

CALIBRATION AND CHARACTERIZATION OF PRESSURE GAUGES UP TO 1 GPa

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Abstract: Pressure gauges including strain-gauge transducers and Manganin gauges are calibrated and characterized in the pressure range up to 1 GPa. For the calibration and characterization, the pressure generating system using a pressure balance and a precise pressure multiplier has been developed as a pressure standard. In this paper, the pressure generating system, the method for calibrating the pressure gauges by using the system and the results obtained are presented. The temperature coefficients of Manganin gauges are also evaluated in the pressure range.

Keywords: pressure gauge, pressure standard, calibration, characterization.

1. INTRODUCTION

At the National Metrology Institute of Japan (NMIJ), AIST, two pressure standards have been developed for generating high pressure up to 1 GPa precisely. One is a controlled clearance pressure balance whose clearance between the piston and the cylinder can be changed by adjusting the jacket pressure which is applied on the outer cylindrical surface of the cylinder. Although a controlled clearance pressure balance is the most effective device to generate the pressure with smaller uncertainty in such high pressure range, the operation is relatively complicated and detail characterization is necessary to evaluate the uncertainty of the pressure generated [1, 2]. Another is the pressure generating system using a pressure balance and a pressure multiplier [3, 4]. In this article, the latter is used as a pressure standard to apply the pressure to pressure gauges.

Currently, many commercially available high pressure gauges are used to measure the pressure up to 1 GPa. In this study, several pressure gauges including strain-gauge transducers and Manganin gauges are calibrated and characterized in the pressure range up to 1 GPa using the pressure generating system. The detailed method and results are presented. The temperature coefficient of the Manganin gauges is also evaluated in the pressure range.

2. PRESSURE STANDARD

For high pressure generation up to 1 GPa, a commercially available precise pressure multiplier is used [3]. Using the pressure multiplier and a pressure balance, the pressure generating system up to 1 GPa has been developed [4]. The structure and operation of the pressure multiplier

used were reported in detail [3]. The multiplier includes two different piston-cylinder assemblies which are linked in the housing of the multiplier. The nominal effective areas of both piston-cylinder assemblies are approximately 50 mm² and 5 mm², respectively. Therefore, the multiplying ratio of the multiplier, which is the ratio of high pressure to low pressure, is about 10. The material of both piston-cylinder assemblies is tungsten carbide. Both the pistons are linked and are rotated by a motor. The clearance between piston and cylinder in each assembly is always filled with hydraulic fluid. The mechanical contact between piston and cylinder in each assembly is negligibly small. The pressure multiplier has low and high pressure ports and is capable of generating pressure of 1 GPa at the high pressure port when pressure of 100 MPa is applied to the low pressure port. The pressure for the low pressure port can be applied accurately using a pressure balance [4, 5].

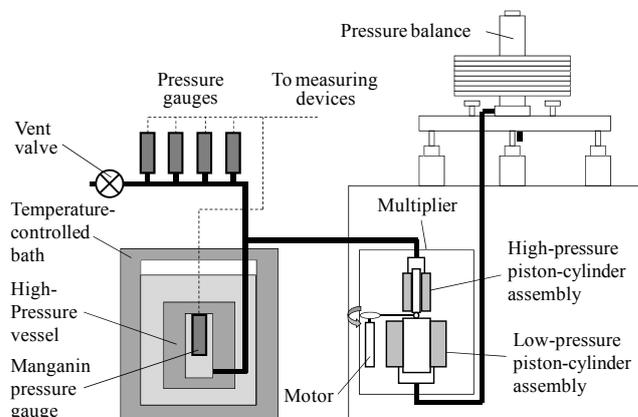


Figure 1 Schematic diagram of the equipment configuration for generating pressure using a pressure balance and a pressure multiplier.

The method for evaluating the multiplying ratio of the multiplier up to 1 GPa is reported [4]. When low pressure, p_L , and high pressure, p_H , are applied to the low and high pressure ports of the multiplier, respectively, the relation between p_L and p_H is defined as equation (1),

$$p_H = K_p(p_L - p_0), \quad (1)$$

where K_p is the multiplying ratio of the multiplier and p_0 is the offset pressure which is mainly generated by the

gravitational force due to the floating objects including both the pistons in the multiplier. K_p can be expressed as a function of p_H by equation (2),

$$K_p = K_{m0}(1 + \lambda_m p_H), \quad (2)$$

where K_{m0} is the multiplying ratio of the multiplier when p_H is zero and λ_m is the pressure distortion coefficient of the multiplier.

