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CALIBRATION OF CAPACITANCE DIAPHRAGM GAUGE WITH 1333 PA FULL SCALE BY DIRECT COMPARISON TO RESONANT SILICON GAUGE AND STATIC EXPANSION SYSTEM

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Abstract: Two capacitance diaphragm gauges (CDGs) with 1333 Pa full scale were calibrated by three different methods; direct comparison to a resonant silicon gauge calibrated by a pressure balance, direct comparison to a CDG with 133 Pa full scale calibrated by a static expansion method, and the static expansion method. The calibration results by the three calibration results show in good agreement within their claimed uncertainties. It is demonstrated that calibrated pressure points by the pressure balance and the static expansion system are linearly interpolated by considering the calibration uncertainty of the CDGs appropriately.

Keywords: pressure, vacuum, standard, calibration, capacitance diaphragm gauge, thermal transpiration effect

1. INTRODUCTION

Since pressure/vacuum gauges are calibrated at plural pressure points, interpolating between their points is necessary for practical pressure measurements. In the case that the pressure points are calibrated by single standard technique with good linearity, the interpolation generally has high reliability. At the pressure lower than 10^3 Pa, however, the interpolation between pressure points owing to two different standard techniques is often required. In such a case, the validity of the interpolation should be confirmed. A capacitance diaphragm gauge with 1333 Pa full scale (CDG-10Torr) is used for the precise pressure measurement in the range from 1 Pa to 10^3 Pa. There are at least four candidates for standard technique; pressure balance, static expansion system (SES) [1-5], force-balanced piston gauge [6,7], and oil manometer [5,8,9] to calibrate CDG-10Torr.

In this paper, the calibration results of CDG-10Torr based on two different standards are presented. One is the direct comparison to the resonant silicon gauge (RSG), which is calibrated by the pressure balance. RSG is used as a reliable transfer gauge in the field of the pressure and vacuum standard [10,11]. The other is the static expansion system [4]. These calibration results are compared. The validity of the interpolation is discussed.

2. EXPERIMENTAL

2.1 Apparatus

Figure 1 shows the schematic diagram of the static expansion system (SES) and the direct comparison system (DCS) for the calibration of vacuum gauges. These two systems are connected each other through all metal valves. Two resonant silicon gauges with 130 kPa full scale (absolute) are located as reference gauges on SES (RSG_{SE}) and DCS (RSG_{DC}). A capacitance diaphragm gauge with 133 Pa full scale (CDG-1Torr) is located between SES and DCS, and used as a reference gauge for DCS. Two capacitance diaphragm gauges with 1333 Pa full scale were used as test gauges. A high accuracy absolute type capacitance diaphragm gauge with a heated sensor head at

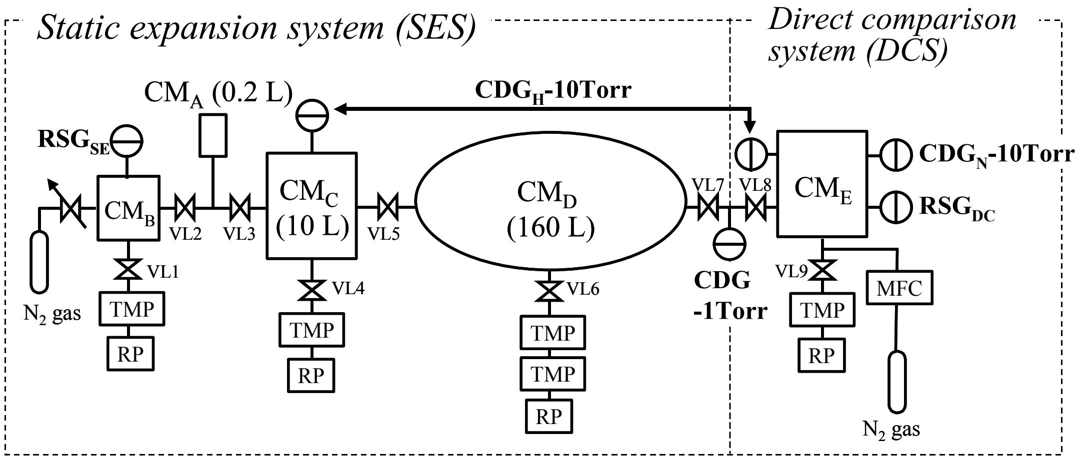

Fig.1 Schematic diagram of the static expansion system (SES) and the direct comparison system (DCS) for the calibration of vacuum gauges.

