ULTRASONIC GAS FLOW METERS FOR CUSTODY TRANSFER MEASUREMENT

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Summary

This paper outlines the operating principal and application of ultrasonic gas flow metering for custody transfer. Basic principals and underlying equations are discussed, as are considerations for applying ultrasonic flow meter technology to station design, installation and operation. These applications are illustrated based on operating experience with the Instromet 3 path and 5-path Q.Sonic custody transfer flow meter, however, many of these issues may be generalized to devices manufactured by others.

1.0 Introduction

Ultrasonic gas flow meters, employing the absolute digital transit time measurement principal, have gained acceptance for fiscal accounting of gas transfer. Among this technology's advantages are:

- Wide measuring range, 60:1 turndown
- High accuracy
- High repeatability
- Negligible offset
- Negligible pressure drop
- Generally unaffected by dust and liquid deposits
- Insensitive to fluctuations of the gas composition
- Little maintenance

Extremely accurate and reliable multipath ultrasonic metering systems have emerged as the measurement technology of choice for large volume gas transfer. Pushed by continuously improving signal processing technology and pulled by increasing customer requirements, multipath instruments provide state of the art gas flow measurement. Its accuracy and reliability was initially certified by NMI, and is now continuously certified during routine flow calibrations by users in N. America at CEESI, Southwest Research Institute and TC Calibrations. An operating guideline has been established by AGA (TMC Report 9), and contractual requirements have been successfully defined by parties for this device's use in custody transfer applications.

2.0 Operating Principal

Acoustic techniques for the measurement of flow have been applied for nearly fifty years. Depending upon the magnitude of the Mach number, v / c, and due to the rapid change in electronics, different measurement methods have been applied in meters which appeared on the market over this time interval. For instance:

1. The sing-around method (1950's) which essentially is phase-shift measurement
2. Continuous wave frequency shift method (1960's)
3. Analog differential time-delay measurement (1970's)
4. Digital absolute travel time measurement (1980's)

Although some of the older methods occasionally reappear in new instruments (mainly because of their inexpensive manufacturing cost), they cannot compare with modern methods that employ high speed digital signal processing techniques and advanced piezoceramic transducers, in terms of accuracy and repeatability. The first three methods are problematic when:

- Gas composition, temperature or pressure are fluctuating
- The gas is not completely clean
- Pulsating flow is present

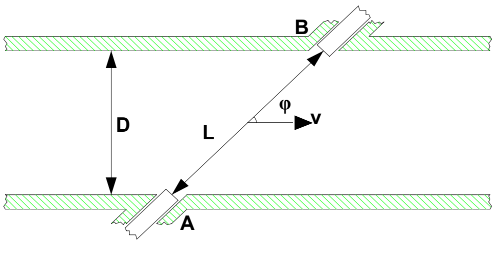
Using state of the art digital signal processing electronics, modern ultrasonic instruments employ the method of absolute digital travel-time measurement, which is discussed in detail below.

2.1 The Absolute Digital Travel Time Method

2.1.1 General

In ultrasonic flow measurement, acoustic pulses are transmitted and received by a pair of piezoelectric transducers. Figure 1 shows the simple geometry of two transducers, A and B, at an angle φ with respect to the axis of a straight cylindrical pipe.

Figure 1



D denotes the diameter, L the path length and V the velocity vector.

Some instruments, like the Q.Sonic, employ reflection paths like that shown in Figure 2, where the acoustic pulses reflect one or more times against the pipe wall.

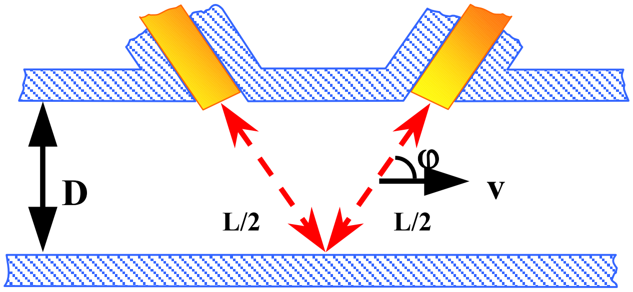


Figure 2

Other instruments employ chordal, or point-to-point, pulse transmission paths as shown in Figure 1.

