Verification of accuracy of flowmeters installed in mineral processing plants

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ABSTRACT

A common problem and the source of much confusion in minerals processing plants is how to determine if flowmeters that have been physically installed are operating properly. This is a challenging task due to the difficulty associated with passing a controlled amount of fluid through the meter and the inability to remove the meter for testing. Several techniques are available to verify operation of the flowmeter – the entire system as well as subsystems – all of which fall short of a true laboratory calibration. However, when carefully executed these techniques can provide the user with a satisfactory level of confidence.

The current paper first reviews the essentials of a true laboratory calibration of flowmeters and the associated accuracy uncertainties, which provide fundamental understanding of the basic principles of calibration as a basis for using and understanding the subsequent in-plant techniques. It then reviews the various in-plant techniques and presents examples.

Next, verification by tank test is presented, which provides the user with the greatest assurance and lowest uncertainty of the flowmeter accuracy. The basic test steps are presented, and the various uncertainties are examined and quantified for a typical test. Although the most useful, this test is often the most difficult to implement; therefore, other techniques are presented.

For flowmeters installed in closed circuit grinding applications in beneficiation plants, an available technique involves comparing the flow through the cyclone battery with the theoretical cyclone performance using cyclone inlet pressure and manufacturer's performance data. Additionally, the meter performance can be determined by looking at correlations between flow rate and other parameters, such as pump amps or pump power.

Finally, techniques for verifying performance of flowmeter subsystems are presented, which involve electrical tests performed by the flowmeters themselves, as well as tests with external dedicated test instruments. Advantages and limitations are discussed.

INTRODUCTION

An important and common maintenance challenge in mineral processing plants is determining if installed flowmeters are providing accurate readings. This is challenging due to the difficulty of providing a known 'reference signal', which means passing a known amount of fluid through the meter. A typical meter has a calibrated accuracy of +/-1%, which means that a calibration procedure requires a reference flow with an uncertainty three to ten times smaller, i.e. 0.3% to 0.1%. In the field this is extremely difficult. The challenge then becomes choosing a procedure that is practical, executing it with care, and evaluating the associated uncertainties so as to provide a level of confidence about the accuracy of the flowmeter. This will lead to higher instrument reliability, greater availability, and lower overall maintenance costs.

The assurance of measurement uncertainty at the installed end user location consists of two basic parts: the calibration of the meter in ideal laboratory conditions, and the reproduction of the laboratory measurement conditions on site. The inevitable differences can be estimated using theoretical and experimental data, but they are commonly ignored. Typical measurement errors found in over 1,000 first time field verification tests performed by a highly experienced company using the nuclear tracer method on water lines show that the accuracy measured in the field is typically more than a ten times worse than specified by the flowmeter manufacturer. This suggests that the meter is probably the most accurate component in the measurement chain, and the most significant errors come from other sources.

Measurement uncertainty associated with the entire measurement chain on site has many components, which are typically combined using a root-mean-square (RMS) technique. These uncertainty components are: meter calibration uncertainty (specified accuracy), mechanical and electrical installation tolerances, fluid properties, non-ideal flow profile, meter stability, fluid-to-sensor coupling, signal transmission to control room, data acquisition system tolerances, etc.

The field procedures presented here have a wide range of implementation difficulties and associated uncertainties. The tank test method typically produces the lowest uncertainty, but is often not an option because a suitable tank is not available. The cyclone feed flow rate measurement is such a case where other options are presented. The transit time technique using radioactive tracer is an option sometimes used where no other technique is practical. It is widely used in Europe but little used in South American mining applications, probably because it requires skilled personnel and the handling of radioactive material.

Instrumentation personnel are usually familiar with basic statistics associated with means and standard deviations of test data. Few are familiar with determining the associated confidence intervals and levels. Determination and use of confidence levels has historically been done using traditional statistical methodology. Recently, standards laboratories and industry are moving toward using the Monte Carlo Simulation (MCS) technique, which requires less statistical knowledge to implement and eliminates some of the mathematical simplifications of traditional statistical methods. An example of its implementation is presented.

METHODOLOGY

True laboratory calibration of flowmeters

To appreciate the challenges of verifying the performance of a flowmeter installed in an industrial mining process, it is useful to understand the standard laboratory calibration process with water under controlled conditions and the associated uncertainty of that process. Only then can one understand the added level of difficulty and uncertainty associated with any attempt to validate performance of a flowmeter once it is installed in a process circuit.