the temperature of 45 °C (CDG_H-10Torr) was tested at both SES and DCS. Another capacitance diaphragm gauge with unheated sensor head (CDG_N-10Torr) was tested at DCS only. Pumping systems are consisted of turbo molecular pumps (TMP) and rotary pump (RP). N_2 gas was used as a test gas in this study.

The calibration procedure of SES is briefly summarized. The gas in the initial chamber CM_A was expanded to the chamber CM_C or both the chambers CM_C and CM_D depending on the calibration pressure range. To avoid changing in the volume and the temperature, a reference gauge to measure the initial pressure before expansion is not located on the CM_A. The initial pressure was measured by RSG_{SE} located on the chamber CM_B by closing the both valves of VL1 and VL3 and opening the valve of VL2. After the initial pressure measurement, the static expansion was performed by closing VL2, VL4, VL6, and VL8 and opening VL3 only and/or VL3, VL5 and VL7. The calibration pressure ranges are from 1 Pa to 2000 Pa and from 10^{-4} Pa to 150 Pa at CM_C and CM_D, respectively. Details of the SES are shown in Ref [4].

DCS was constructed based on the ISO 3567 Vacuum gauges – Calibration by direct comparison with a reference gauge [12]. Two reference gauges are located in DCS. One is the resonant silicon gauge with 130 kPa full scale absolute (RSG_{DC}). The other is the high accuracy absolute type capacitance diaphragm gauge with 133 Pa full scale with a heated sensor head at the temperature of 45 °C scale (CDG-1Torr). CDG-1Torr is used as a reference gauge without detaching the sensor head from the chamber by controlling VL7 and VL8. The pumping system is consisted of a turbo molecular pump (200 L/s for N_2) and a rotary pump. A static method is adopted for direct comparison. The valve on TMP (VL9) was closed after the background pressure reaches lower than 10^{-4} Pa, which is measured by an ionization gauge. The zero points of CDGs and RSG_{DC} were measured every time before each calibration. The test gas was introduced to CM_E by a computer-controlled mass flow controller (MFC) with a full scale of 10 sccm until the pressure in CM_E reached to the target pressure. The test gauge was calibrated by comparing to the reference gauges while the test pressure is kept constant for 300 s.

2.2 Traceability chain in this study

The traceability chain of the pressure in this study is summarized in Fig.2. RSG_{SE} and RSG_{DC} were calibrated by the pressure balance from 5.0×10^3 Pa to 1.3×10^5 Pa. RSG_{DC} was sometimes calibrated by direct comparison to RSG_{SE} to check the long-term stability. CDG-1Torr was calibrated by the SES at the chamber CM_D from 0.1 Pa to 130 Pa. In the SES, both the expansion ratio and the initial pressure at the chamber CM_A, which are important parameters to determine the standard pressure, are measured by RSG_{SE}.

CDG_H-10Torr with a heated sensor head was calibrated by three methods; (1) direct comparison to RSG_{DC} from 100 Pa to 1300 Pa, (2) direct comparison to CDG-1Torr from 1 Pa to 130 Pa, and (3) static expansion method at the chamber CM_C from 1 Pa to 1300 Pa. CDG_N-10Torr with an unheated sensor head was calibrated by using two methods (1) and (2). The direct comparison to RSG_{DC} was performed by extrapolating the calibration results obtained from 5.0×10^3 Pa to 1.3×10^5 Pa. The procedure of the extrapolation is shown in section 3.1.