The multiplying ratio of the multiplier was precisely measured as a function of pressure by applying known low and high pressures generated by two pressure balances to the low and high pressure ports of the multiplier. For the measurement, p_L was changed from 5 MPa to 50 MPa in steps of 5 MPa and p_H was changed from 50 MPa to 500 MPa in steps of 50 MPa. From the measurement results, the parameters used for characterizing the multiplier, such as K_{m0} , λ_m , p_0 , have been evaluated. The reproducibility of K_p during two years has been evaluated relatively less than 1×10^{-5} [4]. Using the parameters evaluated, the multiplying ratio K_p was linearly extrapolated in the pressure range up to 1 GPa. The calculated K_p and its uncertainty are shown in figure 2. The error bar shows the standard uncertainty of K_p , $u(K_p)$.

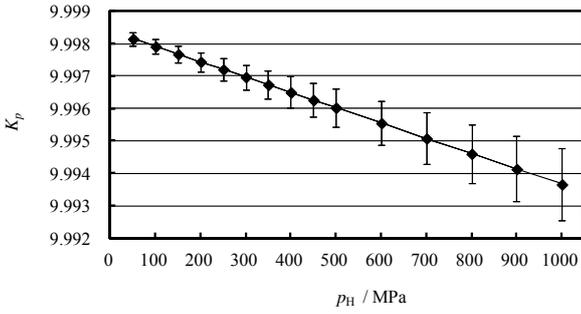


Figure 2 Evaluated multiplying ratio and its uncertainty as a function of pressure.

To generate pressure up to 1 GPa, the pressure balance which can generate pressure up to 100 MPa and the precise pressure multiplier are used together. The characteristic of the pressure balance has been evaluated in detail and the relative standard uncertainty of the pressure generated is about 20×10^{-6} . It has been confirmed through interlaboratory comparisons [6, 7] that the pressure generated is reliable within the claimed uncertainty.

When p_L is applied to the low pressure port of the multiplier, the pressure generated at the high pressure port, p_H , is calculated by using equation (1) and the evaluated K_p .

From equation (1), the standard uncertainty of p_H can be expressed as

$$u(p_H) = \sqrt{[u(K_p)(p_L - p_0)]^2 + [K_p u(p_L)]^2 + [K_p u(p_0)]^2}, \quad (3)$$

where $u(p_L)$ and $u(p_H)$ are the standard uncertainties of p_L and p_H , respectively [8]. The uncertainty of pressure generated at the high pressure port is estimated up to 1 GPa using equation (3). The expanded ($k = 2$) uncertainty of p_H , $U(p_H)$, has been estimated as $U(p_H) = 20000 + 0.3 p_H^2$ [Pa], where the unit of p_H is MPa. In figure 3, the relative

expanded uncertainty of p_H is plotted by black symbol as a function of pressure and is less than 3.2×10^{-4} in the pressure range from 100 MPa to 1 GPa. For reference, the relative expanded ($k = 2$) uncertainty of the pressure generated by a pressure balance up to 500 MPa is also plotted by white symbol in figure 3.

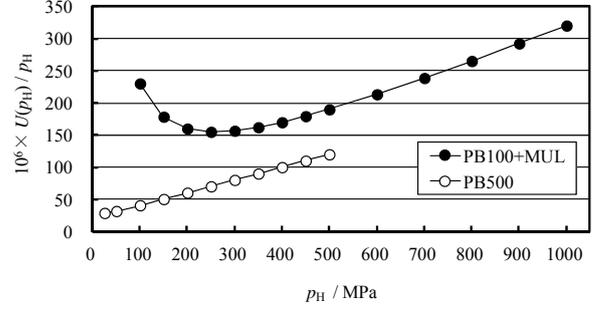


Figure 3 Expanded uncertainties of pressure generated (coverage factor $k = 2$) by the pressure generating system using a pressure balance and a pressure multiplier (PB100+MUL) and a pressure balance (PB500).

3. CALIBRATION

Several types of pressure gauges have been calibrated against the pressure generating system by direct comparison. Examples are presented here. The calibration procedure is as follows. Clean dioctyl sebacate is used as hydraulic working fluid for the measurement. The density of fluid as a function of pressure has been reported [9]. A tube whose inner diameter was 1.6 mm is used for the high pressure tubing. Usually the viscosity of fluid increases for high pressure. To reduce the pressure gradient in the tubing, the length of tube is adjusted as short as possible.

The calibration points are eleven points (hydraulic pressure: 50 MPa, 100 MPa, 200 MPa, 300 MPa, 400 MPa, 500 MPa, 600 MPa, 700 MPa, 800 MPa, 900 MPa and 1000 MPa). First, the pressure is increased from 0 MPa to 100 MPa in steps of 50 MPa, then from 100 MPa to 1000 MPa in steps of 100 MPa. Next, the pressure is decreased from 1000 MPa to 100 MPa in steps of 100 MPa, then from 100 Pa to 0 MPa in steps of 50 MPa. Between increasing and decreasing pressures, a longer waiting time of more than 30 minutes are taken. During the waiting time, the pressure is kept as close to 1000 MPa as possible. The relative difference between the actual pressure applied and the nominal value is adjusted to be below 10^{-3} . A vent valve was opened to apply zero gauge pressure to pressure gauges. At each measurement point, the pressure is kept to stabilize for 15 minutes after applying the pressure. After the waiting time, measurements are performed at the latest, within 5 minutes.

