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Automated Piston Gauge Calibration System

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Abstract: Piston gauges or pressure balances are important primary standards for the realization of the SI unit of pressure, the pascal. Because of their long-term stability, they are also used as secondary or working standards in the dissemination of the pressure scale. The National Institute of Standards and Technology (NIST) operates and maintains a calibration service for these devices, and has recently undertaken a modernization effort. Following a preliminary investigation into the feasibility of using transducers as instantaneous in-situ transfer standards, we now present the results of a near fully automated calibration system. This effort includes the design, building, and validation of an automated gas-handling manifold, and the development of a new software suite. The new system demonstrates an expanded uncertainty on the order of 1 in 10^5, comparable to the traditional system, but offers a five-fold decrease in calibration turnaround time.

1. Introduction

Piston gauges are widely maintained as calibration standards by industry and government stakeholders, unless they experience some kind of trauma (such as scratching, exposure to corrosives or contaminants, etc.) they are indefinitely stable. This is because in principle their calibration depends entirely upon their physical geometry, the quantity of interest being the effective area, A_{eff}. The National Institute of Standards and Technology (NIST) has a pair of primary standard gauges that have been characterized dimensionally to better than 25 nm [1], and cross-checked against a primary pressure realization using an alternate method (the NIST mercury manometer). This traceability to dimensional metrology makes them suitable for use as primary standards. NIST owns a suite of secondary standards that, through comparison calibrations, provide customers with traceability and uncertainties on the order of one part in 10^5. In order to make this service available to a broader customer base through decreased turn-around time and decreased cost, NIST has undertaken a modernization effort in which most of the calibration is performed by software and automated hardware. In this article, we present a summary of the software and hardware design, and show the results of in-house verification tests.

2. Method

A piston gauge calibration at NIST is traditionally done using a cross-float in which a NIST standard gauge generates a particular pressure and a customer gauge under calibration responds to that pressure [1]. In order to balance the generated pressure and determine the effective area, masses are loaded onto the customer gauge until a balanced condition is achieved. This operation requires resolution down to the order of milligrams out of tens of kilograms, requiring the operator to painstakingly load tiny trim masses, a process that is time-consuming and depends on the skill of the operator. As demonstrated in a previous investigation [2], it is possible to achieve comparable uncertainties without undergoing the tedious task of using trim masses to get an exact balanced condition, and instead use a pressure transducer as an immediate transfer standard. The essence of the method is that the NIST standard gauge and the customer gauge are loaded with masses to bring them into approximate pressure equilibrium, and the small residual pressure difference between them is measured with a high-resolution pressure transducer that is sequentially connected to each piston gauge [3]. This reduces the dependence of operator judgement and "feel" and opens up the possibility of a fully automated system. We have designed and built a manifold containing two such transfer transducers, all the requisite tubing and valves, as well as coordinated mass-flow controllers to provide inlet gas control necessary to generate pressure on the piston gauge standard. Two transducers are used to cover a wide range of pressures, while still having adequate pressure resolution at the low end (the absolute resolution of a transducer is the same over its entire operating range, meaning the relative resolution increases near the low end of its operating range). An external pressure generator can be used as well, bypassing the mass-flow controllers. Well-characterized high-pressure relief valves are included as a safety feature, but note that they introduce a potential error mechanism (that is, they can get stuck slightly open) and therefore need to be considered when troubleshooting system failure. Our system uses a 310 kPa and a 13.8 kPa transfer transducer, (Paroscientific models 745-45A and 745-2 K, we will refer to them as T_L and T_H,

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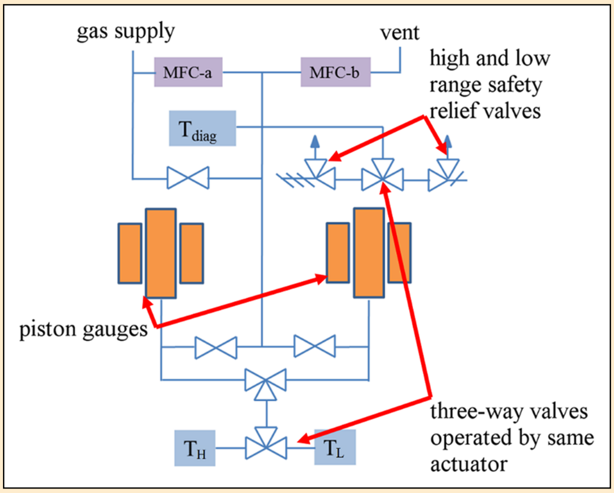

Figure 1. Manifold.

