

A MEASUREMENT ASSURANCE PROGRAM FOR FLOW CALIBRATION BY THE TRANSFER METHOD – CS2500



– JEFF PEERY SEPT. 21, 2010

This document outlines the Measurement Assurance Program (MAP) for *Seametrics* CS2500 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 and k-factor, flow rate, and volume 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 four secondary flow meters. All components are connected by stainless steel 304 tube. The pump or gravity may be used to drive fluid from the storage tank to the primary and secondary flow meters; maximum flow rate is approximately $1.58 \times 10^{-3} \text{ m}^3/\text{s}$ and minimum flow rate is approximately $1.89 \times 10^{-7} \text{ m}^3/\text{s}$. Upstream of the primary and secondary meters are sections of straight pipe that are sufficient in length to fully develop flow. Solenoid valves are used

to regulate low flow rates the pump is used to regulate high 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

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

UNCERTAINTY ANALYSIS

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

$$w_R = \frac{S}{1} w_1^2 + \frac{S}{2} w_2^2 + \dots + \frac{S}{n} w_n^2 \quad (1)$$

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).

$$M_{Pri} = \rho \left(\Delta V_S + V_{Sec} \Delta V_S + V_{Sec} \Delta V_{Sec} \right) \quad (2)$$

where ρ was density kg/m³, V was volume m³, 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):

$$V = V_0 (1 + \alpha T) \quad (3)$$

$$\rho = \rho_0 (1 - \alpha T) \quad (4)$$

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.

$$M_{Pri} = \rho_w \left(\Delta V_w + V_{Sec} \Delta V_w + V_{Sec} \Delta V_{Sec} \right) - \rho_{pi} \left(\Delta V_{pi} + V_w \Delta V_{pi} + V_w \Delta V_w \right) \quad (5a)$$

$$M_{Pri} = \rho_w \left(\Delta V_w + V_{Sec} \Delta V_w + V_{Sec} \Delta V_{Sec} \right) - \rho_{pi} \left(\Delta V_{pi} + V_w \Delta V_{pi} + V_w \Delta V_w \right) \quad (5b)$$

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

$$\bar{Q} = \frac{M_{Pri}}{t} \quad (6)$$

where t was time s, and \bar{Q} was average volumetric flow rate m³/s.

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

RESULTS

Greatest uncertainty in flow rate measurement was 0.2% (Tab. II) with coverage factor equal to 2.0x10⁰. Uncertainty of flow rate was most sensitive to uncertainty of test time, and uncertainty of secondary meter volume. Test time was maintained at 6.0x10¹ seconds.

Proficiency test results are listed in table III. K-factors measured by *Colorado Experimentation and Engineering Station (CEESI)* agreed well with those measured by the system described herein (*Seametrics*). At each flow rate, the 95% confidence interval for measurements collected by *CEESI* was within the 95% confidence interval for measurements collected by *Seametrics*.

CONCLUSIONS

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

REFERENCES

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Jeffrey T. Peery This author was born in Bellevue, Washington, on October 5, 1978. He earned his Bachelor of Science in mechanical engineering in June of 2001 and his Master of Science in mechanical engineering in June of 2003 from the University of Washington, Seattle, WA. He published his first two papers regarding thermal modeling in biomechanics while working at the Veterans Affairs Puget Sound Health Care Center and the Center for Excellence in Limb Loss Prevention and Prosthetic Engineering, during 2002 and 2004. He currently works as a mechanical engineer for Seametrics Inc., a designer and manufacturer of mechanical and electro-magnetic liquid flow meters. His work focuses on flow meter R&D, numerical analysis, design and experimentation..

TABLE I
THIS TABLE LISTS THE UNCERTAINTIES OF MEASUREMENT VARIABLES.

Variable	Standard Uncertainty	Type	Degrees of Freedom
Temperature (K)			
Thermometer	1.90×10^{-1}	A	7
Thermistor ¹	1.0×10^{-2}	B	
ΔT^2	1.0×10^{-1}		
Time (s)			
PLC Scan Time ³	1.7×10^{-2}	B	
PLC Time Resolution ⁴	1.0×10^{-2}	B	
Δt^5	1.6×10^{-2}		
Pulse Count (counts)			
PLC (at 500 Hz)	3.39×10^0	A	5
Volume (%)			
V_s	6.0×10^{-2}	B	
Secondary Meter Volume ⁶	1.25×10^{-1}	B	NA
Coefficients of thermal Expansion (K⁻¹)			
Water ⁷	2.8×10^{-7}	B	NA
Structural Steel A36 ⁸	1.2×10^{-9}	B	NA

TABLE II
THIS TABLE LISTS UNCERTAINTY ANALYSIS RESULTS.

Flow Rate (m ³ /s); (gpm)	Test Time (sec)	Uncertainty K _{factor} (%)	Uncertainty Flow Rate (%)
3.15×10^{-7} ; 0.005	6.0×10^1	1.28×10^{-1}	1.28×10^{-1}
6.31×10^{-6} ; 0.1	6.0×10^1	1.25×10^{-1}	1.25×10^{-1}
6.31×10^{-5} ; 1.0	6.0×10^1	1.25×10^{-1}	1.25×10^{-1}
1.26×10^{-3} ; 20	6.0×10^1	1.25×10^{-1}	1.25×10^{-1}

TABLE III
THIS TABLE LISTS THE FLOW RATE PROFICIENCY TEST RESULTS⁹. FOR EACH FLOW RATE, THE DEGREES OF FREEDOM WERE FIVE AND COVERAGE FACTOR WAS 2.571 (STUDENTS T₉₅).

Flow Rate (m ³ /s); (gpm)	Test Time (sec)	Seametrics		Accredited Laboratory ¹⁰	
		K _{factor}	Uncertainty (%) ¹¹	K _{factor}	Uncertainty (%)
3.155×10^{-3} ; 50	6.0×10^1	3.0004×10^2	9.01×10^{-1}	2.9905×10^2	1.36×10^{-1}
9.464×10^{-3} ; 150	6.0×10^1	2.9991×10^2	9.05×10^{-1}	2.9897×10^2	2.08×10^{-1}
2.524×10^{-2} ; 400	6.0×10^1	2.9978×10^2	9.02×10^{-1}	2.9885×10^2	1.71×10^{-1}
5.047×10^{-2} ; 800	6.0×10^1	2.9995×10^2	9.00×10^{-1}	2.9901×10^2	1.67×10^{-1}

¹ Manufacturer spec.

² Evaluated using the law of propagation of uncertainty. Components of uncertainty included those for circuit components.

³ PLC scan time (one loop through ladder logic code).

⁴ PLC time resolution.

⁵ Test Time uncertainty was the RSS of PLC scan time and PLC time resolution.

⁶ Manufacturer specification.

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

⁸ Taken as the smallest tabulated unit of precision from reference 7.

⁹ Uncertainty calculated as $t_{95} \frac{\sigma}{\beta}$, where σ is standard deviation, t_{95} is students t, β is measurement uncertainty. $t_{95} = 2.571$.

¹⁰ Colorado Experimentation and Engineering Station Inc., (CEESI).

¹¹ Uncertainty in flow rate as calculated from the uncertainty analysis herein.