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DIFFERENTIAL PRESSURE CALIBRATION AT HIGH STATIC PRESSURE - A PRACTICAL APPROACH TO OPTIMISING UNCERTAINTY

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Abstract: The majority of high volume sales gas metering is carried out using orifice plate systems at high static pressures. The system will include one or more differential pressure sensors that will require calibration at the working static pressure in order to maintain traceability at an acceptable uncertainty. Calibration is generally carried out using a twin-post deadweight tester, but some components of uncertainty are unique to each instrument and are difficult to assess. This paper demonstrates a practical approach to the characterisation and uncertainty analysis of a twin post deadweight tester, which was used by the author to gain the lowest accredited uncertainties in the UK. The results are shown to correlate well with exhaustive experimental measurements, which would be beyond the budget of a commercial calibration laboratory.
Keywords: traceability, uncertainty, differential pressure

1 INTRODUCTION

When natural gas is traded between organisations or countries, the majority of metering is carried out using orifice plate systems at high static pressures. Calibration of the differential pressure sensor at the working static pressure is essential for maintaining traceability at an acceptable uncertainty. Twin-post deadweight testers are commonly used for the calibration of differential pressure sensors at high static pressure, but the assessment of uncertainty is far more complex than for a conventional deadweight tester.

Exhaustive measurements have been carried out to determine the magnitude of uncertainty components for a typical twin-post deadweight tester [1], but such measurements would be beyond the budget of a commercial calibration laboratory.

This paper outlines a characterisation regime and uncertainty analysis, which has been used to obtain optimum uncertainties for a commercial twin-post deadweight tester.

2 ASSESSMENT OF UNCERTAINTY

Some of the components of uncertainty will be common to single and twin-post deadweight testers and will not be considered here in any detail. Others are more complex and will vary in significance as a function of the static pressure (SP) and differential pressure (dp).

Inspection of the uncertainty budget reveals that the most significant contribution comes from “Change in temperature difference between the piston-cylinder units (PCUs)”, so it is the analysis and reduction of this component which will be dealt with in most detail.

The uncertainty combination illustrated in Table 2 is for a Desgranges et Huot 5502 twin post deadweight tester. A similar instrument was evaluated in detail by the UK National Physical Laboratory (NPL) [1]. Where appropriate, a comparison is made between the results obtained.

2.1 Effective area and mass

The high-pressure piston-cylinder unit is calibrated as a gauge mode pressure balance and its calibration uncertainty and long term stability can be directly expressed as a proportion of the differential pressure. The calibration uncertainty and long term stability of the weights used to generate the differential pressure can be treated in a similar way. The uncertainty of the weights used to generate the static pressure will not contribute directly to the uncertainty of the differential pressure because the high and low pressure PCUs are balanced to give zero differential pressure prior to each calibration cycle. It should be noted that the measurement results can be corrected for a small residual differential pressure at nominal zero.

The effect of these uncertainty components is relatively small, so a fairly routine calibration of the mass and effective area values will be adequate - typically 50 ppm for the effective area and 10 ppm for the masses.

2.2 Temperature effects

There will be an uncertainty in the calculated differential pressure value resulting principally from temperature gradients between the working components of the PCU and the temperature sensor. This component will be dependent on the positioning of the sensor and the temperature distortion coefficient of the PCU. The effect of temperature differences between the high and low-pressure PCUs are initially eliminated by the balancing procedure, but any subsequent change will have a significant effect.

2.2.1 Change in temperature difference between the piston-cylinder units (PCUs)

If the pistons have been balanced, and the temperature of both PCUs change by the same amount then the pressure generated by each weight column will change equally and there will be no net differential pressure generated. If there is a difference in the temperature changes, then the resultant change in differential pressure will be proportional to the static pressure and the change in temperature difference. For the conditions illustrated in Table 2, a change in temperature difference of 0.1 °C will affect the differential pressure by 13 Pa (0.13 mbar).

In practice, it is not possible to measure small temperature changes directly because of the positioning of the temperature sensor. However, such temperature changes will affect the balance between the high and low-pressure PCUs at nominally zero differential pressure. This effect can be measured by observing the difference in pressure indicated by the unit under test when the isolating valve between the high and low-pressure PCUs is opened or closed.

Such “valve open/valve closed” measurements can be used to evaluate suitable temperature and pressure stabilisation periods for normal operation of the twin post deadweight tester. The maximum effect that is probable under the resultant operating procedures can be determined in a similar way, and it is this value that will be included in the uncertainty budget. However, this is generally the largest component of uncertainty, and cannot be fully evaluated during a short commissioning period for the equipment. It is therefore essential that “valve open/valve closed” measurements are made at the start and end of every calibration cycle to ensure that the operating parameters have been met. These measurements will also provide comprehensive data, which will enable the operating procedures and environment to be optimised and the uncertainty reduced.