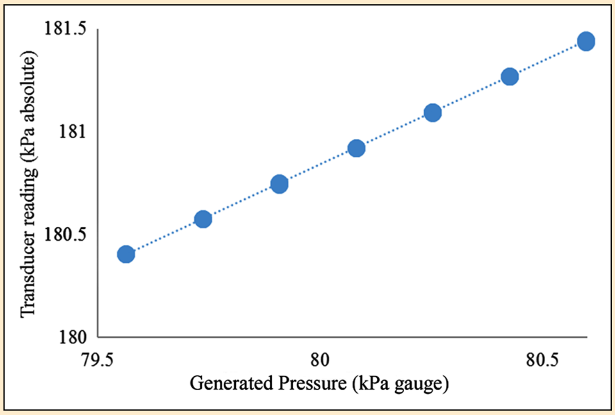

Figure 2. High-resolution linearity of Transducer T_L over a restricted range spanning approximately 1 kPa.

respectively[1]), and can cover the pressure range of rough vacuum to 7 MPa. Other system components limit the full-scale range of the system. As of time of writing, the entire method has been verified up to 1.4 MPa. The manifold model and schematic are shown in Figure 1. It is housed in an enclosure to reduce the effects of air currents and temperature fluctuations in the lab (temperature needs to be maintained to within 1°C), and can be operated in either automatic (computer controlled) or manual mode. The three-way valves that select the transducers T_L or T_H and the pressure relief valves are operated by the same actuator to ensure that the correct pressure relief valve is selected for the pressure range of interest.

In order to ensure the integrity of our results, it was first necessary to assess the linearity and drift characteristics of the transducers. For linearity, we recorded transducer readings at a number of known pressures (generated by the NIST standard). For each transducer, we did a high-resolution scan (2 parts in 10^3) over a small pressure range, and a low-resolution scan (1 part in 10) over the entire pressure range. For all four test cases (two resolutions for each of two transducers), the deviation from linearity was negligibly small, $u_l <$ 1 part in 10^6, which is sufficient for use as an immediate in-situ transfer standard. The high-resolution linearity is of greater importance, but it is not feasible to do a high-resolution scan of the entire range because it would take many weeks. Instead, a high-resolution scan was completed over a restricted range and was considered alongside the low-resolution scan over the entire range. We argue that this approach provides the necessary assessment of the linearity and drift characteristics of the transducers. Figure 2 shows a typical high-resolution data set for T_L.

The drift of each transducer was assessed by taking >500 successive data points under constant conditions at 15 second intervals at a pressure of 86 kPa for T_L and 1400 kPa for T_H. As necessary the piston was re-floated, causing instability in the readings. Data collection was paused until the readings stabilized. As the transducers measure absolute pressure and the piston gauges were operated in gauge mode, our readings were adjusted for changes in barometric pressure. We measured barometric pressure at the beginning and end of the test, assumed a constant linear change, and subtracted the interpolated value from the raw transducer readings to arrive at a grossly corrected transducer reading. It is likely that the change in barometric pressure was not constant, so we can reasonably conclude that the transducer drift is less than this worst-case scenario. Note that since this transducer is used as an immediate transfer standard, only the short-term drift/stability is of interest. The long-term stability of similar instruments has been investigated [4]. The maximum corrected drift of the low-pressure transducer T_L has value 2.5×10^{-2} Pa /10^6 Pa /s, and that of T_H is 1.1×10^{-4} Pa /10^6 Pa /s. This means that in order to corrupt the data at 10^{-6} level, the comparison between piston gauge and transducer would have to take 250 seconds for T_L and 11,000 seconds for T_H. The actual time scale for this comparison is on the order of ten seconds, certainly less than these worst-case limits. We are therefore confident that transducer drift is of no consequence in these measurements.

3. Software

To further reduce both the time required to complete a calibration, and the risk of transcription errors associated with manual entry, we developed a suite of software that includes the following components:

1. database with NIST and relevant gauge information;
2. on-the-fly generation of operator instruction to generate pressures;
3. manifold operation;
4. data reduction and analysis;
5. report generation; and
6. historical database.

We refer to it as the Piston Gauge Automation Suite (PGAS).

1. When a calibration is initiated, NIST collects relevant data such as the nominal effective area of the gauge, its range, serial number, manufacturer, and type. This information is stored in a

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[1] Certain equipment or materials are identified in this article in order to specify the experimental procedure adequately. Such identification is not intended to imply endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available.

database along with similar data for the NIST-owned gauges and mass calibration information.

