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REPEATABILITY AND UNCERTAINTY OF TCC'S ISLE DES CHENES TESTING FACILITY

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Abstract: The elements required to design TCC's new high-pressure calibration facility for the least uncertainty are summarized. Results obtained during commissioning are shown, indicating the results according to the ISO Guide to the expression of Uncertainty of Measurements (GUM).
Key words: Calibration stations, Gasmeters, High-pressure meter testing, testing facilities.

1 INTRODUCTION

The recently commissioned gas meter calibration facility of TCC in Îsle des Chênes near Winnipeg was designed with the aim to satisfy the increased demand for accuracy in gasmetering caused by the new regulatory framework being established in many countries. In this new regulatory framework, transmission and distribution companies charge a fee for the simple function of transporting gas from third parties through their system. The balance between input and output of a system therefore is critical, especially for transmission over short distances where the cost of a metering error could be higher than the transmission fee. Formerly, in vertically integrated gas industries the main risk was the amount of gas that was recoverable. The uncertainty in the size of the field would greatly outweigh any metering error.

Until recently there were no facilities available in the Americas for the calibration of large size high-pressure gas meters. These meters were often sent to Europe where NMi operates the Gasunie owned Bernoulli laboratory in Westerbork, capable of calibrating meters up to 40 000 m^3/h at a pressure around 60 bar. The cost and delays of transportation created a demand for a similar facility in North America. TCC's new facility has been designed for calibration of 30" meters at a velocity of about 30 m/s. This translates to about 50 000 m^3/h. The facility can easily be expanded for higher flow rates.

2 GENERAL CONSIDERATIONS

The station has been built on the site of a TCPL compressor station. One of the outgoing lines is equipped with a 36" control valve that is by-passed by the facility. Closing the control valve forces gas through the station. A second, 8" by-pass with control valve, serves as a vernier control.

The measuring principle relies on the comparison of volumetric flowmeters of which one is calibrated and is traceable back to primary standards. The meters operate at nearly identical pressures and temperature so that only the difference in operating conditions has to be taken into account.

Experience at Instromet's own 8 bar calibration station has shown that testing with two reference meters in series has great advantages. Both references have to give consistent results and any discrepancy points at an error in some of the measurements or data. It is unlikely that two meters would change their behavior in a similar fashion and thus hide an erroneous measurement.

For this reason a series connection of two meters: a Turbine meter and an Ultrasonic meter was chosen. Using two meters with different operating principles makes it even more unlikely that the meters would react in a similar fashion to external disturbing factors.

The meters used are Instromet's turbine meters type SM-RI-X and Instromet Q.Sonic Ultrasonic meters. Over the years the turbine meters have proven to be very reliable and repeatable and have a meter factor that varies only slightly with operating conditions. Their Reynolds dependency is consistent which means that over a wide operating range of flow rates and densities the error is a function of Reynolds only. Their sensitivity to flow profile distortions is very small.
Though there is less experience with Q.Sonic meters, they have already built up a very good reputation. Their extensive diagnostic capabilities are particularly valuable where it comes to reliable calibration. The multipath, reflection path design greatly reduces their sensitivity to deviating flow profiles.

An automatic data processing unit determines continuously the deviation between the meter under test and the reference meter. The statistics of these results can be used to determine stability and the time required to achieve a desired level of uncertainty.

3 MECHANICAL DESIGN

3.1 Reduction of dead volume

As it is TCC's desire to be able calibrate meters from 8" up to 30", the station comprises two systems in parallel. The large system has 6 reference meter runs of 16" diameter that for the moment will operate at flow rates up to 8 000 m^3/h each but have a maximum flow rate of 10 000 m^3/h. The small system features two 8" reference runs with a maximum flow rate of 1 600 m^3/h each. In this way the dead volume is reduced when testing small meters.

The facility has at present an operational range from 50 to 50 000 m^3/h and could be extended easily to 60 000 m^3/h.

3.2 Velocity profile

Most flow meters are sensitive to velocity profiles. It is known that notably swirl is very persistent and may need over 100 pipe diameters to dampen out. For this reason the system was designed to comprise a minimum number of bends that are not in one plane. Exceptions are the inlet and outlet header.