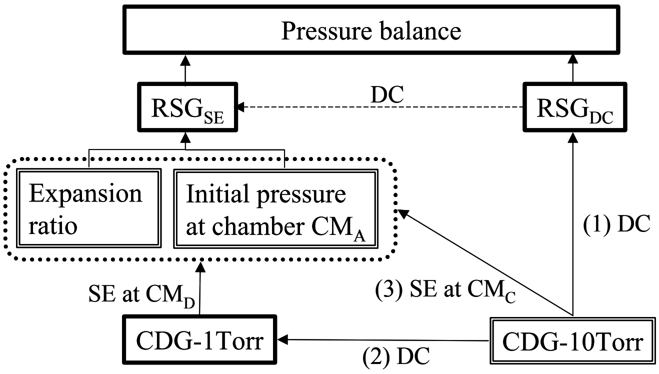

Fig.2 Traceability chain of the pressure in this study. SE and DC are static expansion and direct comparison, respectively. Two capacitance diaphragm gauges with 1333 Pa full scale (CDG-10Torr) were calibrated by three methods (1) DC to RSG_{DC}, (2)DC to CDG-1Torr, and (3)SE at CMc.

3. RESULTS

3.1 Calibration results of the reference resonant silicon gauges (RSG)

Calibration results of reference RSG_{DC} and RSG_{SE} by the pressure balance are shown in Fig.3. The vertical axis is the deviation of the calibrated standard pressure (p_S) from the pressure indication (p_I) of RSGs. The sensitivity coefficient S for RSGs is defined as equation (1) in the pressure range down to 100 Pa,

$$S = (p_I - p_{I0}) / p_S = \Delta p_I / p_S, \tag{1}$$

where p_{I0} is the pressure indication at background pressure, in other words, at zero point, and Δp_I is the difference of p_{I0} from p_I. The $S(RSG_{DC})$ is plotted in Fig. 4 with a logarithmic scale of the horizontal axis. The $S(RSG_{DC})$ has a constant value of 0.999987 ± 0.000027. The standard pressure ($p_{RSG\text{-}DC}$) in DCS from 100 Pa to 1300 Pa is determined by equation (2),

$$p_{RSG\text{-}DC} = \Delta p_I / S\,(RSG_{DC}). \tag{2}$$

The calibration uncertainty $U(p_{RSG\text{-}DC})$ with a confidence level of 95 % (k=2) is estimated by equation (3),

$$U(p_{RSG\text{-}DC})\ [\mathrm{Pa}] = -1.3\times10^{-11}\,\Delta p_I^2 + 5.0\times10^{-6}\,\Delta p_I + 3.0, \tag{3}$$

which is the best fitting curve between Δp_I of RSG_{DC} and its expanded uncertainty. That means the relative expanded uncertainty of $p_{RSG\text{-}DC}$ from 100 Pa to 1300 Pa is in the range from 3.0 % to 0.23 %.

