Flow Meter Dye Dilution Test Literature Review

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Task 1: Literature Review of Magnetic Flow Meter Calibration Using Dye Tracers

Flow meters are typically calibrated in a laboratory prior to use. However, there is a limited number of laboratories that can handle large flow meters similar to the one under investigation. Therefore, in-situ calibration is necessary to either ensure that the meter is performing according to the manufacturer's calibration or to ensure that the measurements made are accurate. In-situ calibration is especially necessary when there are contractual limits or regulatory issues. The flow meter in this study is a magnetic type flow meter, where the flow is used to report effluent flow values to regulatory agencies. Flow measurement is based on Faraday's law to estimate the flow velocity and then calculate the flow rate from the flow velocity and flow area.

The extensive literature review conducted under this task revealed that little information is available about the calibration and verification of this type of meter using dye dilution studies. However, there are abundant studies in the literature for other types of flow meters (J. J. Miau et al. (2005), Garcia et al. (2005), R.J.W. Peters, et al. (2006), Fujimura et al. (2001), and Replogle et al. (2000)). The types of meters reported in these studies ranged from a current meter to a Doppler flow meter. The studies that were located and relevant to the current study are presented herein.

Dekker et al (1998) of Camp Dresser and McKee (consultant for the City of Detroit and part of the Flow metering Task Force) conducted a study of the Detroit City sewer system (the

Greater Detroit Regional Sewer System , GDRSS) to assess the utility of dye dilution testing in flow meter calibration in the GDRSS. The assessment of the meter accuracy was conducted in both laboratory testing and field implementation. The factors influencing meter accuracy considered in their study were: standard curve preparation, temperature correction, presence of suspended solids, and background fluorescence concentration. The impact of these factors is presented below.

Standard Curve Preparation

Standard curves are developed by plotting several dye (Rhodamine WT) dilution concentrations versus measured fluorescence. Standard curves typically behave as a linear function. The investigators were trying to find the optimal concentration range over which concentration measurement could be accurately made using the dye dilution testing technique with the standard curve still behaving as a linear function. To find the optimal Rhodamine WT concentration used in the standard curve preparation and directly impacting the meter accuracy, they conducted laboratory tests with different concentrations: 0-200ppb, 0-500 ppb, and 0-1000ppb. The investigators reported that at lower concentration ranges, all the curves prepared exhibited highly linear characteristics. As the Rhodamine WT concentration increased, a nonlinear behavior was observed, with the highest deviation from the linear behavior observed for the concentration range of 0-1000ppb. They noted that even a small deviation from a linear behavior will result in a large increase in the concentration prediction error. Based on their laboratory investigation, Dekker et al (1998) concluded that the optimal concentration (upper limit) that will aid in minimizing the error associated with the Rhodamine WT concentration measurements is for the range 0-200 ppb.

Temperature Correction

Dekker et al (1998) evaluated the need for temperature correction when measuring fluorescence. The relationship between the measured fluorescence and the corrected fluorescence to the reference temperature is an exponential relationship with the dye specific temperature coefficient (k). If the natural logarithm of fluorescence is plotted versus the temperature, the downward slope of the best fit curve is the temperature coefficient k. To evaluate the temperature coefficient, the investigators prepared two standards at concentrations of 10 and 50 ppb. They passed these two concentrations (one at a time) through the flow-through fluorometer cell. Controlling the temperature of the cell by either heating or cooling the cell, they were able to establish a relationship between the temperature and natural logarithm of fluorescence concentration to determine the temperature coefficient for each standard concentration. They reported that the data of temperature versus natural logarithm of fluorescence was linear with a negative slope. Different test batches produced consistent results, but the temperature coefficient was highly dependent on the batch and could vary by as much as 10%. However, temperature correction to a single reference temperature value introduced a small error that could be neglected.

Suspended Solids

The degree of turbidity of a sewage stream reduces accuracy in the determination of the dye dilution concentration due the absorption of the light used to determine the dye concentration. In reality, the suspended solids content will fluctuate with time. In order to quantify the impact of suspended solids on the dye dilution accuracy, Dekker et al (1998) developed a spectrophotometric method to measure the light transmittance for the two wave lengths (550 and 580 nm) used to measure the Rhodamine WT. They prepared two standards at 20 ppb and 100 ppb Rhodamine WT. They measured fluorescence and absorbance under well-mixed, high suspended solids conditions and again after removal of a large amount of suspended solids by settling and centrifuge methods. They determined that the removal of suspended solids decreased absorbency and increased the strength of the measured fluorescence. They also noted that the concentration of Rhodamine WT (20 ppb and 100 ppb) did not impact the accuracy in the measured fluorescence. Dekker et al reported that suspended solids in the sewage stream was one of the major error sources in the determination of meter accuracy.