Regardless of the path geometry, the operating principal is the same, and basic transit time equations applicable. At zero flow, the travel time is equal in both directions and the measured time of flight difference between them (t_u-t_d) is zero. However if there is flow, the travel time of the sound pulse transmitted in the same direction as the flow decreases due to its being accelerated by the moving gas. Conversely, the pulse traveling upstream suffers an increased transit time due to the retarding effect of the gas flow. Transit times in the up and down stream directions may be calculated as:

$$1) \qquad t_{up} = \frac{L}{c - v\cos\varphi}$$

and

$$2) \qquad t_{down} = \frac{L}{c + v\cos\varphi}$$

where L is the length of the path, φ is its angle with respect to the axis of the pipe, and c is the speed of sound in the gas (about 300-450 m/s or 1000-1500 ft/s at typical transmission pressures). If the speed of sound is constant during both measurements, the two equations can be combined

$$3) \qquad v = \frac{L}{2\cos\varphi}\left(\frac{1}{t_{down}} - \frac{1}{t_{up}}\right)$$

where v denotes the flow velocity, positive in downstream direction. The history of this method goes back to Rütten (1928), who filed the first patent on the application of ultrasound in flow measurement. From the above equations the speed of sound can be calculated:

$$4) \qquad c = \frac{L}{2}\left(\frac{1}{t_{down}} + \frac{1}{t_{up}}\right)$$

Since the speed of sound is related to the density of the medium in the transport system, it can be used to calculate mass flow. Further, it is noted that the cancellation of c from the average velocity equation (gas properties such as density affect both t_{up} and t_{down} equally) means that absolute velocity measurement is ***not dependent on gas density***. That is, pressure, temperature and gas composition have no effect on the velocity calculation from pulse transit time.

2.1.2 Pulse Generation

Specially designed transducers are used for the generation of ultrasonic pulses that both transmit and receive these pulses. The main component within a transducer performing these functions is a piezoceramic element. In the transmitting mode these piezoceramic elements are excited with a characteristic voltage that results in the emission of a well-characterized sound pulse. When used as a receiver, the incoming sound pulse generates a small voltage, which is processed after amplification. The frequency and directivity pattern of a transducer depends for the most part on the dimensions and characteristics of the piezoceramic element.

The transducers developed by Instromet have been designed for the generation of short, powerful pulses in order to exploit the advantages of single and double reflection paths at high repetition rates at operating pressures ranging from atmospheric up to 5000 psi. Because they are fabricated within tight specifications under strict quality control, and with detailed characterization, they can be exchanged without parameter adjustment or meter recalibration.

2.1.3 Pulse Detection

Before pulse detection and recognition take place, the received acoustic pulse is pre-processed using an Automatic Gain Control and filtering circuitry to ensure pulse discrimination. After the pre-processing stage (detection) takes place, the signal is digitized and compared with a 'fingerprint' of a reference pulse. This method provides the unique ability to check the quality of every single pulse against preset standards before processing for velocity measurement purposes. The pulses are either:

* **accepted** when the signal completely meets the preset quality standards

or:

*** rejected** when a deviation from these quality standards is detected.

Only when both pulses are accepted, are their travel times used to calculate flow velocity and speed of sound. This method results in the highest precision yet achieved by flow measurement devices. During signal detection and processing, built-in diagnostics supply real-time information about the system's performance to the user, and may be used to set alarm limits on meter performance. These parameters will be discussed in more detail later.