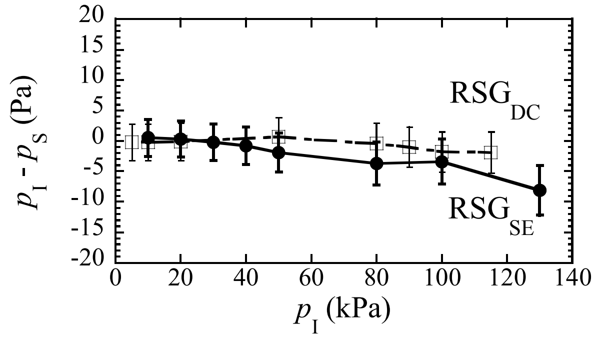

Fig.3 Calibration results of RSG_{SE} and RSG_{DC}

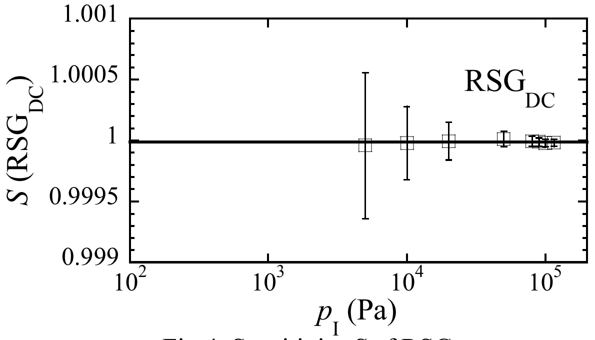

Fig.4 Sensitivity S of RSG_{DC}

3.2 Calibration result of the reference capacitance diaphragm gauge with 133 Pa full scale (CDG-1Torr)

A calibration result of reference CDG-1Torr by SES is shown in Fig.5 (a). The vertical axis is the S of CDG-1Torr, which is similarly calculated by eq. (1). The S(CDG-1Torr) increases with decreasing the pressure by the thermal transpiration effect because CDG-1Torr has a heated sensor head at the temperature of 45 °C [10,13-15]. Fig.5 (b) shows the compensated S(CDG-1Torr) by Takaishi-Sensui (T-S) equation [15,16]. The S(CDG-1Torr) after the compensation by T-S equation has a constant value of 1.0081 ± 0.0014. The relative expanded uncertainty of the calibration from 0.1 Pa to 130 Pa is in the range from 2.8 % to 0.33 % [4].

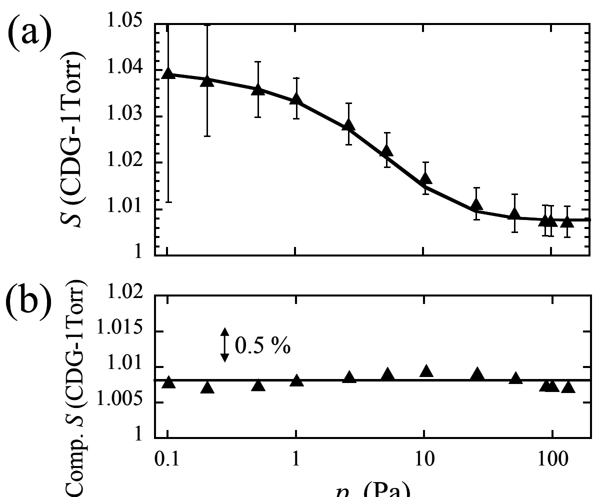

Fig.5 Sensitivity of CDG-1Torr before (a) and after (b) compensation of thermal transpiration effect by Takaishi-Sensui equation.

3.3 Calibration result of two capacitance diaphragm gauges with 1333 Pa full scale (CDG-10Torr)

CDG_H-10Torr was calibrated by three methods; (1) direct comparison to RSG_{DC} from 100 Pa to 1300 Pa, (2) direct comparison to CDG-1Torr from 1 Pa to 130 Pa, and (3) static expansion method from 1 Pa to 1300 Pa. Table 1 shows the uncertainty budget of (1) and (2). The calibration uncertainty of (3) is in the range from 1.0 % to 0.26 % [4]. As is shown in Fig. 6 (a), three calibration results for CDG_H-10Torr show in good agreements within their required uncertainties. The sensitivity of CDG_H-10Torr, S(CDG_H-10Torr), also increases with decreasing of the pressure by the thermal transpiration effect. The S(CDG_H-10Torr) after the compensation of T-S equation also has a liner characteristic within ± 0.2 % as shown in Fig.6 (b).

CDG_N-10Torr with unheated sensor head was calibrated by two methods (1) and (2). The calibration results and the uncertainty budget are shown in Fig. 7 and Table 2, respectively. No compensation for the S(CDG_N-10Torr) by T-S equation was needed because thermal transpiration effect was negligible in this gauge.

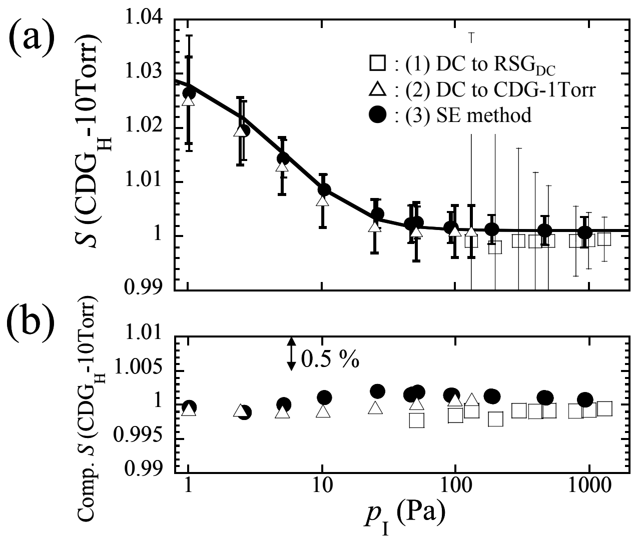

Fig.6 Sensitivity of CDG_H-10Torr with a heated sensor head at 45 °C before (a) and after (b) compensation of thermal transpiration effect by Takaishi-Sensui equation [15,16].

