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DEVELOPMENT OF HIGH GAS PRESSURE CALIBRATION SYSTEM FOR PRESSURE TRANSDUCER

Hideaki Iizumi [1], Hiroaki Kajikawa [1], Tokihiko Kobata [1], Kenichi Fujii [1]
[1] National Metrology Institute of Japan, AIST, Tsukuba, Japan, h.iizumi@aist.go.jp

Abstract – The National Metrology Institute of Japan, AIST (NMIJ/AIST) has developed the high gas pressure standard for pressures up to 100 MPa for more reliable pressure measurements. A high gas pressure calibration system using a liquid-lubricated pressure balance has been developed. The effective area of the piston-cylinder assembly is determined from the comparison against hydraulic pressure balances. Calibration results of a pressure transducer are compared with those using the hydraulic pressure standard.

Keywords: pressure standard, high gas pressure, liquid-lubricated pressure balance, calibration system

1. INTRODUCTION

The National Metrology Institute of Japan, AIST (NMIJ/AIST) has set and maintained the national pressure standards. The pressure standards have been disseminated to the industry and the user through the NMIJ/AIST pressure calibration service.

Recently, fuel cell vehicles and hydrogen stations have been extensively developed for the realization of a hydrogen society. Fuel cell vehicles have been introduced into the market in 2015. Hydrogen gas of more than 70 MPa is used in fuel cell vehicles and hydrogen stations. NMIJ/AIST has developed the high gas pressure standard for pressures up to 100 MPa. The purpose of the development is to establish a high gas pressure standard up to 100 MPa, and to start a high gas pressure calibration service for ensuring the reliability of high gas pressure measurement.

In this article, a high gas pressure calibration system is explained. Next the effective area evaluation of the piston-cylinder assembly for the liquid-lubricated gas pressure balance, which is used as a standard in the calibration system, is presented. Then, the generated pressure is evaluated with the uncertainty. Finally, an example of calibration results of a pressure transducer by developed calibration system is shown.

2. HIGH GAS PRESSURE CALIBRATION SYSTEM

Fig. 1 is the schematic drawing of high gas pressure calibration system. The calibration system is mainly composed of a liquid-lubricated gas pressure balance, an automatic weight handler, a gas pressure controller, and a gas booster. The gas booster is used in order to pressurize the gas from a gas bottle up to about 100 MPa. In this system, the outlet pressure of the gas booster is measured with a pressure transducer. When the gas is pressurized beyond the target pressure, the further pressurization drive of the gas booster is stopped. The gas pressurized by the gas booster is supplied to the pressure controller. The pressure controller is used to adjust the gas pressure accurately and to supply sufficiently stable pressure to the pressure balance and the device under calibration. The pressure generated by the liquid-lubricated gas pressure balance was applied to the device to be calibrated. The calibration is conducted by comparing the applied pressure with the output value of the device under calibration.

An automatic weight handler is used to load/unload weights onto the pressure balance. The set of weights used consists of a 4 kg weight, a 5 kg weight and nine 10 kg weights. The total mass that includes a piston and a bell weight is about 100 kg. All the equipment in the system can be operated from the computer. All the measured data are acquired by the computer. The pressure calibration can be performed automatically by the developed program.

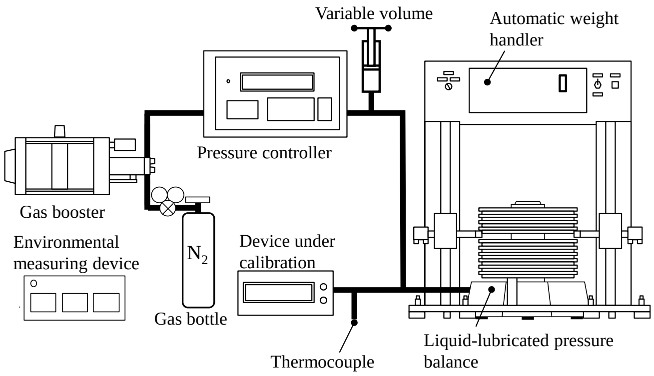

Fig. 1. Schematic drawing of high gas pressure calibration system.