In recognition of the magnitude of this component of uncertainty, a 5-sided enclosure was built to house Sira’s twin post deadweight tester, in order to provide a temperature stable environment.

Initial characterisation of Sira’s differential pressure calibration facility lead to an overall uncertainty of differential pressure measurement equal to ±(8 Pa + 0.6 ppm SP + 20 ppm dp). This was later reduced by around 40 %, principally as a result of on-going “valve open/valve closed” measurements, together with on-going repeatability measurements as described in 2.4 below.

The current uncertainty assessment at Sira is based on numerous measurements of change in balance point, which will include contributions from fluid head and repeatability. These are considerably smaller than the contributions suggested by the NPL, but this may reflect assumptions that were made about typical operating procedures and working environment.

2.3 Fluid head and buoyancy effects

The vertical separation of the twin-post deadweight tester and the instrument under test is accounted for in the pressure calculation, assuming the pressurising gas to be near ideal. A much more significant effect can be caused by changes in temperature of the high and low pressure connections made to the instrument under test. These are minimised by running the high and low pressure pipe-work adjacent and shielding it from drafts and other potential causes of temperature gradients.

There will also be a fluid head effect, proportional to the static pressure, due to differences in height of the measuring pistons at each calibration point. In order to achieve an optimum uncertainty with cost effective procedures, it will be necessary to find a compromise between vertical oscillation (bounce) of the weight columns and having them float at exactly the same level. The effect of this vertical oscillation is most noticeable when an instrument with a large sensing diaphragm, which can transmit pressure pulsations between the high and low pressure PCUs, is calibrated using a deadweight tester with a small piston area. The use of additional height sensors enables the Sira pistons to be positioned within ±0.2 mm, following operating procedures designed to minimise “bounce” during periods when measurements are being taken.

Changes in ambient air density during the calibration will have a proportional effect on the buoyancy of the weight columns. In most cases the net effect will be small and proportional to the differential pressure. However, it should be noted that certain twin post deadweight testers have high and low pressure weight sets constructed from materials of differing density, so the effect of air density changes could be quite considerable.

2.4 Instrument specific characteristics

There are a number of instrument specific factors, which will affect the repeatability of measurements made using a twin-post deadweight tester. These are principally piston “taper”, angular velocity of the weight columns and cyclical pressure variations related to the interaction of the rotating weight columns. The NPL has evaluated these factors in detail for two instruments [1], but such exhaustive measurements would not be appropriate for most calibration laboratories.

Each of these factors will contribute to the repeatability of the results obtained using the deadweight tester, so it is possible to estimate their combined effect from repeated measurements under normal operating conditions.

The cyclical pressure variations can be characterised by measuring the standard deviation of the output from a fast responding test instrument. The principle component of these variations has a period equal to mean rotational velocity of the weight columns, so it is straightforward to select a sampling rate that avoids the possibility of aliasing. It should be noted that the applied differential pressure is dependent on the precision to which initial balancing can be carried out, which is also limited by the cyclical variations. The effect of these two components is reduced by averaging 20 or more measurements over a short time period at each calibration point. The degrees of freedom associated with these components are taken to be infinite because the standard deviation is verified at every calibration point. If the expected standard deviation is exceeded because the vertical oscillations were not sufficiently damped, then the measurement point is repeated.

The other components can be characterised by performing multiple calibrations on a single instrument following normal operating procedures. Measurements should include the effect of returning the system to atmospheric pressure and should cover the entire range of static pressures. Sira were able to use results obtained from the calibration of a precision quartz Bourdon-tube pressure gauge which enabled sets of 15 measurements to be evaluated at 4 static pressures. However, many typical dp transmitters can be shown to have minimal repeatability and hysteresis during their normal calibration at atmospheric pressure. When such an instrument is subsequently calibrated over three pressure cycles at static pressure then 6 useable results (3 rising and 3 falling) will be available at each differential pressure, which can be used to estimate the overall repeatability of the measurements. If a significant, progressive change in balance point is evident, then a linear correction should be applied before repeatability figures are calculated.

The results obtained by NPL and Sira are of a similar magnitude, but reflect differences in operating procedure as well as metrological characteristics of the specific instruments. The combined effect of piston taper and rotational velocity determined by NPL was approximately ±4.5 Pa independent of static pressure, compared to Sira’s figures which vary from ±3 Pa at 1 MPa to ±5 Pa at 20 MPa static pressure. These figures will not be representative of other instruments, operating procedures and working environments, and demonstrate the necessity of characterising each instrument within its normal operating conditions in order to obtain realistic uncertainties.