Calibration determines a meter's performance compared to an accepted standard, which is commonly agreed to be primary measurements (weight, time, temperature) traceable to internationally agreed reference standards, e.g. national laboratories.

A true flowmeter calibration facility must have a highly trained staff that follows strict procedures using carefully maintained instruments traceable to national reference standards. CiDRA conducts its calibration of reference flowmeters at Alden Laboratories, which is the largest supplier of National Institute of Standards and Technology (NIST) traceable water flow meter calibrations in the United States, with over 150 years of experience.

Alden uses the gravimetric procedure with a measurement uncertainty of better than 0.1%. It involves primary measurements of weight, time and temperature that can be measured with low uncertainty using proven instruments traceable to national reference standards. Using this method, the ratio of weight / time yields mass flow rate, and then the ratio of mass flow / fluid density yields volumetric flow rate, which is the desired final result.

Methodology for laboratory calibration of flowmeters

The procedure involves first establishing a constant flow rate from a pump or a large-volume constant-head reservoir to a return sump tank. Next, at time zero, a diversion valve is actuated that directs the flow to a weigh tank. When the tank is nearly full, the diversion valve is again actuated directing the flow back to the return sump tank, and the end time is recorded. The actual flow rate is calculated from the following relationship:

$$actual\ \ flow = \frac{mass\ flow}{fluid\ density} = \frac{(\frac{weight\,*}{time})}{fluid\ density} = \frac{W}{T\rho_w \beta_c}$$

*corrected for buoyancy and local gravity

Uncertainty analysis of laboratory calibration of flowmeters

Measurement uncertainty is a widely misunderstood subject, but a basic understanding as described (Bell, 1999) and demonstrated (Richmond, 2000) is essential in properly interpreting the results of calibration and verification of instruments, such as flowmeters. Uncertainty is the doubt that exists about a measurement. Two numbers are needed to quantify it: one is the width of a measurement interval, and the other is a confidence level indicating how sure we are that the 'true value' is within that interval. For example: flow rate of 1000 m^3/h +/- 10 m^3/h at a confidence level of 95%.

The uncertainty analysis for a gravimetric calibration is quite complicated and beyond the scope of this report. In general it involves the uncertainty associated with the measurements of weight, time, temperature, and their traceability. The general steps using statistical methodology involve: deciding what inputs and calculations are needed to produce the final result; obtaining the inputs by measurements; estimating standard uncertainty for each input; calculating results; finding combined standard uncertainty; expressing uncertainty in terms of coverage factor giving a confidence interval and level.

Uncertainties can be of two types: Type A, obtained from statistics from repeated measurements; and Type B, obtained from other information such as experience, published information, and common sense. All contributing uncertainties must be expressed at same confidence level by converting into standard uncertainty which can be thought of as +/- one standard deviation (68%). The standard uncertainty can then be scaled to another confidence level by multiplying by a coverage factor 'k'. For example a 'k' of 1 gives a confidence level of 68%, and a 'k' of 2 gives a confidence level of 95% which is the most commonly used. This statistical methodology has been standardized (International Organization of Legal Metrology, 2008/2010) and traditionally used in both laboratory and field work. Recently, the national standards laboratories have been transitioning toward greater use of the MCS technique (International Organization of Legal Metrology, 2008) due to benefits of simplicity of implementation and elimination of some mathematical approximations and assumptions required by traditional methodology. In this report, MCS will be used to evaluate uncertainty in a flowmeter evaluation by tank test.

Verification of installed flowmeters by tank test

A carefully performed tank test is a good way to verify performance of the entire flow measurement system because it involves passing a measured amount of fluid through the meter, thus simulating a laboratory calibration, although with much higher uncertainty. Considerable care must be used and appropriate procedures must be followed because the uncertainties introduced are significantly larger than a laboratory calibration, and in fact can easily be so large as to make the tank test results useless. The tank should be large enough to provide a relatively constant flow rate, ideally for several tens of minutes. The procedure involves establishing a constant flow condition, then taking tank height measurements at time intervals so as to generate approximately ten readings of height vs. time. The volume of fluid passing during each interval and the average flow rate during the interval can then be calculated for the tank. Total-flow readings from the flowmeter taken during the same intervals are used to obtain the average flow or flow rate at each interval.