The inlet header is equipped with Etoile straighteners immediately behind each bend. The objective is to eliminate any swirl immediately without creating undue pressure loss.

The swirl generated by the downstream header does not influence the measurement.

For constructional reasons the small system had to be preceded by two bends out of plane. However, the distance between the bends is sufficient to prevent bulk swirl formation.

The straight lengths upstream of the meters under test are at least equal to 10 D. Straighteners can be inserted according to the requirements of the customer.

3.3 Pulsations

As all the compressors are centrifugal and located at a considerable distance there are no compressor induced pulsations at the facility.
However, as the facility is a complicated network of piping, there is a considerable risk of flow induced pulsations. These occur for example when high velocity gas flow passes a tee branch with a tuned dead volume. The branch may then act as a resonator similar to an organ pipe.
The station was carefully designed to avoid situations where this could happen by avoiding dead ends in critical places.

4 TECHNICAL BACKGROUND

4.1 Introduction

Meters are tested by installing them in series with a working standard of which the deviation is accurately known. By comparing the two outputs and taking the difference in pressure and temperature in the two meters into account the deviation of the meter under test can be determined. Depending on the flow rates one or more working standards can be chosen for this purpose.

4.2 Testing

The test relies on the continuity principle i.e. the quantity of matter in a defined space is the difference between what went into and what went out of that space. The “space” is here defined as the volume enclosed by the reference meters on the one hand and the meter under test on the other hand.

The equation of state for a real gas can be written as:

$$P \bullet V = n \bullet Z \bullet R \bullet T \tag{1}$$

with n the number of kMoles, V the volume, Z the compressibility and T the absolute temperature. The volume V is dependent on the size of the test run and of the position of the meter under test in the test run.

The rate of increase $\frac{dn}{dt}$ in the quantity of gas in volume V can then be equated as:

$$R \bullet \frac{dn}{dt} = \frac{P_r \bullet q_r}{Z_r \bullet T_r} - \frac{P_x \bullet q_x}{Z_x \bullet T_x} = \frac{d}{dt}\left(\frac{P_v \bullet V}{Z_v \bullet T_v}\right) \tag{2}$$

with q_r and q_x the volumetric flow rate through the reference and the meter under test respectively, P_r, P_x, T_r, T_x, Z_r and Z_r, the pressures, temperatures and compressibility’s at these locations, and P_v, T_v and Z_v these parameters in the volume between the two meters.

From this we find for the ratio of the two flow rates:

$$\frac{q_x}{q_r} = \frac{\mathrm{P_r}}{P_x} \bullet \frac{Z_x \bullet T_x}{Z_r \bullet T_r} - \frac{1}{q_r} \bullet \frac{Z_x \bullet T_x}{P_x} \bullet \frac{d}{dt}\left(\frac{P_v \bullet V}{Z_v \bullet T_v}\right) \tag{3}$$

For pressure it is more accurate to measure only one absolute pressure and determine the other by measuring the pressure differential. If the absolute pressure at the meter under test is read then the pressure $\mathrm{P_r}$ can be found from:

$$\mathrm{P_r} = P_x + dP \tag{4}$$

where dP is the pressure differential.
From this we find

$$\frac{q_x}{q_r} = \left(1 + \frac{dP}{P_x}\right) \bullet \frac{Z_x \bullet T_x}{Z_r \bullet T_r} - \frac{2 \bullet V}{q_r} \bullet \frac{Z_x \bullet T_x}{P_x} \bullet \frac{d}{dt}\left\{\frac{2 \bullet P_x + dP}{(Z_x + Z_r) \bullet (T_x + T_r)}\right\} \tag{5}$$

if we assume that the relevant pressure and temperature in the volume are equal to the average between inlet and outlet.

The meter under test does not necessarily indicate the value q_x but will show in general a flow rate q_{xi}, which is equal to

$$q_{xi} = q_x \bullet (1 + E) \tag{6}$$

in which E is the deviation or error of the meter at that flow rate.

In general a stable situation is easier to attain at high flow rates than at low flow rates. The term following the minus sign (5) is only Important for low flow rates and less stable conditions. The TCC facility proves to be very stable so that the term is in general negligible. In the foregoing it is assumed that all instruments respond sufficiently fast to follow the process variables.