Background Fluorescence Concentration

In order to evaluate the impact of the measured background fluorescence concentration, Dekker et al (1998) prepared standard curves at very low concentrations (0-0.2 ppb and 2 ppb) in distilled water. The same linear trend was observed for the high concentration standards with nonlinear behavior observed for concentrations <0.1 ppb. Samples collected throughout the GDRSS showed that the background concentration of fluorescence was between 0.2 to 1.0 ppb. This range is smaller, by a factor of 20, than the effective lower limit concentration of 20 ppb. Dekker et al (1998) concluded that as long as the measured fluorescent concentration is much higher than the background concentration, the background concentration will have little or no effect on the fluorescent concentration.

Flowrate Comparison

Dekker et al (1998) compared flowrates determined using dye testing, magmeter and drawdown test at the Greenfield pump station in Detroit. The flow rate from the drawdown test was determined using the pump station wet well. They reported that the volume of the wet well was calculated by multiplying the cross-sectional area of the wet well by the change of depth during the test period (test period was five minutes). The results of the drawdown test for one measurement showed that the estimated flowrate was 21.3 cfs. The dye dilution test and magmeter readings were performed at five minute intervals for a total test period of thirty minutes. The dye testing flowrate during the test period ranged from 20.7 cfs to 18.3 cfs. The magmeter measured flow rate ranged from 20.5 cfs to 19.0 cfs during the same test period. They reported that the results of this test were consistent with the results of another test conducted in March of 1997. The maximum difference between the magmeter measured flowrate and the dye dilution test estimated flowrate was 3.8%. The maximum dye dilution test uncertainty as reported by Dekker et al (1998) was 5.1%. The maximum difference between the magmeter measured flowrate and drawdown test flow rate was 16.4% and between the dye dilution estimated flowrate and drawdown test flow rate was 12.1%.

Stonehouse et al (2001) used dye dilution testing to assess the accuracy of seven commonly used meter technologies. They conducted 150 tests during the duration of their study. The meters they tested were: Electromagnetic meter, magmeter, ultrasonic (multipath and single path), open channel (multidepth and ultrasonic), flume and weir. The magmeter is the focus of this review and therefore, the discussion of the Stonehouse work will be limited to magmeters. Discussion of the other meter technologies Stonehouse studied will not be included in this review. The magmeters (diameter range 3 to 5.5 feet) used in the Stonehouse study were manufactured by Fisher and Porter, which are similar to the meter owned by Plant

A. They reported that some meters that are considered accurate reported error of 30% and some even reached 70%. However, the overall observed system error was 15.1%. In their study, they implemented “Good Metering Practice” to improve the accuracy of meters as suggested by the flowmeter task force (FMTF). Good metering practice is a set of protocols for installation, maintenance, downtime and meter-collected data developed by the FMTF and adopted afterwards by the City of Detroit DWSD and other cities and counties in the State of Michigan.

Stonehouse et al (2001) used dye dilution testing to assess flow meter accuracy. They used a protocol for dye dilution testing that Camp Dresser and McKee (CDM) prepared for the City of Detroit, Michigan. The key factors listed in this protocol that they believe will improve the accuracy of the dye dilution testing will be discussed later as part of this review.

Stonehouse et al (2001) reported that based on the FMTF the accuracy of the magmeters is between 2 to 5% of the measurement. The initial testing of their magmeters indicated an error of 5.2% which is greater than the expected range reported by the FMTF. After three years of “good metering practice,” the error in the magmeter measurement was reduced to 4.2%. They also reported that magmeters are mostly applicable for small pipe installations. Stonehouse et al (2001), recommended using dye dilution testing in meter calibration because it improves the accuracy of flow meters and improved the overall system accuracy to 5 - 7%.

One of the relevant and comprehensive studies conducted on several types of meters including magnetic meters is the study conducted by the Detroit Water and Sewage Department (DWSD) on the Greater Detroit Regional Sewer System (GDRSS). As part of this study on the GDRSS, several Technical Memorandums (Tech Memos) were prepared. Two of these Tech Memos relevant to the current study are Tech Memo 4-2: "Dye Dilution Testing Protocol” and Tech Memo 4-4: “Meter Uncertainty Analysis.” The Protocol is detailed and was prepared based on one hundred dye dilution tests on a wide range of flow meters. This protocol could be adopted for the current study. A copy of the dye dilution test protocol is included in appendix A for your records. Tech Memo 4-4 listed the factors affecting the meter uncertainty as it relates to dye testing dilution. These factors were assessed in both laboratory and field setting. The factors they investigated as part of their study are:

- Dye injection rate
    - Pump Fluctuation
    - Pump bias

  Error associated with dye injection rate ranged between ±0.8-0.9% for both 250 and 500 ml burettes. Field tests confirmed this range (±0.5-0.9%)
- Dilution measurement
    - Dye concentration

      The error associated with the dye concentration preparation ranged between ±1.9% using the Wheaton pipettor to ±2.5% using the Eppendorf pipettor.
    - Fluorescence measurements

      The error associated with fluorescence measurements ranged between ±0.85 (large cuvette method) to ±1.3% (flow-through method).
    - Standard curve preparation

      The error associated with standard curve preparation ranged between ±0.5 to 2.0%
    - Temperature correction
        - Temperature fluctuation
        - Temperature bias

      The error associated with temperature measurement was 0.5% with bias error very small that could be neglected.
    - Suspended solids
        - Measurement correction
        - Bias

      The error associated with suspended solids can range between 0 to 3.6%.
    - Background fluorescence

      Error associated with the presence of suspended solids can be as much as 16% or as little as 0.8% which is a more typical value according to Tech Memo 4-4.

If errors associated with the above listed factors are compounded, the upper and lower error limits associated with dye dilution testing are 11.6% and 3.2%, respectively. If the maximum observed error (16%) associated with fluorescence background is added to upper and lower error limits, an upper error limit of 27.6% and a lower limit of 19.2% results.

The current knowledge of the existing meter

- *The meter was calibrated by the manufacturer and 5% accuracy was reported.*
- *In 2003, an in-situ attempt to re-calibrate the flow meter at 30 minute intervals resulted in a maximum relative difference of 12.2%, 8.5%, 39.3% for the 9/17/03, 8/28/03, and 7/24/03 test, respectively.*
- *In 2004 another attempt at in-situ calibration of the flow meter was conducted. The study concluded that at 30 minute intervals the relative error was greatly improved when flow signal filtering was applied to attenuate flow signal fluctuations. An empirical equation was derived as part of this study and was applied to the collected data. The maximum relative difference for the 2004 study was 4.6%, 5.0%, and 6.5% for the 9/8/04, 10/21/04, and 10/28/04 studies, respectively. Applying the correction equation resulted in a relative difference in the (±) 1% range.*

In general, the limitations in magnetic flow meter measurement come from several sources. These sources are divided into three main categories; operational, geometrical (installation), and transported liquid. The operational category is dependent on the measurement range and surrounding environment. This category, to some degree, is not as important as the other two categories. The liquid in this case is effluent from a treatment facility where the properties and conditions of the liquid are relatively constant. Variation in some properties of the liquid will increase the uncertainty of the flow meter measurement. The major sources of uncertainty of magnetic flow meter measurement are the geometrical (installation) constraints. Several studies (Bobovnik et al. (2003), Clark and Cheesewright (2003), R.W. Herschy (2002), Cheesewright et al. (2000), and Hanson and Schwankl (1998)) investigated the installation constraints of other types of flow meters (Vortex, Doppler, Coriolis, Propeller, paddle-wheel and Ultrasonic). The main focus in their studies was the location of fittings in the line upstream and downstream of the meter and the length of straight pipe upstream and downstream of the meter. The installation conditions mainly impact head change (drop) and disturbance of the flow and thus variation in the flow velocity profile between the sides and the center of the pipe. Magnetic meters are typically installed at the center of the pipe to measure the flow velocity and if the in-situ velocity profile is not similar to the calibrated conditions then we expect the meter to drift from the true measurement.

The work of Hanson and Schwankl (1998) was more relevant than the other studies cited. They investigated the placement of pipe fittings (check valve, partially closed butterfly valve, partially closed butterfly valve and 90^o bend, single vanes and six vanes) upstream of the flow measurement devices (propeller, Collins pitot tube, Hall pitot tube, and two types of paddle-wheel meters) at distances of 2, 5, 10, and 15 pipe diameters. They reported that having a check valve in the pipe upstream of the meter will result in elevated error in the measurement compared to a control run. For example, for the paddle-wheel meter, the maximum error was -28.5% (control run error is 2.3%). Velocity meter resulted in the highest error (35%, control run error is 14.4%) at a distance of 2 pipe diameter and 22.2% (14.5% control run error) at 10 pipe diameter. For a partially closed butterfly valve at 15 pipe diameters upstream, the error was 10.5% for a paddle-wheel meter and 0.1% for a Collins meter. The Plant A magmeter is located at a distance of 14 pipe diameters downstream of an injection pump and diffusers, which is less than the 15 pipe diameters investigated by Hanson and Schwankl (1998). The magmeter is also located 10 pipe diameters downstream of an abandoned pump housing which will increase the potential for errors in flow measurement. Having a 45^o bend downstream of the magmeter also increases the potential error in the measurement of flow.