Uncertainty analysis of tank test verification of installed flowmeters

The uncertainties associated with the tank and flowmeter readings should then be determined and introduced in the data analysis and evaluated using traditional statistical computation methodology or by repeated random sampling of MCS. There are two significant sources of uncertainty in the tank flow readings: the tank internal diameter and the tank level measurement. The actual as-built diameter of a large site-built tank can be significantly different than the manufacturer's spec. Additionally, with slurry tanks thick scale may be present on the inside wall that varies in thickness with tank height, thus adding much greater uncertainty to the internal diameter measurement. Tank level measurement can be done by a calibrated electronic level gauge or by a manual float method. The as-installed accuracy of the level gauge is typically on the order of 0.5%. The float method accuracy can easily be 1% or greater due to uncertainty associated with dynamic motion of the float and simultaneous manual height measurement with a tape. By taking approximately ten or more measurements as the tank empties or fills, the mean and standard deviation statistics may be calculated that give insight into the quality of the test. The 95% uncertainty level of the flow rate (representing two standard deviations) as computed from the tank measurements is typically 1% to 2% of the mean flow rate. This is commonly ten times higher than the similar uncertainty for the flow rate obtained from the meter. This demonstrates the high uncertainty associated with field measurements of diameter and level.

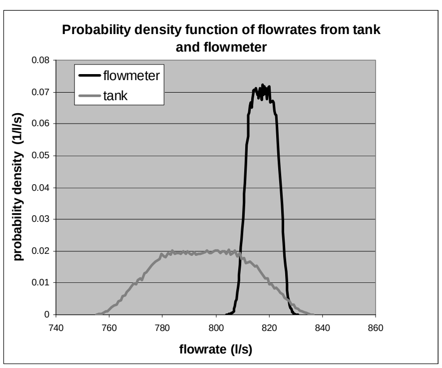
Frequently, tank tests are performed, and important conclusions are made with little attention to uncertainty. The following is an example of a test in which the uncertainties associated with the tank measurements and pipe ID were not evaluated, which led to conclusions with low statistical validity. The tank was sufficiently large, providing approximately 30 minutes of flow, which was divided into ten intervals. Level measurements at each interval were made using a manual float method. The average flow rates for the tank and meter flows were computed as shown in Figure 1, which showed a difference of ~2%. No uncertainty was associated with the tank flow measurement, and since the flowmeter accuracy was +/-1%, it was assumed that the flowmeter was out of calibration.

For this report, the original test data was combined with some reasonable uncertainty assumptions, and a MCS was performed to evaluate the statistical validity of the earlier conclusion that the flowmeter was out of calibration. Uncertainties were determined for pipe ID using standard tolerances and tank ID using assumptions on manufacturing tolerance and scale build-up. Uncertainty for the manual time measurement was assumed to be +/- 1 sec in 180 sec, and +/-20mm for the tank level measurement. The probability density functions (PSD) for the tank and meter flow rates shown in Figure 2 provide valuable insight for understanding this test. The broad shape of the PSD for the tank flow rate indicates it has a much higher uncertainty than the meter flow rate. The flat-top shape of both PSDs is primarily due to the assumption that the uncertainty distributions of the tank and pipe IDs are assumed to be rectangular rather than Gaussian or normally distributed as would be expected by a natural process.

statistic	tank	flowmeter	comment
average flowrate, test (l/s)	799	814	10 measurement intervals
std dev, test (l/s)	16.7	1.83	
average flowrate, MCS (l/s)	796	817	MCS includes Added Uncertainties
std dev, MCS (l/s)	16.4	4.6	
Added Uncertainties:			
pipe ID, per standard tolerances		0.571m; -0.3%, +0.7%	per pipe spec
tank ID plus scale	14m; -25mm, +76mm		14m nominal; +/-26mm wall tolerance, 0-60mm scale

Monte Carlo Simulation Inputs						
MCS input equation =		(X1 * pi/4 * X2^2 * 1000) - (pi/4 * X3^2 * X4 * 1000)				
MCS input quantities						
quantity	unit	PDF	mean	stdev	min	max
X1, meter velocity	m/s	Gaussian	3.177	0.007		
X2, Pipe ID	m	Rectangular			0.570	0.575
X3, Tank ID	m	Rectangular			13.950	14.160
X4, Tank height	m	Rectangular			0.920	0.980
X6, time	s	Rectangular			179.000	181.000