The testing time is then determined by the noise in the signal issuing from the instruments and the flow process. The testing time should be sufficient to average out (filter) all random variations. The amount of noise and its frequency spectrum is instrument specific and may also depend on the installation in which they are installed. Little is known on this subject but orifice plates, for example, may need averaging times of several hours or even longer.[1]

4.3 Uncertainty

For the uncertainty budget we assume perfectly stable conditions. It is based on the working turbine meter references being calibrated in the Gasunie Bernoulli laboratory in Westerbork, the Netherlands. The possibility for improvement by using the Instromet Rotary Piston Prover (IRPP) is not explicitly dealt with in this stage. [2] The possible effect is estimated by assuming different uncertainties in the reference flowmeters.

The uncertainty budget is only given for “type B” uncertainties in accordance with the ISO guide. Evaluation of “type A” uncertainties can only take place in the completed installation.

4.3.1 Flow rate

The reference turbine flow meters are six 16” Instromet SM-RI X G 6500 meters with a nominal maximum capacity of 10,000 m^3/h and two 8” Instromet SM-RI-X G 1000 meters with a maximum flow rate of 1,600 m^3/h. We assume that no extra uncertainty results from the installation. These meters have been calibrated in the Netherlands under supervision of NMI at Gasunie’s Bernoulli Laboratory in Westerbork.

The minimum flow rates for gas with a density of about 50 kg/m^3 for these meters are 80 and 15 m^3/h respectively. Other, installation related, factors may limit the minimum flow rate at a higher value.

Upstream of each of the 16” turbine meters an Instromet multipath Ultrasonic meter has been installed. These meters have been calibrated on site against the following turbine meter, thus providing a footprint. It is presently intended to use the average value indicated by these meters as reference when calibrating other meters.

The transfer of the working references was as follows:

One extra 16” turbine meter was calibrated and also one 16” ultrasonic meter.

The extra 16” turbine meter is equipped with a 4 m straight pipe with a tube bundle straightener in the inlet. The 16” ultrasonic meter is also equipped with a 4 m straight upstream pipe length.

The X4X straightener built into all turbine meters already gives a very large attenuation of any disturbances so the two combined should give a system that is virtually invulnerable to any installation effects. The turbine meter package was followed by the ultrasonic package consisting of a Q.Sonic preceded by 4 m straight length but without the straightener. Both the packages of turbine meter and its straight length and ultrasonic meter with its associated straight length were each bolted together and sealed and calibrated in the same configuration. This combined package was designated “travelling standard” or “sleeping standard”. Travelling standard is used because it is intended for use in future comparisons with other high-pressure installations. Sleeping standard is used because it can be utilized to check the working references.

All other six 16” turbine meters were calibrated in Westerbork with this combined travelling standard package in series. The ratios of the deviations of these meters and the travelling standard packages were accurately determined. The calibration of the 16” travelling standard was effectively repeated 6 times giving a solid statistical basis.

The calibration of the 8” reference meters followed a similar pattern, be it that only one of the runs was calibrated in the Netherlands. An 8” transfer package is subject of another paper. [3]

The process of verification to establish the reference standards in the station was done by the Dutch metrological service NMi. They have operated high-pressure calibration stations in the Netherlands for nearly 25 years. Recently the NMi harmonized their traceability with the German PTB thus improving the uncertainty of their reference to 0.15 %. [4] [5]] Linking into this framework provides a solid reliable and traceable reference for the TCC facility. Apart from the 16” travelling standard NMi provided their own travelling standards to give a multiple link with the installations in Europe. These travelling standards are of the sizes 6”, 8”, 10” and 12”. All NMi travelling standards are equipped with a dedicated upstream pipe section and Zanker straightener.

The main contribution to the uncertainty of the station is in the flow meters and the physical calibration process itself. However, the contribution of secondary instrumentation should be kept to a minimum.

In Winnipeg the travelling standards were installed at the position of the meter under test. All eight reference meters were then tested against these standards.

4.3.2 Pressure

The uncertainty calculated from the specification sheet for the differential pressure transmitter is 0.12 %.