Baker (1993) reported, based on experience by the American National Standard Institute/American Petroleum Institute (ANSI/API), that turbine flow meters need to have straight, unobstructed pipe runs 20 pipe diameters upstream and 5 pipe diameters downstream to effectively reduce turbulence in the flow. ANSI/API also reported that the installation of a valve upstream of the flow meter will require 15 pipe diameters of straight pipe. The Plant A magmeter is located downstream of major flow disturbance structure that is less than the 20 pipe diameters recommended by Baker (1993). A 40° bend is also located at a distance of 0.8

pipe diameters, which less than the 5 pipe diameter distance as recommended by Baker (1993).

Jenny et al. (1987) studied the use of ultrasonic flow meters in the measurement of municipal and industrial flows. They reported that 10 pipe diameters are required downstream of a valve, or pipe bend or twisting flow path. Their recommendation is consistent with the current rule of thumb of having 8-10 pipe diameters of straight pipe section upstream of flow measuring device and 2 pipe diameters of straight pipe downstream of a flow measuring device.

Installation of flow meters was evaluated by West (1961). He concluded that reporting percent error for a flow meter is superficial. He reported that investigating and understanding the flow velocity profile will be more beneficial in the assessment of meter accuracy due to fact that, if the meter is not measuring the actual velocity profile, an error in the measured flow will result.

Abernethy et al. (1983) (an American Society of Mechanical Engineering publication) studied the sources of uncertainty in a measurement and type of error. They came up with models to assess the uncertainty for a single measuring device (flow meter) or the compounded error from several measuring devices (flow meter, temperature, elevation, volume and time). They considered the precision error, which is related to the accuracy of the measurement of the truer value under consideration, and the bias error, which is related to the system error and considered to be constant during the error assessment. Combining the precision error and the bias error will allow for the determination of the overall system error with 95% confidence. The same systematic approach could be implemented for the flow meter calibration study under consideration.

The current knowledge of the existing meter

- *Meter was rebuilt after installation in 1980*

- *Meter bore size is 10 inches (pipe is 120 inches). Omega, a flow meter manufacturer, recommends, as a rule of thumb, that the flow meter be at least 50% of the pipe size*. (Omega website: www.omega.com).
- *Upstream flow disturbances (injection pumps and diffusers), and fittings (type of fittings not clear) are within 14 pipe diameters.*
- *Abandoned pump housing is within 10 pipe diameters upstream of the magmeter.*
- *A 42^o bend is located at 0.8 pipe diameter downstream.*
- *Four 36-inch pipe taps, located on four sides of the flow meter support structure, are within 12.5 pipe diameters and extend to within a foot of the meter.*

Task 2: Assessment and Uncertainty of Flow Determination Using the Volumetric Technique

Several studies like the one conducted by Cheesewright et al. (2000) used the gravimetric technique (measuring the mass of water as a function of time to determine the flowrate) to determine the "true" measured flow rate to be compared with the metered flow rate. They reported the measured gravimetric flow rate uncertainty is (±) 0.1%. They also used in their study an electromagnetic flow meter as another source to measure flow rate. However, they did not report their finding comparing the flowrates obtained using gravimetric flowrate technique estimation and flowrate determined using electromagnetic flowmeter.

Hanson and Schwankl (1998) used the volumetric flow rate technique to determine the "true" measured flow rate in their study to calibrate several types of flowmeters. They took two measurements of volumetric flow rate and averaged them to determine the measured volumetric flow rate. They evaluated and compared the difference between the individual volumetric flow measurement and the mean of the two measurements. This difference was less than 1% for 81% of the measurements they took and 1.25% for 91% of the measurements they took. The maximum reported error between the two individual readings and their mean was 3.6%. They also reported that measuring larger flow rates resulted in bringing the two individual readings closer and thus reducing the uncertainty in the measurement.

The current knowledge of the existing meter

- *The volumetric flow rate was determined by dividing the volume change over a period of time.*
- *The "assumed" error in calculating the volumetric flow rate was (±)2%.*
- *Relative difference increased with the increase of flow measurement. This finding contradicts the findings of Hanson and Schwankl (1998).*
- *Metered flow values were assigned an error of (±) 5% across the board.*
- *The error assessment as reported in the Technical Memorandum No.1 prepared by the Matrix Management, Inc. followed a relatively simplistic approach to come up with the individual error and compound error. A more detailed approach, including the bias error and using a statistical analysis approach that will provide at least 95% confidence level is recommended. This approach will provide an uncertainty bounds (limits) for the system.*
- *For volume calculation error, Matrix Management Inc. assumed a 2% error in the volume calculation. The reason for selecting this error value was not stated in the report.*

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