Figure 1 General statistics and MCS inputs



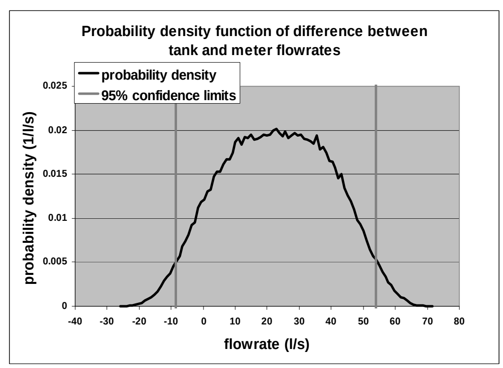


Figure 2 Probability density function of flow rate from tank and flowmeter

Figure 3 Probability density function of difference between tank and meter

Figures 3 shows graphically the probability density function of the difference between flow rates from the tank and the flowmeter. Although the tank flow rate was assumed to be the more absolute measurement since it is based on a measurable tank volume, this MCS analysis shows that its obviously higher uncertainty relative to the flowmeter uncertainty means it has low statistical validity as a 'reference standard.' The 95% confidence interval on the difference is -9 to +54 l/s, and the measured mean difference of +15 l/s is within this range. Therefore, we accept the hypotheses that the means are the same, thus it would not be statistically correct to say the meter is 'out of calibration.'

Verification of installed flowmeters by comparison with cyclone battery flow

For flowmeters installed on lines feeding hydrocyclone batteries, the flow may be approximated based on cyclone manufacturer's data and cyclone battery inlet pressure. The manufacturer can provide graphs for a particular cyclone design and size that shows the relationship between head (inlet pressure) and flow rate for a single cyclone. Thus, if the battery pressure and number of operating cyclones is known, then the flow rate can be determined from the graph. Cyclone manufacturers feel this method has an uncertainty of +/- 5% based on their experience.

This method is based on the basic principle that the cyclone represents an orifice through which an incompressible fluid is flowing. There is one inlet flow on which the flowmeter to be verified is installed, and the outlet flow is comprised of two separate flows: underflow and overflow. Since the two outlet flows discharge to a pressure of one atmosphere, the battery inlet gauge pressure is in fact the differential pressure across the cyclone. This differential pressure is related to the velocity and density of the fluid through it by the well known relationship:

$$\text{Pressure drop} = K \times \tfrac{1}{2} \times \text{density} \times \text{Velocity}^2$$

Where K is sometimes called the minor loss coefficient, and is determined experimentally by the cyclone manufacturer for the particular cyclone size for both water and slurry flows.

Verification of installed flowmeters by correlation to pump power

This technique is suited for verifying a flowmeter installed on the feed to a hydrocyclone battery. In the case of centrifugal pumps the power draw of the pump is related to the flow rate. Even when the efficiency of the pump is not known, this relation can be used to gauge the linearity of the installed flowmeter. It must be assumed, of course, that the efficiency of the pump is constant over the evaluation interval. Therefore; a relatively short interval of, say, two days would seem to be appropriate.

There are two variations of this technique. The first variation is to use historical plant data and examine the correlation between measured pump power or pump amps and flow rate. Use only data during normal operation and relatively constant slurry density. A correlation coefficient greater than ~0.94 indicates good linearity.

The second variation uses comparison of historical plant data. It consists of calculating a flow coefficient based on the pump flow and another based on the pump electrical power. They are related by an unknown efficiency, and when plotted against each other, the pump linearity can be evaluated as shown in Figure 4.

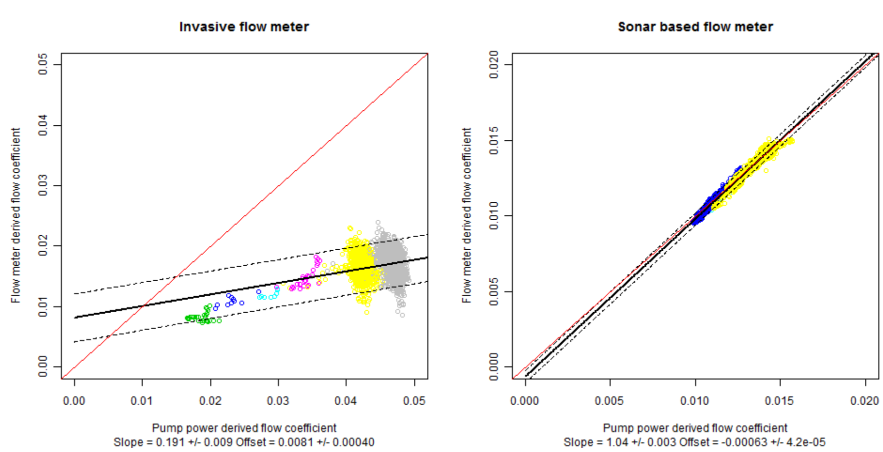


Figure 4 Relation between flow-derived and pump power-derived flow coefficients

In a plot of the flow-derived versus the power-derived flow coefficient we would expect to see a straight line passing through the origin with a slope that is representative of the pump's efficiency if the flow meter were known to be accurate.