2.1.4 Timing characteristics

The accuracy required in the travel time measurement can be found from the equations. For example, when a velocity of 3 ft/s is measured with 0.5 % accuracy along a 3 ft path length in a gas with sound velocity of 1300 ft/s, both travel times are of the order of 2.5 ms, but their difference is about 6 µs, which must be measured with an error no greater than 30 ns! This small travel time difference requires high speed, high accuracy digital electronics.

The travel times of only a few milliseconds enable individual ultrasonic flow velocity measurements at high repetition rates. Typical rates are 20 - 50 Hz, depending on pipe diameter. The need for high repetition rates is evident in cases such as surge control applications, where the flow may drop from its set point to its minimum in less than 0.05 s.

2.2 Path Weighting Factors

The velocity v calculated by equation (3) represents an average along the acoustic path. The velocity of interest, however, is the mean, or bulk, value V over the pipe cross section. This variable is computed by

$$5) \qquad V = k\,v$$

where the meter factor k expresses the influence of the flow velocity profile. The value of the path weighting factor depends on the velocity profile in the duct as sensed by the acoustic path.

2.3 Acoustic path configuration

To create optimal acoustic path configurations for multipath flowmeters, knowledge is required about the actual flow patterns in transport systems.

For smooth straight circular ducts the velocity profile is determined as a function of the Reynolds number ("Re") of the flow. This dimensionless number is calculated using the flow speed, the duct diameter, the density and the dynamic viscosity of the flowing medium. For low Reynolds numbers the flow is laminar (Figure 3), with a parabolic (Hagen-Poiseuille) profile, while for high Reynolds numbers the flow becomes turbulent and with a plug-like (logarithmic) profile, as shown in Figure 4.

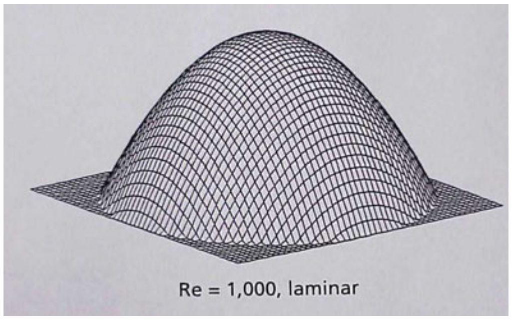


Figure 3

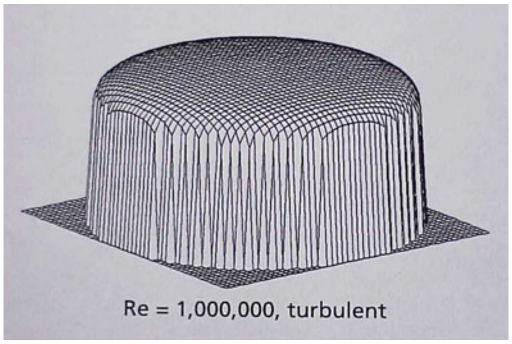


Figure 4

Since the transition from laminar to turbulent takes place (Schlichting, 1968) somewhere between Reynolds number 2000 and 4000, while in typical pipeline systems, the Reynolds numbers usually range from 100,000 to 150,000. Therefore, the turbulent profile is that most commonly encountered in high pressure gas transmission systems.

Due to the presence of one or more, possibly out of plane, bends in the transport system, the flow profile will always be distorted with respect to the ideal logarithmic shape. A single elbow induces a dual-eddy pattern, which has two counter rotating vortices on either side of the center plane of the elbow. The resulting transverse flow is directed outward, with axial velocities much lower than in corresponding ideal velocity profiles. This double-eddy pattern decays faster than the single-eddy one induced by double bends out of plane. This important form of distortion is called swirl. Although the presence of swirl does not contribute to, or detract from, bulk flow, it causes a distortion of the velocity profile, which ususally results in an effect on travel time that introduces an error in flow velocity measurement. Mathematical modeling has been used to characterize and account for swirl's influence on average velocity measurement. Instromet chose a bounce path design based on profile studies to better characterize bulk velocity under variable conditions. A three-path example of such a design is shown in Figure 5.