The ratio of differential pressure to absolute pressure would have an uncertainty of 0.15 %, which at 500 mbar would be 0.001 % in the factor $(1 + dP / P_x)$ of equation (5)

Additional pressure related uncertainties might result from the pressure tapping and the direction in which it is struck by the gas. In the reference meters the position of the pressure tapping is fixed as during calibration. In the meter under test this is not necessarily the case.

4.3.3 Temperature

The uncertainty in the temperature measurement is determined by: the sensor and its ancillary instrumentation, the adequate heat transfer to the sensor and the stagnation vs. flowing temperature of the gas

Another source of uncertainty is the influence of the pipe-wall. The question is whether the sensor assumes the gas temperature or whether the pipe-wall temperature is still of influence.

Taking this into account it was decided: not to use temperature wells, to insulate the pipes, to use sensors with low heat conductivity to their fixtures and to use sensors with a small heat capacity.

4.3.4 Gas composition

The gas composition is used for the calculation of the compressibility.

The uncertainty in the compressibility as calculated from AGA report no. 8 is about 0.1 %. However, the compressibility at both locations is calculated with the same gas composition and what really only matters is the uncertainty in the change of the compressibility with temperature and pressure. This uncertainty is necessarily much smaller and can be neglected.

4.3.5 The type B uncertainty budget

The resulting type B uncertainty budget is given in table 1.

Table 1. The resulting type B uncertainty budget for three different flow reference uncertainties.

Flow meter	0,200%		0,15%		0,10%	
Squares flow meter		4,00E-06		2,25E-06		1,00E-06
Uncedrtainty in (1+ dP/P)	0,001%		0,001%		0,001%	
Squares pressure term		1,00E-10		1,00E-10		1,00E-10
Temperature ratio	0,050%		0,050%		0,050%	
Squares temperature ratio		2,50E-07		2,50E-07		2,50E-07
Total squares		4,25E-06		2,50E-06		1,25E-06
Total (Type B) uncertainty		0,21%		0,16%		0,11%

4.4 Dynamic considerations

Up to now only stable conditions were assumed. Conditions are never entirely stable in practice, if only because the flow rate has to be adjusted to the desired value.

For this reason it is important to estimate the response time of the different components.

The dynamics of turbine meters is well known.[6] The rotor speed behaves as a first order system with a time constant, which is inversely proportional to flow rate and to fluid density. For the 16" meter the time constant would be 0.009 s at maximum flow rate (10 000 m^3/h) and 0.09 s at 1000 m^3/s. The 8" meter would have a time constant of 0.013 s at 2500 m^3/h and 0.28 s at 100 m^3/h.

The response time of the ultrasonic meter is much shorter, however, as the signal contains a certain amount of noise, it will have to be filtered.

Turbine meters and ultrasonic meters behave differently, especially at low flow conditions. The advantage of turbine meters is that they inherently average the flow due to the inertia of the rotor. Consequently turbulent fluctuations have less influence, an influence that is also limited by the vortex stretching in the acceleration of the flow around the meter's bluff body. The essentially non-linear dynamics of the turbine meter may result in errors specifically at high frequencies, low flow rates and high pulsation amplitude.

Ultrasonic meters have a much wider bandwidth and are able to measure flow fluctuations up to about 1 kHz. Therefore the actual flow velocity, including the turbulent fluctuations, is measured. For use as a reference standard or when being tested, these turbulent fluctuations have to be eliminated from the final result.

In order to make an estimate of the averaging time required, the following reasoning can be made:

In a normal "fully developed" flow, the turbulence level is approximately 4% and the size of the energy containing vortices is approximately ¼ D. Due to their Gaussian distribution the scattering is reduced with the square root of the number of vortices passed. To reduce the 4% to a level of 0.1%, this requires an averaging length of 1600 vortices. With their average size of ¼ D, this results in a length of 160M. in a 16" pipe. At a flow velocity of 1 m/s, the averaging time has to be then at least 160 seconds and at 0.5 m/s, 320 seconds.

Or as a formula:

$$T_{av} = 400 \bullet D / V \qquad (7)$$

with *V* the velocity in m/s and *Tav* as the time needed to reduce the uncertainty to 0.1%.

The pressure transducers have a quoted response time of about 50 ms. The long connections to the pressure differential gauge will introduce an additional delay.