Ideally all data points should coincide with a line with a slope of 1 passing through the origin. The black line is the linear regression line through the data points. The dotted lines show the 95% (wide) prediction interval based on the variance in the data. In Figure 4 the more linear meter is obvious.

Verification of installed flowmeters using radioactive tracers

Although the tank test method is widely used in the South American mining industry, in Europe the transit time method using radioactive tracers is widely used and standardized (International Organization for Standardization, 1977). One company in Finland (Oy IndMeas AB) has performed over 10,000 field calibrations with this method. In this method, an amount of radiotracer with very short half-life is rapidly injected into the process pipe, typically before a pump or other mixing source to ensure the tracer is well mixed across the flow profile. After a certain distance, enough to ensure the tracer has been well mixed into the flow, radiation detectors are mounted around the cross-section at a minimum of two different points on the pipe to detect the radiotracer as it passes. The flow can then be calculated by multiplying the average velocity of the flow by the pipe volume between the detectors. This test is repeated for various flow rates to reduce potential errors in the measurement, including errors in pulse detection, random fluctuations in flow rate, irregularities in pipe resulting in inaccurate inner pipe diameter, etc. The accuracy of this calibration method is claimed to be typically 1%.

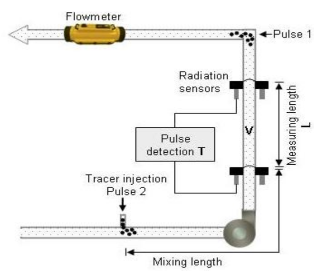


Figure 5 Flowmeter verification, transit time method using radioactive tracers

Verification of installed flowmeters by subsystem testing

Most flowmeter manufacturers provide a means of testing various subsystems or components of their meter using standard or custom test instruments, and/or internal diagnostic software. It is important to understand that since no fluid is passing through the meter, these only evaluate subsystem functionality and should not be considered a full system 'calibration'. For example, certain electromagnetic flowmeter manufacturers provide custom test instruments that can be connected to the flowmeter to evaluate electronic subsytems and electrode status and provide a hard-copy report. The SONARtrac flowmeter has internal diagnostic software that performs tests of electronic subsystems and sensor status and provides an electronic output via a USB port. Both techniques are roughly equivalent.

CONCLUSIONS

The uncertainty associated with field verifications of installed flowmeters is often overlooked or misunderstood, leading to false conclusions about performance. This uncertainty can be quantified by statistical methodology and/or Monte Carlo Simulation, thus giving a confidence interval with associated confidence level to enable better decisions. It has been shown that proper calibration of flowmeters having ~+/-1% stated accuracy requires a gravimetric procedure performed by an experienced laboratory that ensures the uncertainty of the reference flow is five to ten times less than the stated accuracy of the meter under test. It was shown for a tank test that realistic uncertainties in field verifications can result in the reference flow having an uncertainty much greater than the stated accuracy of the flowmeter. Thus, it is often impossible to conclude that a flowmeter is 'out of calibration' unless its values are very different from the tank test reference flow. Other verification methods are available such as the nuclear tracer method, which is widely used in Europe; however, it requires specialized personnel and the use of nuclear material, which presents safety issues. Other methods, such as correlation with pump power and comparison with hydrocyclone performance curves, are easier to implement and can provide a reasonable level of confidence depending on the application requirements. Even if none of these procedures are used, some assurance of performance can be obtained by utilizing external or built-in test capabilities of the flowmeters themselves to evaluate their subsystems independent of fluid flow. For highest assurance a combination of the above is recommended. When these recommendations are followed, maintenance costs can be reduced and reliability and availability of flowmeters can be increased by eliminating tests that are unnecessary or that lead to conclusions that are statistically not valid.

NOMENCLATURE

W = mass of water

T = fill time

ρ_w = water density

$$\beta_c = buoyancy\ correction = 1 - \frac{\rho_{air}}{\rho_{water}}$$

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