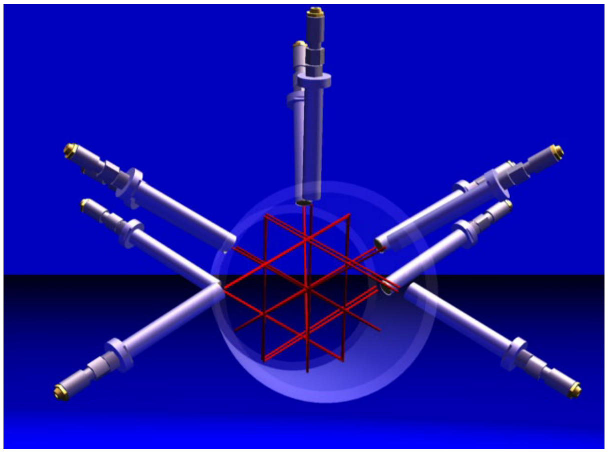


Figure 5

2.4 Accuracy

The average velocity flux measured by a single path ultrasonic flowmeter is calculated using the following equation:

$$6) \qquad Q = k\,A \frac{L}{2\cos\varphi}\left(\frac{1}{t_{down}} - \frac{1}{t_{up}}\right)$$

where A denotes the cross-sectional area of the pipe. From this equation, the total accuracy depends upon the individual accuracies of all factors involved and can be split into three parts:

- the accuracy of the geometry
- the accuracy in the travel time measurement
- the accuracy of the velocity profile

2.4.1 Geometry

Meter geometry is a function of the path length L, angle φ, pipe diameter and the mechanical measurements of these components. Even when tight mechanical tolerances are used in the manufacturing process, and careful measurements made, it is not possible to perfectly harmonize these variables and individual transducer characteristics (delay times, crystal response, etc). Therefore errors caused by geometrical factors must be reconciled otherwise. A unique methodology has been developed to eliminate the mechanical uncertainties in path length, angle and measurements of them. Controlling the signal processing electronics' clock, the media in which the meter is characterized and knowledge of the media's thermodynamic properties, may be used to derive "Acoustic Path Length". That is, a meter can be filled with a pure fluid such as nitrogen whose properties are well known, its pressure and temperature precisely measured, and the meter measured speed of sound, given these knowns, recorded. Since the speed of sound in a homogeneous (or pure, single phase) fluid is well characterized, a comparison of the meter measured and characterized values can be made. Assuming the SPU's clock is stable, the measured and characterized values for speed of sound may be reconciled to agree with one another by adjusting the meter's path lengths. These adjusted path lengths are referred to as "acoustic path lengths", and this reconciliation, which forces agreement of meter output with documented fluid properties, eliminates mechanical variabilities in transducers and geometric variables caused resulting from meter body construction.

2.4.2 Travel Time

The accuracy of the time measurement is limited only by the signal to noise ratio and the digital clock frequency. The pulse's travel time measurement is based on high resolution quartz controlled electronics. Since samples of travel times are available at a rate of about 20 to 50 hz, the resulting mean error can be reduced to just a few ns.

2.4.3 Flow Profile Accuracy

To assure that fluid distortions don't impact the accurate determination of bulk flowing velocity, it is possible to modify the velocity profile (velocity distribution) with a high performance flow conditioner (not a tube bundle). Flow conditioner generated profiles do not generate either of the fully developed velocity distributions characterized by Laminar of Turbulent flow regimes, however, they do have the advantage of generating repeatable flow profiles. That is, regardless the type disturbance entering the flow conditioner, the profile exiting the device is the same. Therefore, an ultrasonic meter flow calibrated with a flow conditioner, will produce the same measurand for velocity in both the flow laboratory and in the field installation thus eliminating the concern regarding effect of variable velocity distributions.