At each measurement point, the outputs of pressure gauges are acquired simultaneously. The measuring amplifier is used to read the signal from the pressure gauges. The maximum relative resolution of the measured value by one measuring amplifier is 1×10^{-6} . The output of each pressure gauge through measuring amplifier is sampled

twelve times by a computer and the mean value of the data is calculated at each measurement point. Also environmental condition, for example, atmospheric pressure, ambient temperature and relative humidity, are measured. Then the pressure applied for each pressure gauge is calculated at the vertical height of each connecting port.

The outputs of pressure gauges for increasing and decreasing pressure points of each cycle are offset by the outputs at the beginning or the end 0 MPa points, respectively. The increasing and decreasing pressure calibration sequences are repeated three times in total. The value at each calibration point is calculated by averaging the three values obtained from the three calibration sequences. From the averaged values as a function of pressure, a best fitting straight line for each pressure gauge was calculated by a linear least square method.

Figure 4 shows an example of the results obtained from the calibrations of two different strain-gauge transducers and a Manganin gauge and those are identified as S1, S2 and M, respectively. Two transducers are set up with vertical position. In the figure, the horizontal axis shows the pressure applied and the vertical axis shows the relative deviation from the best fitting straight line to the full scale (%FS) of the output of each gauge. The repeatability of the measured results with S1 and S2 transducers is better than 0.02 %FS and 0.005 %FS, respectively, as the standard deviation in all the points calibrated. The repeatability of the Manganin gauge is about 0.04 %FS. From the results presented here, it can be stated that accurate calibration was performed with the pressure generating system. As shown in figure 4, in case of the strain-gauge transducers, there is clear hysteresis between the results obtained from increasing and decreasing pressures and the maximum difference is found at 500 MPa which is the middle of the pressure range that the calibration was performed. The maximum differences for S1 and S2 transducers are about 1.6 %FS and 0.24 %FS, respectively. The amount of hysteresis is one of the important characteristics for pressure gauge and less hysteresis is better for precise measurement. From the viewpoint of the repeatability and hysteresis, S2 transducer is superior to S1.

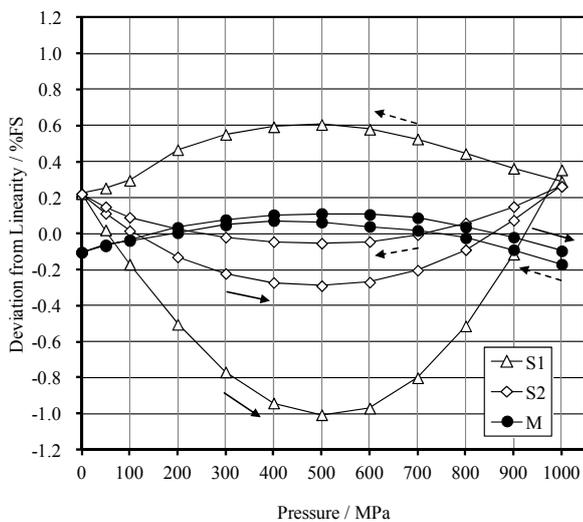


Figure 4 Example of calibration results of two strain-gauge transducers (S1, S2) and Manganin gauge (M).

The sensing element of S2 transducer is a foil strain-gauge. In the results obtained for Manganin gauge (M), there is no obvious hysteresis. However, the outputs at zero pressure obtained from increasing and decreasing pressures are changed about 0.08 %FS.

4. TEMPERATURE COEFFICIENT OF MANGANIN GAUGE

Using the developed system shown in figure 1, the resistance change of commercially available Manganin gauges by temperature is evaluated. Manganin gauges are put in the high-pressure vessel which is installed in the temperature-controlled bath. The temperature of the bath can be changed from 0 °C to 40 °C with a temperature distribution of less than 0.1 °C. The pressure generating system using the multiplier and the pressure balance is operated at the room temperature of around 23 °C.

First the temperature of the bath is set to t °C. After setting the temperature, appropriate acclimatization time is taken before starting measurement. The resistance of a Manganin gauge at t °C as a function of pressure, $R_t(p)$, is obtained by repeating the increasing and decreasing pressure calibration sequences more than three times. Then, the resistances of the Manganin gauge at $(t-\Delta t)$ °C and $(t+\Delta t)$ °C as a function of pressure, $R_{t-\Delta t}(p)$ and $R_{t+\Delta t}(p)$, are also obtained in the same manner, respectively.