2. Based on the test gauge information, PGAS generates complete instructions for setting up and running the calibration. It recommends a NIST standard gauge for the comparison calibration and mass sets for both the standard and customer gauge. The gauges are compared at a number of distinct pressure points spanning the range of the customer gauge; PGAS calculates target values for these points, and determines the most efficient subset of masses to load onto each gauge in order to reach that pressure and float the pistons.
3. When the calibration setup is complete, the operator controls the manifold in manual mode by activating valves in the appropriate sequence at the appropriate time. Automatic control of the manifold by PGAS is currently under development. The automatic mode will only control the manifold, masses must still be loaded onto the gauges manually, and in most cases, spinning the gauges is performed manually as well.
4. To analyze data, PGAS assumes that the operator has correctly loaded masses according to its recommendation. If the operator chooses to load a different combination of masses, she can input the actual masses used. We considered the possibility of capturing mass information by an optical sensor, but this was determined not to be feasible because adding permanent optically detectable markings to the masses represented both high cost and high risk (making markings would alter the mass). Following [2], the measurement equation for the test gauge using the transducer method is

   $$P_T = \frac{\Delta P}{l} + \left(\frac{1}{A_{eff}}\right)\frac{\sum_i m_i g\left(1-\rho_a/\rho_b\right)}{1+\left(\alpha_p+\alpha_c\right)\left(T-T_r\right)}. \tag{1}$$

   In addition to the masses m_i and the pressure differential, ΔP, measured by the transducer we capture the temperature T automatically. Air density ρ_a is calculated from the measured air pressure and humidity. The reference temperature T_r is set at the discretion of the protocol. The linearity of the transducer l is generally unity as described in the referenced work. Other quantities in Eq. (1) are constants retrieved from the database. The data are fit to

   $$A_{fit} = A_0(1+b_1P) - t/P, \tag{2}$$

   where either or both of the fit parameters, b_1 and t, can be constrained to zero

   The uncertainty calculation follows that described in [1] with an additional term due to the transducer, that is equal to the standard deviation of the mean of the transducer readings at a particular pressure. In general, the uncertainty is a function of pressure, and is calculated at each measurement point. Results of the analysis, including graphical displays, are presented to the operator for review and acceptance.
5. After the data have been analyzed, PGAS is used to generate a report in which all relevant artifact and calibration data are inserted into a standard template along with analysis details and the uncertainty calculation.
6. The results of past calibrations are being added to a historical database. Once it is completed, this database will allow comparison between current and previous results, giving the artifact owner a better understanding of its stability over time, and may be used to inform the calibration interval. Introduction of the PGAS has reduced the total number of data values documented by the operator during the calibration process by 86% and, of the remaining data values to be documented, 32% can be selected from a known set of potential values [5]. These improvements have significantly reduced the opportunities for transcription errors as well as the time required to complete a calibration.

4. Results

To ensure that our methods are valid and that our manifold is well constructed, we did a series of tests exploring the possibility that we may have introduced unexpected systematic errors. We used NIST reference piston gauges as the standard and test for each test, but did all possible combinations of base and position (side of manifold) several times. We call the bases simply "base A" and "base B." The positions are labeled 1 and 2, where 1 is the usual standard side (to the left of the manifold) and 2 is the usual test side (to the right of the manifold). All tests were done with the new automated system. NIST piston gauges are designated PG37 and PG34, both with a full-scale range of 1.4 MPa. The tests are listed in chronological order in Table 1.

The data were fit to a straight line with the t parameter constrained to zero, where $A(P) = A_0 + b_1P$. The effective area at zero pressure, $P = 0$, found in each test is plotted in Figure 3. The average of these calibrations compares to the value obtained by a traditional cross-float to well within the expanded uncertainty, differing from the accepted value by less than one part in a million or $0.8\ \mathrm{m}^2/1 \times 10^6\ \mathrm{m}^2$. The accepted value is depicted as a 95% confidence interval in Figure 3, represented by an orange band. Any of these individual tests compares favorably to the accepted value as well, and we can conclude that the

NIST ID	PG 37 set up	PG 34 set up
9017	base A, position 1	base B, position 2
9018	base A, position 1	base B, position 2
9019	base B, position 2	base A, position 1
9020	base B, position 2	base A, position 1
9021	base A, position 1	base B, position 2
9022	base A, position 2	base B, position 1
9023	base B, position 1	base A, position 2
9024	base B, position 1	base A, position 2
9025	base B, position 1	base A, position 2
9026	base A, position 2	base B, position 1
9027	base A, position 1	base B, position 2
9029	base B, position 2	base A, position 1
9031	base A, position 1	base B, position 2
9031	base A, position 1	base B, position 2
9031	base A, position 1	base B, position 2