3.0 Meter Station Design Considerations

3.1 Footprint

Space limitations, and the environment in which the station will operate, often dictate equipment selection and configuration. If shorter meter runs are required, headers and several tees may be involved which generate significant flow disturbances. High performance flow conditioners may be desirable to insure consistent velocity profiles in short coupled meter tube installations.

3.2 Sizing

Ultrasonic meters are typically sized on the basis of actual velocity. Therefore, when selecting the meter, one must consider the pressure, temperature and flow range stated in SCF per unit time. Basic calculation programs to size ultrasonic meters based on these parameters are available from most manufacturers.

In addition to meter size, designers need consider the nature of the operation and the maintenance requirements for the particular station:

- Are multiple runs needed to provide redundancy, or flexibility should a meter require out-of-pipe service or recalibration?
- Are multiple runs needed in stepped line size to enhance station rangeability?
- Are there pressre or control valves that might require installation of additional attenuating elements such as blind tees?
- Will a building enclose the meter runs, and clearance between meter and building wall be an issue if transducers are retracted?

These are several of the potential questions designers should consider when laying out a station: there may be others peculiar to a given installation.

3.3 Gas Quality

In wet gas environments (hydrocarbons or water vapor), designers need consider whether the meter run needs to be angled, or include siphon drains to assure liquids don't collect in the pipe or can be drained if they do.

If Sulfur content is a consideration, it needs to be specified to insure corrosion resistant transducers are provided.

Carbon Dioxide in concentrations exceeding 15% (this level varies somewhat depending on operating pressure) can attenuate ultrasonic signals such that transmissibility of pulses fails, and measurement does so also.

Good, representative, samples of gas quality are necessary to facilitate calculation of reference speed of sound values needed to evaluate meter operating condition. Depending on the nature and importance of a particular meter station, designers need consider whether a gas chromatograph is necessary, or whether a spot sample will suffice. If it is determined a GC is needed, gas quality may dictate whether the instrument required to characterize SOS need be C9+ or C6+. Likewise, if sampling is determined to be an acceptable mechanism, judicious selection the sampling point is needed: only a spot sample (composite will not provide desired results) will suffice since the meter measured SOS must be chronologically correlated with the spot sample draw to provide a valid comparison of meter measured SOS to that calculated from the analysis. Pressure and temperature data are also required as part of the data collected at the time of sample draw.

4.0 Meter Installation

Several steps occur prior to physical installation, the judicious monitoring of which can assure a successful start-up as well as providing benchmark performance criteria upon which to evaluate meter's operating condition over the life of the station.

4.1 Dry Calibration

This terminology is somewhat of a misnomer, since this process is intended to characterize electronic performance, and in the case of Instromet, tighten up path length data, rather than generate a meter factor as the result of an actual calibration.

Pure Nitrogen is used to assess meter functionality at high pressure prior to flow calibration of these devices. Electronics (SPU and transducers) are given their final QC check by running a static test on the meter at stable conditions (known gas, steady temperature and pressure).

In addition to insuring electronic functionality, Instromet utilizes this opportunity to compare meter measured speeds of sound to calculated, certified, values. Path length is adjusted to provide agreement with the calculated, certified, values so that the meter exits the assembly process with tight per path performance tolerances that may reliably be used as baseline meter performance criteria.

4.2 Flow Calibration

Once a custody meter is successfully dry calibrated, it is generally sent to an independent testing facility to certify its meter factor. Flow tests are recommended for any meter that is used for custody service, and particularly whenever a flow conditioner is proposed for use as part of the meter run.

Flow calibration not only certifies meter performance traceable to a recognized standard, it also alleviates many measurement disputes. These tests generally consist of flowing gas through the meter under test ("MUT") at various flow rates across its capacity range, and comparing the MUT's output to a reference, or transfer, standard. AGA Report 9 does not require flow calibration, but does specify that manufacturers meet uncalibrated ("out of the box") performance criteria of +/- 0.7 % for meters 12 inch and larger, or 1.0% for meters of lesser diameter. It is obvious that these established criteria are not sufficient for acceptable fiscal measurement, particularly in light of recently high natural gas prices. Therefore, it is prudent practice to certify a meter at a traceable facility.