The temperature sensors are probably slowest and their response time could be several seconds depending on the gas velocity.

The other aspect is the frequency spectrum of the signals. This is primarily determined by the stability of operation of the compressor station. The second major factor is the equality of ambient and gas temperature.

4.5 Data processing

Traditionally gas meter testing is carried out in the following manner:

- The desired flow rate is established.
- The conditions of flow rate, pressure and temperature are monitored to achieve sufficiently stable condition.
- Testing is carried out over a time interval that is sufficiently long to attain the desired uncertainty. For frequency outputs the number of pulses integrated is a determing factor.
- The test is repeated at least two times to check for consistency.

In this facility the error is calculated and reported continuously with very short time intervals (1 sec). The turbine meter output frequency is determined from the periodic time between two pulses rather than from pulse counting.

The criterion for stability can therefore be the stability of the error rather than the stability of the all components. In this way a large number of data is also collected which allows the assessment of the type A uncertainty in a much better way.

The sampling frequency should be high enough to prevent aliasing. If the supervisory system needs a lower frequency the raw signal should first be filtered. Filters should however not be too restrictive in frequency, as data would then only be gathered slowly, testing time would increase and more importantly, this would discourage any interactivity in the testing process. One should for example not be discouraged from repeating a test in the interest of time.

The flow signal has the highest frequency content. Averaging is used to filter out these high frequencies.

The data collection system calculates the average and the standard deviation on line. One can therefore calculate the required number of samples needed to achieve a desired type A uncertainty.

The required number of samples is:

$$N = \frac{4s^2}{U^2} + 1 \qquad (8)$$

Where s is the standard deviation in the individual samples and U is the uncertainty of the end result (U=2s).

Traditionally one would have averaged over 100 seconds with at least two repeats. The statistics to indicate the type A uncertainty would then be based on only three measurements.

Using the same three hundred seconds and using all data points allows us to quantify the type A uncertainty as $2s/\sqrt{n-1} = 1/\sqrt{299} = 0.07\%$ for the series of table 1 with 0.5 % standard deviation.

The type A uncertainty as discussed above only relates to changes in time. There are however a number of other influences that may give variations in the final result. For example: If one conducts the same process with different size meters or using different testing runs one may not necessarily get the same results. This aspect has to be checked and incorporated in the uncertainty statement. Unlike the uncertainty mentioned above it cannot be improved by increasing testing time!

5 THE REFERENCE STANDARDS

To establish the reference standards of the facility the travelling standards are installed in a testing line and the data are generated in the same way as for a meter under test. A deviation is found that is different from the deviation that has been established for the travelling standards against primary standards. The indication of the reference meters has to be corrected so that the difference is reduced to zero.

In practice only a limited number of flow rates can be tested. The problem is then to interpolate for the intermediate values. Usually a polynomial is determined linking the measured data points. Computer programs exist that do a curve fit with a polynomial from any degree. The higher the degree, the better the fit. Taking a polynomial of a degree that is one less than the number of data points gives a perfect fit to the points. It may, however, not describe the behavior of the meter between the measured data points to any degree of credibility.

If instead, the polynomial is of a form that is based on, however crude, a physical model, the curve fitting indirectly estimates the values of some real physical parameters. In this case the accuracy of fitting becomes a measure for the uncertainty in the determination of those physical parameters and is much to be preferred to the purely mathematical approach.

Equations to describe the behavior of turbine meters have been established by Lee & Evans [7], Lee & Karlby [8] and by P.A.K. Tan. [9] These indicate that the equation for the deviation should at least involve negative powers of the flow rate. The fact that the pressure can only be measured in the vicinity of the blades gives rise to a term proportional to the square of the flow rate. For these reasons NMi uses an equation of the form:

$$E = A/Re + B + CRe + D\,Re^2 + E\,Re^3 \qquad (9)$$

with E the deviation, A, B, C,D and E constants and Re the Reynolds' number.

Comparison of the data for four different travelling standards (10", 12", 16" turbine meters and one 16" US meter) covering the same range gives an estimated uncertainty of 0.05 %.

The tests with the travelling standards give the correction that has to be applied to the original established curve of the reference meters in order to compensate for the specific installation. The correction for one of the 16" meters is given in figure 1.