Table 1. Validation test setup summary

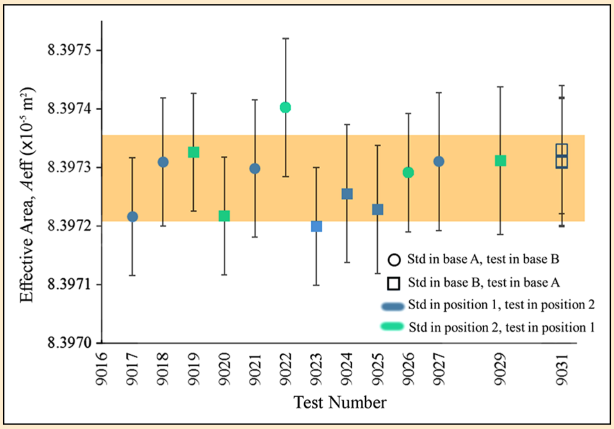

Figure 3. Tests NIST 9016 through NIST 9031 as described in the Table 1. The A_0 coefficient of the fit for PG34 is plotted as a function of test number. There is no significant dependence on base or position of standard and test piston gauges. The open squares in test NIST 9031 are three separate tests run one after the other, with slight variations in technique to verify repeatability. The colored band is the $k = 2$ confidence interval of the standard.

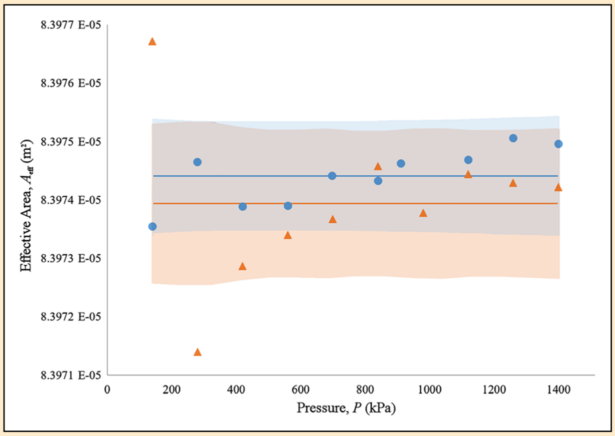

Figure 4. Calibration of customer-owned gauge, method comparison. Blue circles are data from the traditional method, orange triangles are automated data. The lines correspond to the best fit constant for *Aeff,* shaded bands are the 95% confidence interval for the corresponding method.

method described in this article can be substituted for the traditional method, without concern about which base or position is used for the standard and test piston gauges.

A final example test was to calibrate a non-NIST owned gauge by the traditional method and by using the automated system, and compare the results both in terms of amount of time to perform the calibration and agreement in the results. We again used PG37 as the standard. The calibration data as shown in Figure 4 agree within the expanded uncertainty of the automated method from 400 kPa to 1.4 MPa, and show differences larger than the expanded uncertainty for two pressures below 300 kPa. The $k = 2$ uncertainty associated with the automated method ($\sim 15 \times 10^{-6}/A_{\text{eff}}$) is slightly larger to that of the traditional method ($\sim 11 \times 10^{-6}/A_{\text{eff}}$) for this test. The effective area found using the automated system (8.397394×10^{-5} m^2) agrees to within 5.6×10^{-6} of the effective area found by the traditional method, well within uncertainties to that found using the traditional system. The difference in the two methods could be due to changes in ambient conditions or performance issues of the customer's gauge. It should be noted that the traditional method and automated method are not done simultaneously, and this particular comparison required independent calibration runs.

In terms of time to perform the calibration, there was a dramatic reduction in the set-up, data acquisition, and report generation for the automated method. With this automated system, all data can be collected and analyzed in a single day. This decreases the operator time by at least a factor of 4, and is expected to result in a significantly faster turnaround time for customer calibrations. The automated system represents an 86% reduction in manual inputs, which leads to reduced likelihood of operator error.

We expected the results to show that the manifold operation can be done in either automatic or manual mode without consequence, and indeed we discovered that there was no significant variation in the result. The relative uncertainty for the TAC method validation tests was found to be between about 12×10^{-6} and 14×10^{-6} and the results agree to each other and to the accepted value within that uncertainty. A traditional cross-float calibration requires much longer for set-up and data analysis.

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