From the measurement results obtained at three different bath temperatures, The temperature coefficient of the Manganin gauge at t °C as a function of pressure, $\beta_t(p)$, is calculated using the following equation,

$$\beta_t(p) = \frac{R_{t+\Delta t}(p) - R_{t-\Delta t}(p)}{2\Delta t \cdot R_t(p)} \quad (4)$$

Figure 5 shows the evaluated temperature coefficients of two Manganin gauges as a function of pressure in the pressure range 50 MPa to 1000 MPa. Here, the temperature of the bath was varied from 20 °C to 26 °C, that is, $t = 23$ °C and $\Delta t = 3$ °C. In this example, the temperature coefficients are almost constant in the pressure range above 300 MPa within the repeatability. The averaged temperature coefficients of the two Manganin gauges in the pressure range from 300 MPa to 1000 MPa are 0.031 %K⁻¹ and 0.032 %K⁻¹, respectively. Those values give close agreement with the reported value (0.04 %K⁻¹) in [10].

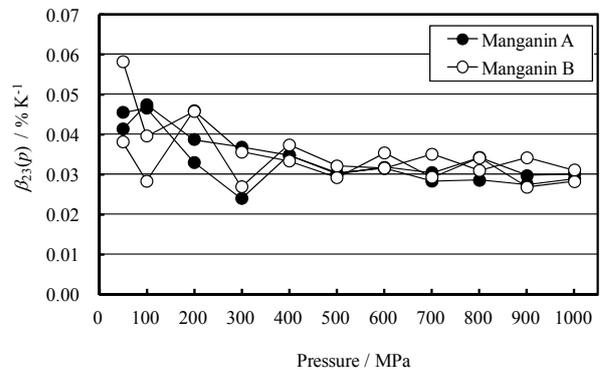


Figure 5 Example of evaluated temperature coefficients of Manganin gauges.

5. CONCLUSIONS

The pressure generating system up to 1 GPa has been developed as the pressure standard using a pressure balance and a precise pressure multiplier at NMIJ/AIST. Using the pressure generating system, several commercially available pressure gauges including strain-gauge transducers and Manganin gauges are calibrated in the pressure range 50 MPa to 1000 MPa in gauge mode. The calibration and characterization methods and results are presented in this paper.

From the calibration results, the characteristics of pressure gauges, repeatability and hysteresis, are evaluated. The hysteresis of the strain-gauge transducers is from 0.24 %FS to 1.6 %FS. The hysteresis of the Manganin gauges is much smaller than that of the strain-gauge transducers and less than 0.1 %FS. One strain-gauge transducer shows sufficiently good repeatability better than 0.01 %FS. The temperature coefficients of the Manganin gauges are also evaluated. From the results obtained, it has been confirmed that accurate calibration and characterization are conducted using the pressure generating system and the method developed.

5. REFERENCES

- [1] T. Kobata, J. W. Schmidt, D. A. Olson, "Characterization of a Controlled-Clearance Piston Gauge using the Heydemann-Welch model," *Trans. of the Society of Instrument and Control Engineers*, vol. 39, pp. 349-356, 2003.
- [2] H. Kajikawa, K. Ide, T. Kobata, "Methods of precisely estimating the jacket pressure coefficient of controlled-clearance piston-cylinders at pressures up to 1GPa," *Metrologia*, vol. 48, no. 5, pp. 352-358, 2011.
- [3] P. Delajoud, "The pressure multiplier," *BIPM Monographie*, vol. 89, no. 1, pp. 114-124, 1989.
- [4] T. Kobata and K. Ide, "Development of Pressure Standard up to 1 GPa using a Precise Pressure Multiplier," in *Proc. of SICE-ICASE, 2006. International Joint Conference*, pp. 3367 - 3371, Bexco, Busan, Korea, 2006.
- [5] OIML R 110 Pressure Balances, 1994.
- [6] W. Sabuga et al, "Final Report on Key Comparison CCM.P-K7 in the range 10 MPa to 100 MPa of hydraulic gauge pressure," *Metrologia*, vol. 42, Technical Supplement, 07005, 2005.
- [7] T. Kobata et al, "Final Report on Key Comparison APMP.M.P-K7 in hydraulic gauge pressure from 10 MPa to 100 MPa," *Metrologia*, vol. 42, Technical Supplement, 07006, 2005.
- [8] ISO/IEC Guide 98-3, Guide to the Expression of Uncertainty in Measurement (GUM), 2008.
- [9] W. Sabuga et al, "Finite element method used for calculation of the distortion coefficient and associated uncertainty of a PTB 1GPa pressure balance—EUROMET project 463," *Metrologia*, vol. 43, no. 3, pp. 311-325, 2006.
- [10] S. Yamamoto, "Manganin Resistance Manometer II, Seasoning," *Bulletin of the N.R.L.M.*, series number 25, pp. 1-6, 1972.