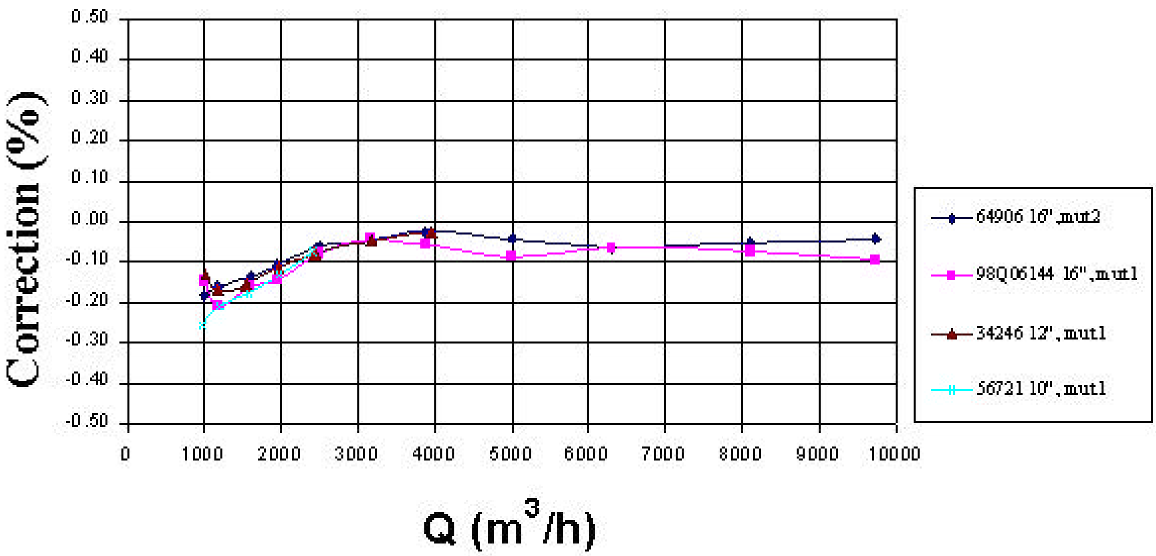

Figure 1. Correction for one of the 16" reference meters

6 RESULTS AND CONCLUSION

By combining the type A and B uncertainties a total uncertainty is found of 0.2% for flow rates from 1600 to 60 000m^3/h. For lower flow rates the uncertainty will increase but at the moment of writing no definite figure could yet be quoted.

As a final test the deviation of one of the travelling standards was determined with the newly established reference standards and compared with the deviation established earlier in Gasunie's Bernoulli laboratory. The results are given in figure 2.

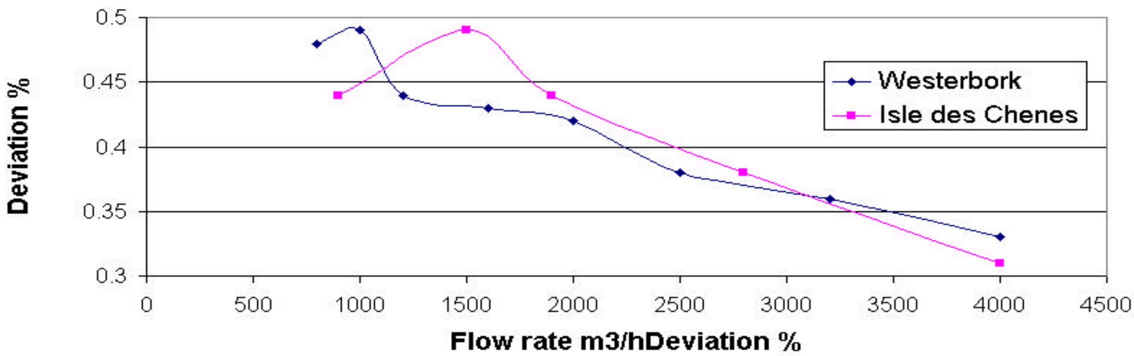

Figure 2. The results

It is expected that the full implementation of the capabilities of the IRPP system will improve the uncertainty further.

In conclusion, the TCC facility has shown to be capable of repeatably and reliably calibrating large gas flow meters with uncertainties that are comparable to the best available at present.

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