2.1. Liquid-lubricated pressure balance

A liquid-lubricated gas pressure balance [1] is used as the high gas pressure standard device. Fig. 2 is the sectioned drawing of the piston-cylinder and the peripheral housing of the liquid-lubricated pressure balance. This pressure balance is featured in that the reservoir is located outside the cylinder. The reservoir is connected to the piston-cylinder gap, through two holes bored in the cylinder. As shown in the figure, the pressure generated at the piston bottom is applied also to the upper portion of the liquid reservoir. The hydraulic pressure applied to the piston-cylinder gap is the sum of the pressure generated at the piston bottom and the pressure due to liquid column height in the reservoir. At the bottom of the piston-cylinder gap, this pressure is always larger than the original pressure applied to the gap. Then, the piston-cylinder gap will be filled with liquid.

When the pressure medium below the piston bottom is liquid, this pressure balance can also generate hydraulic pressure. Its effective area is theoretically the same as the liquid medium [2]. Then, the effective area of the liquid-lubricated piston cylinder assembly is determined from the comparison against the hydraulic pressure balances. In the experiments, dioctyl sebacate was used as the liquid in piston-cylinder assembly of the liquid-lubricated pressure balance.

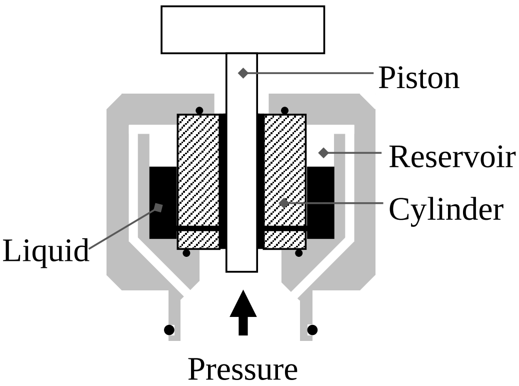

Fig. 2. Piston-cylinder assembly of liquid-lubricated pressure balance.

2.2. Temperature change by adiabatic compression and expansion

Gas temperature rises when the gas is adiabatically compressed, and drops when the gas is expanded. When the adiabatic process occurs during a calibration, the temperature change of the pressure medium might affect the calibration results. In this study, sheathed thermocouple of 0.5 mm diameter was inserted into the piping and valves. Then, the temperature change was monitored during a stepwise calibration cycle, in which the pressure is increased from 0 MPa to 100 MPa in steps of 10 MPa, and then decreased from 100 MPa to 0 MPa insteps of 10 MPa. Abrupt temperature changes are observed when the pressure is changed from one measurement point to next. For example, the gas temperature rises by 2.3 °C when the pressure starts to change from 0 MPa to 10 MPa. The temperature rapidly decreases and returns to the initial value when the pressure reaches 10 MPa. Since the temperature is stable and equilibrated with a room temperature at the time of data acquisition, the temperature change in pressure piping during pressure change does not affect the calibration results.

3. EVALUATION OF PRESSURE GENERATED

3.1. Calculation of pressure

The main constituent elements of a pressure balance are a piston-cylinder and weights. If a pressure is applied to float the piston with the weights up to an appropriate position, then the generated pressure p is given by (1).

$$p = \frac{Mg\left(1 - \frac{\rho_\mathrm{a}}{\rho_\mathrm{w}}\right) + \gamma C}{A(0, t_\mathrm{r})(1 + \lambda p)[1 + \alpha(t - t_\mathrm{r})]} + (\rho_\mathrm{f} - \rho_\mathrm{a})gH \qquad (1)$$

where, M is the total mass of weights and the piston. ρ_w is the average density of the piston and weights, and ρ_a is air density. g is gravity acceleration at the location where a measurement was made. γ is the surface tension of the medium. C is the circumference of piston. $A(0, t_\mathrm{r})$ is the effective area at the reference temperature t_r under atmospheric pressure. λ is the pressure distortion coefficient. α is the sum of thermal expansion coefficient of the piston and the cylinder. t is the temperature. $(\rho_\mathrm{f} - \rho_\mathrm{a})gH$ is the pressure corrected by head difference. ρ_f is the density of medium used. H is the height difference between the measurement position and the reference level of pressure balance. When the measurement position is relatively lower, H is positive.