Key factors to assess during calibration are the repeatability and linearity of the meter's proof curve. Proof curves may be linearized (usually to characterize low flow performance), but an optimal proof curve is one composed of tightly clustered data points that form a flat, straight line. Criteria for acceptable linearity and repeatability are published in AGA TMC Report 9.

4.3 Physical Installation

Report 9 also describes criteria for ID match of spool pieces that comprise the meter run. When bolting up for final installation, it is essential to assure proper spool alignment and insure joint gaskets do not protrude into the flowing stream. One can make that assurance by either assembling the meter run at the site and installing it as a unit, or by making a visual inspection of the assembled run as each spool is installed in the station piping.

4.4 Start-up

Once the meter is physically installed, it is important to generate base-line documentation of its performance. Such information, generated when the meter is new and in pristine condition, may be used during subsequent routine inspections to assure meter condition has not changed. Key elements to capture data for baseline characterization are average SOS, per path SOS, per path gain levels and per path gain limits. Interpretation of these parameters is addressed in the maintenance section that follows.

5.0 Field Applications & Routine Maintenance

5.1 Dirty Gas

In real-world gas pipeline systems, actual conditions may differ considerably from the ideal encountered in flow measurement labs. Major disturbing factors are pollution (i.e., dirt and liquids) and ultrasonic noise. Many gas flow meters are sensitive to dust and liquid residue in the flowing stream. Through the use of digital pulse recognition techniques, the acoustic flow meter can be made relatively immune to these deposits. If the signal is attenuated too much by deposits on transducers, measurement is no longer possible. Due however to digital signal processing of time of flight measurements, dust and liquid residue does not affect the accuracy of the meter.

5.2 Ultrasonic Noise

Although many new control valve designs are promoted as 'low noise', they are the main source of interference encountered in the field. During tests at various installations these 'low noise' valves, when nearly closed, appeared to create much non-audible ultrasonic noise that may interfere with the transmitted sound. This is problematic for ultrasonic meters since the reduction of audible control valve noise has been accomplished by shifting it to ultrasonic, or non-audible, frequencies used by these meters. While measurement accuracy is not compromised, pulse detection may become impossible causing a loss of measurement.

5.3 Performance Monitoring

Meter diagnostics, made available by virtue of signal processing routines, may be applied to determine if sediments or ultrasonic noise compromise meter function.

Transducer Gain Levels: The "sound volume" of the pulse is usually controlled automatically with electronic gain controls. Monitoring gain levels over time provides an indication of whether sediments may be attenuating pulse transmission (gains will be found to increase).

Signal Rejection: Pulse signals are rejected when they fail to match the fingerprint of an electronically stored reference pulse. Signal rejection indicates potential transducer failure, but is usually indicative of noise interference from devices such as control valves.

Speed of Sound: Ultrasonic meters measure the speed of sound in the flowing media (reference equation 4). Using AGA TMC Report 8 equations of state, the speed of sound may be accurately calculated using flowing temperature, pressure and gas composition as inputs. Comparisons of meter measured SOS may be made against this calculation as a "health check". Direct correlation between meter accuracy and SOS has yet to be established, but it is known that correct meter function is doubtful if the SOS calculation is in error. Per equation (4), poor SOS comparisons suggest clock or transducer problems.

Using the sophisticated capabilities of flow computers, or an on-board electronics archive, these parameters may be trended and alarm limits established for these important operating characteristics, thus signaling users of maintenance requirements or failure onset.