2.5 Electrical measurements

One of the most common calibrations will be of an analogue (4-20 mA dc) differential pressure transmitter. Typical uncertainty components that can be achieved in a laboratory environment have been included for completeness.

3 OPERATIONAL PROCEDURES

The calculated best measurement uncertainty will only be achieved if the operator is sufficiently skilled in using the twin-post deadweight tester. For this reason, it is necessary to check each stage of a calibration against operating parameters so that the calculated uncertainty will be verified. The parameters are derived from the expected uncertainty components listed in Table 1. For example, limits must be set on the minimum number of measurements recorded at each point and the maximum allowable repeatability of those measurements. Similarly, there must be measurable requirements for piston height and limits for the change in balance point before and after a calibration cycle. The majority of these parameters can be recorded automatically by a data processing system and can subsequently be used to refine the procedures and uncertainty budgets.

Table 1. Combination of uncertainty components

Source of uncertainty [5]	Value [5] ±	Unit	Probability distribution	Divisor	Sensitivity c_i f(SP, dp)	Standard uncertainty u_i (Pa)	Degrees of freedom v_i or v_f
Effective area of high pressure piston-cylinder unit (PCU)	50.0	ppm dp	normal	2	0.05	1.25	i
Long term stability of effective area	12.0	ppm dp	rectangular	√3	0.05	0.35	i
Mass added to generate differential pressure (±0.4 mg)	0.2	Pa	normal	2	1	0.10	i
Long term stability of masses (±0.8 mg)	0.4	Pa	rectangular	√3	1	0.23	i
Temperature of high pressure PCU (±0.5 °C) [4]	4.5	ppm dp	rectangular	√3	0.05	0.13	i
Change in temperature difference between PCUs (±0.04 °C) [4]	0.35	ppm SP	rectangular	√3	15	3.03	i
Fluid head effect	0.025	ppm SP	rectangular	√3	15	0.22	i
Air buoyancy	1	ppm dp	rectangular	√3	0.05	0.03	i
Stability at zero [1]	1.4	Pa	normal	1	1	1.40	i
Stability at differential pressure [1]	1.4	Pa	normal	1	1	1.40	i
Repeatability of calibration point [2]	2.6	Pa	normal	1	1	2.60	14
Voltmeter calibration	20	ppm dp	normal	2	0.05	0.50	i
Voltmeter deviation from nominal, including drift	35	ppm dp	rectangular	√3	0.05	1.01	i
Resolution [3]	0.05	μA	rectangular	√3	3.1	0.09	i
Resistor calibration	25	ppm dp	normal	2	0.05	0.63	i
Long term stability of resistor	10	ppm dp	rectangular	√3	0.05	0.29	i
Combined standard uncertainty			normal			4.84	168
Expanded combined uncertainty			normal	k for v_f	2	9.68	168

	Static pressure (SP)	150 bar	(15.0 MPa)	**Equivalent uncertainty values (±)**
	Differential pressure (dp)	500 mbar	(50.0 kPa)	0.10 mbar
1	Number of readings at each point	20		0.019 % reading
2	Number of rising and falling runs	3		
3	Resolution on certificate	0.0001 mA		
4	Temperature coefficient of PCUs	9.1 ppm/°C		
5	See text for details			

4 OVERALL MEASUREMENT CAPABILITY

Initial characterisation measurements made during 1992, enabled Sira to obtain the lowest accredited uncertainties in the UK at static pressures up to 20 MPa (200 bar):

Best measurement capability 1993 ±(8 Pa + 0.6 ppm SP + 20 ppm dp)

On-going measurements made during routine calibrations over the subsequent 4 years led to significant reductions:

Best measurement capability 1997

0 to 50 kPa differential	±(4 Pa + 0.35 ppm SP + 20 ppm dp)
50 to 200 kPa differential	±(3 Pa + 0.30 ppm SP + 45 ppm dp)
200 to 1000 kPa differential	±80 ppm dp

5 CONCLUSION

The practical characterisation and uncertainty analysis methods described have been used to obtain the lowest accredited uncertainties in the UK. Specific operational procedures must be employed to demonstrate that the calculated uncertainty is not exceeded. The resulting uncertainty components are consistent with the most detailed experimental data available and can be reliably assessed in a realistic timescale.

REFERENCES

[1] Mark Hay, David Simpson, Development of high-line differential pressure standards, NPL report CMAM 41, 1999

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