3.2. Effective area of piston-cylinder assembly

The effective area of a liquid-lubricated piston-cylinder assembly was precisely evaluated as a function of the pressure from the comparison against the hydraulic pressure balance of the same pressure range. The cross-float measurements were performed by the comparator method which uses a precise pressure transducer and two constant volume valves. The detail of the comparator method was reported [3].

Fig. 3 shows the measured results of the effective areas of the piston-cylinder assemblies used for the liquid-lubricated pressure balance as a function of pressure. The vertical axis shows the effective area at reference temperature of 23 °C. The effective area is average value of six data which is obtained by repeating ascending and descending pressure measurements 3 times. The standard deviation of six data is less than $2{\times}10^{-6}$ relatively and is sufficiently small. The effective area decreases almost constantly with pressure, and can be approximated by the linear function. The pressure distortion coefficient is $-2.3{\times}10^{-6}$ MPa^{-1}.

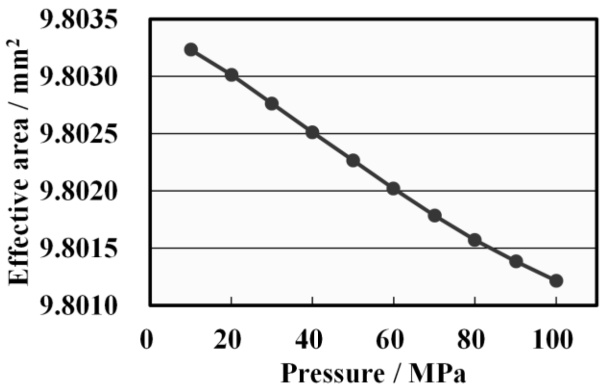

Fig. 3. Effective area of piston-cylinder assembly for liquid-lubricated pressure balance. Nominal effective area: 9.8 mm^2, Maximum pressure: 100 MPa.

3.3. Uncertainty evaluation

The uncertainty of the generated pressure can be estimated by considering all parameters in the right side of (1) as uncertainty components. Here, the uncertainty is evaluated in the case of $t = t_r$, $H = 0$. Table 1 shows an example of uncertainty evaluation of pressure generated at 100 MPa when the liquid-lubricated piston-cylinder assembly with nominal effective area 9.8 mm^2 is used. It lists the standard uncertainties of major parameters. Here, the uncertainty component whose effect to the generated pressure is relatively less than 1×10^{-6} is disregarded. The uncertainties of $A(0, t_r)$ and λ are evaluated from the results obtained by the cross-float measurements described in section 3.2. Relative expanded (k=2) uncertainty of the generated pressure is roughly estimated to 3.6×10^{-5} at 100 MPa.

Table 1. Uncertainties of major parameters at 100 MPa.

Uncertainty factor	Value	Standard uncertainty	Relative standard uncertainty /10^{-6}
$A(0, t_r)$	9.8 x 10^{-6} m^2	1.31 x 10^{-10} m^2	13.4
λ	-2.3 x 10^{-6} MPa^{-1}	1.1 x 10^{-7} MPa^{-1}	10.9
t	23 °C	0.2 °C	1.8
M	100 kg	250 mg	2.5
Total		1.76 kPa	17.6

4. CALIBRATION

4.1. Calibration of pressure transducer using developed system

The calibration of a pressure transducer can be performed automatically using the developed calibration system. Fig. 4 shows an example of the calibration result of a quartz bourdon-type pressure transducer. For this measurement, we used high purity (more than 99.9999 %) nitrogen as the gas medium. The target pressure was varied from 10 MPa to 100 MPa and then from 100 MPa to 10 MPa in steps of 10 MPa. At each measurement pressure, the pressure generated by the liquid-lubricated gas pressure balance was applied to the device to be calibrated. After waiting for 7 minutes, the output value of the device under calibration was sampled 18 times at 10 seconds interval. Above 30 MPa, the relative standard deviation of 18 outputs at each measurement pressure is less than 2×10^{-6}. This calibration system is able to generate sufficiently stable pressure.

In the figure, the average values obtained from three cycles are plotted separately for ascending and descending pressure. The vertical axis shows the deviation of the indication of the pressure transducer from the pressure applied by the liquid-lubricated gas pressure balance. The result after offset correction is shown. The standard deviation of three data which are obtained by three cycles at each measurement pressure is less than 0.4 kPa, relatively 4×10^{-6} of the maximum pressure.