5.4 Ultrasonic Meter Maintenance

Ensuring proper function of custody measuring devices is a measurement technician's major responsibility. Field operating experience indicates ultrasonic meters, while nearly trouble free, may require special maintenance in addition to routine inspection. A typical routine inspection might consist of the following:

1. Pressure transmitter calibration.

2. Temperature transmitter calibration.

3. Verification of pulse output (if used) accuracy (i.e. validation of D/A converter performance).

4. Collection and review of meter data logs which typically include SOS, signal acceptance rate, gain and gain limit data.

Performance parameters from collected logs should be compared to a baseline log or trended against previously recorded logs. A "baseline" log is one collected when the meter's condition was known to be satisfactory; usually taken at the time of initial meter start-up, or after re-certification.

Special maintenance is required when performance monitoring dictates, or complete meter failure occurs. The signals identified for monitoring may be interpreted as follows:

Increasing Gain Levels: If performance monitoring reveals gain levels have increased over time, it is an indication of potential transducer fouling. In this event, transducers should be carefully removed, inspected, and cleaned if necessary. If the meter is blown-down to accomplish this, it is advisable to clean the nozzles (transducer receptacles in the meter body) as best as possible.

Signal Rejection: Should performance monitoring reveal excessive signal rejection rates, suggesting ultrasonic noise is a problem, control valves or throttled valves should be inspected and/or experimented with to determine if accommodation can be made (i.e., change in valve position or trim).

SOS Comparisons: Discrepancies between measured and calculated SOS indicate a fundamental meter problem (clock or transducers). However, one must recognize the sensitivity of the equation of state calculations to gas composition and temperature, prior to assuming meter malfunction. Seemingly insignificant concentrations of heavier hydrocarbons greatly influence the accuracy of the calculation (comprehensive sensitivity analysis of this effect is lacking, but it is advisable to obtain an extended analysis for SOS calculations if aggregate C6+ is greater than 0.5 mol %). Likewise, accurate temperature measurement is necessary: Calculated SOS can differ from that measured, by as much as 3-5 fps, if measured temperature is in error by 1 degree Fahrenheit at typical pipeline operating pressures (800-1000 psig). SOS comparison is an extremely useful tool, but be sure inputs to the calculation are correct (good gas analysis and assured temperature transmitter calibration) before spending time and money to review meter characterization.

6 Q.Sonic performance

After extensive proprietary testing of the Q.Sonic by the manufacturer, a calibration run was conducted by the NMI (the official Netherlands Measurement Institute) to certify the meter for custody use in Europe. NMI is an independent test institute that performs all calibrations for Gasunie (the major gas company of the Netherlands), and many other gas transmission companies internationally. The results are given in the figure below.

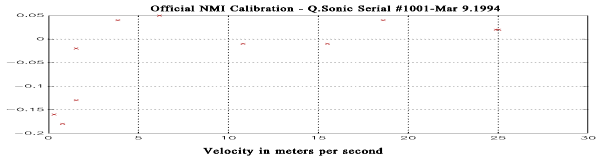


Figure 6

Subsequently the meter was installed in the Gasunie export station at Winterswijk near the German border. Up till now the meter performance is within 0.2 % of the installed turbine meters. The instrument has been operating for nearly a year with virtually no maintenance, as only performance monitoring and pressure/temperature calibrations have been conducted.

Subsequent to this certification and commercial introduction of the product, many successful calibrations have been conducted both in Europe and North America. It is estimated that more than 500 Instromet multi-path meters are now in custody service in North America alone.

7 Conclusion

Ultrasonic gas meters have become the measurement device of choice for large capacity transmission and city gate measurement stations. They are also finding wide acceptance for use in power plant fuel gas measurement applications because of their wide rangeability and robust operating characteristics.

If properly monitored, ultrasonic meters afford customers the highest measurement accuracy levels yet encountered, with the lease maintenance requirements.

The Instromet Q.Sonic multipath flow meter has proved itself as an accurate and reliable custody transfer gas flow meter, which requires only minimal maintenance.

Acknowledgment

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