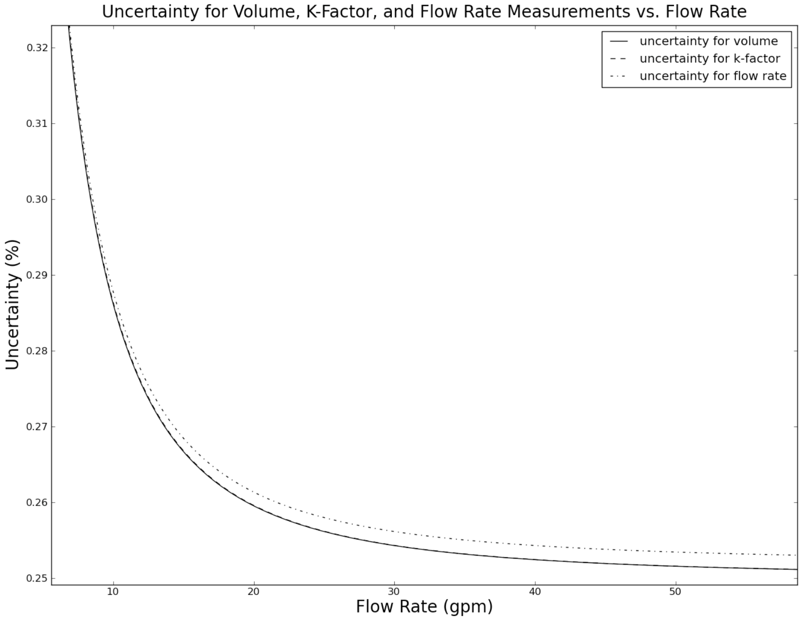

Figure 1 This figure illustrates combined uncertainty volume, k-factor, and flow rate measurements versus flow rate.

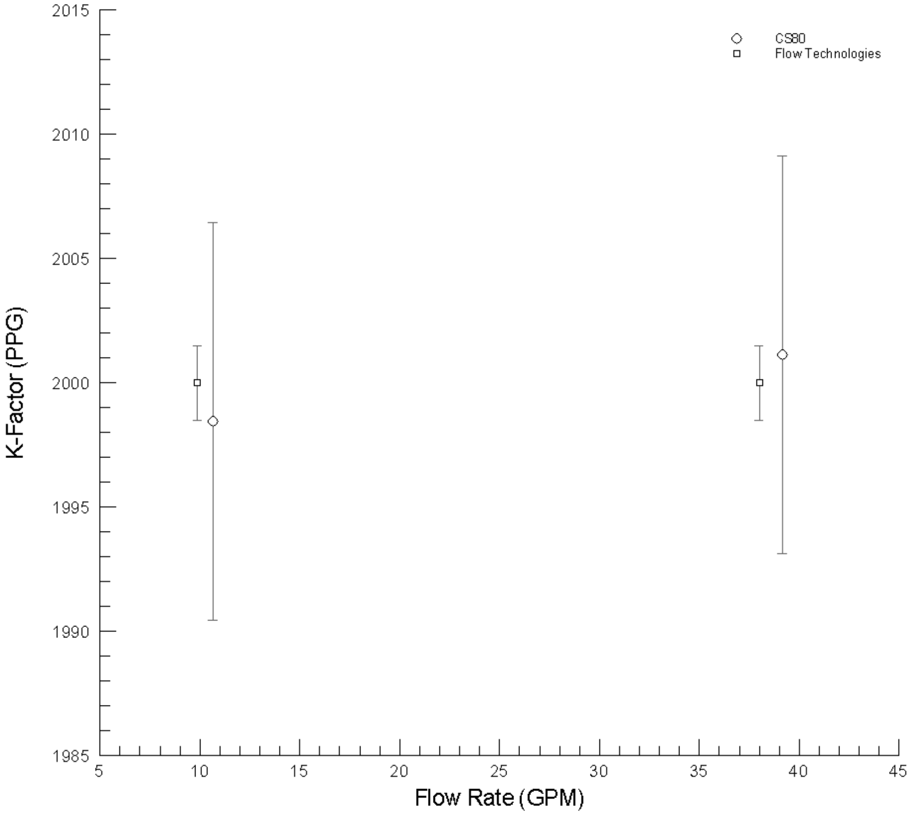

Figure 3 This figure illustrates the proficiency test results.