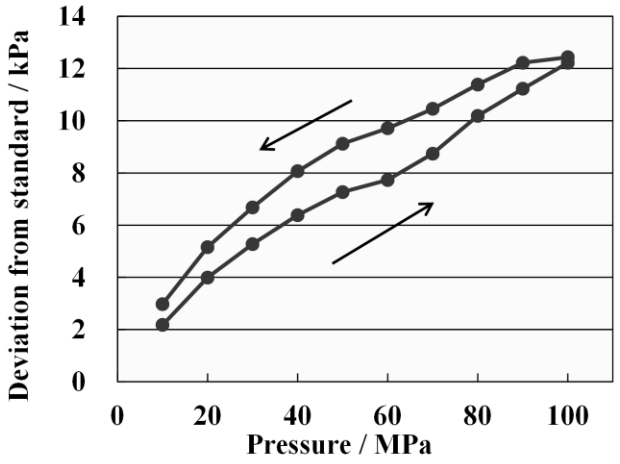

Fig. 4. Example of calibration result of pressure transducer obtained using high gas pressure calibration system.

4.2. Comparison of calibration result with hydraulic pressure standard

The pressure transducer which was calibrated in section 4.1 was also calibrated using hydraulic pressure standard. For hydraulic pressure calibration, we used dioctyl sebacate as the hydraulic medium. Fig. 5 shows difference between the two calibration results from the gas pressure standard and from the hydraulic pressure standard. The difference at each target pressure is less than 0.5 kPa, relatively 5×10^{-6} of the maximum pressure. In the low pressure, there is a difference between the result of increasing process and the result of decreasing process. The cause of this hysteresis may be related to the dissolution of the gas in the liquid inside the liquid-lubricated piston-cylinder assembly.

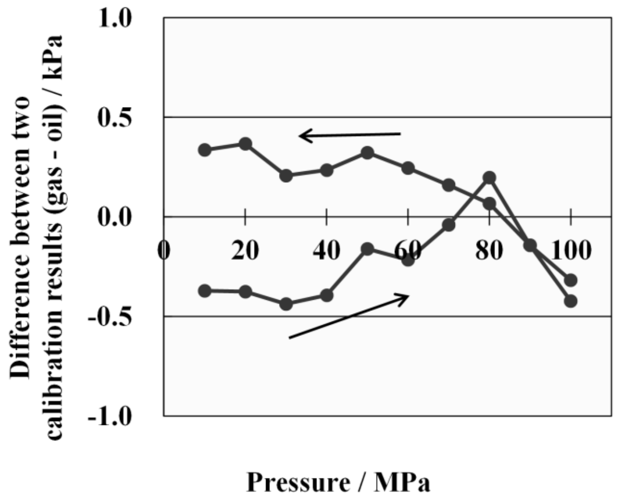

Fig. 5. The difference between the two calibration results of a pressure transducer from the gas pressure standard and from the hydraulic pressure standard.

5. SUMMARY

NMIJ/AIST has developed the high gas pressure standard for pressure up to 100 MPa and the calibration system for pressure transducers. The calibration system uses the liquid-lubricated gas pressure balance as standard. The effective area of the piston-cylinder assembly for the liquid-lubricated pressure balance was determined beforehand from the comparison against the hydraulic pressure balance.

Example of calibration result of a quartz bourdon-type pressure transducer by developed high gas pressure calibration system was shown. The pressure transducer was also calibrated using hydraulic pressure standard. The difference between the two calibration result from the gas pressure standard and from the hydraulic pressure standard was less than 0.5 kPa, relatively 5×10^{-6} of the maximum pressure.

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REFERENCES

[1] P. Delajoud and M. Girard, "A New Piston Gauge to Improve the Definition of High Gas Pressure and to Facilitate the Gas to Oil Transition in a Pressure Calibration Chain", Proc. of International Symposium on Pressure and Vacuum IMEKO TC16, pp. 154-159, Beijing, China, Sept. 2003.

[2] T. Kobata, "Improved methods for comparing gas and hydraulic pressure balances", Metrologia, Vol. 46, No. 5, pp. 591-598, 2009

[3] T. Kobata and D. A. Olson, "Accurate determination of differential pressure between two pressure balances using a pressure transducer", Metrologia, Vol. 42, No. 6, pp. S231-S234, 2005.