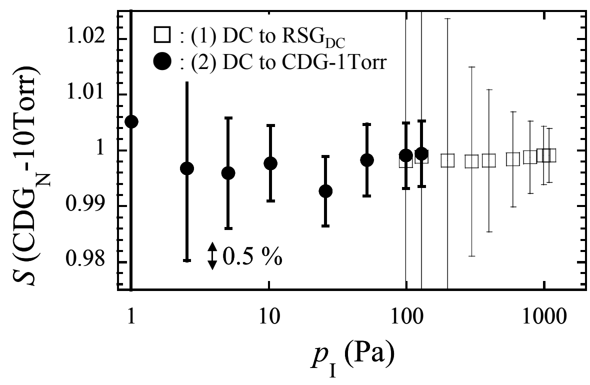

Fig.7 Sensitivity of CDG_N-10Torr with an unheated sensor head.

Table 1 The uncertainty budget of the calibration results of CDG_H-10Torr by the direct comparison. RSG_{DC} and CDG-1Torr is used as a reference gauge depending on the pressure range.

Reference gauge			(1) RSG_{DC}	(2) CDG-1 Torr
Pressure range (Pa)			100 - 1300	1 - 130
Relative standard uncertainty with $k = 1$	Reference gauge	Calibration uncertainty	1.5 % – 0.12 % (3.0 Pa / 2)	0.22 % – 0.16 %
		Fluctuation of p_I	0.11 % – 0.01 %	< 0.03 %
		Resolution	0.29 % – 0.02 % (1 Pa / $2\sqrt{3}$)	< 0.02 % (6.7×10^{-4} Pa / $2\sqrt{3}$)
		Temperature	1.3 % – 0.10 % (1.3 Pa)	-
		Attitude	1.5 % – 0.12 % (1.5 Pa)	-
		Compensation of thermal transpiration effect [15]	-	0.2 % / $\sqrt{3}$
		Long-term stability	0.006 % / $2\sqrt{3}$	0.2 % / $\sqrt{3}$
	CDG_H-10Torr	Fluctuation of p_I	< 0.03 %	0.11 % -0.02 %
		Resolution (6.7×10^{-3} Pa / $2\sqrt{3}$)	< 0.002 %	< 0.19 %
	Calibration system	Pressure distribution	0.1 %/ $\sqrt{3}$	0.3 %/ $\sqrt{3}$
		Height	< 0.01 %	
	Reputability		0.29 % – 0.01 %	0.10 % – 0.002 %
	Combined standard uncertainty		2.6 % – 0.24 %	0.40 % – 0.29 %
Relative expanded uncertainty with k=2			5.1 % – 0.48 %	0.80 % – 0.58 %

Table 2 The uncertainty budget of the calibration results of CDG_N-10Torr by the direct comparison. RSG_{DC} and CDG-1Torr is used as a reference gauge depending on the pressure range.

Reference gauge			(1) RSG_{DC}	(2) CDG-1 Torr
Pressure range (Pa)			100 - 1300	1 - 130
Relative standard uncertainty with $k = 1$	Reference gauge	Calibration uncertainty	1.5 % – 0.12 % (3.0 Pa / 2)	0.22 % – 0.16 %
		Fluctuation of p_I	0.11 % – 0.01 %	< 0.03 %
		Resolution	0.29 % – 0.02 % (1 Pa / $2\sqrt{3}$)	< 0.02 % (6.7×10^{-4} Pa / $2\sqrt{3}$)
		Temperature	1.3 % – 0.10 % (1.3 Pa)	-
		Attitude	1.5 % – 0.12 % (1.5 Pa)	-
		Compensation of thermal transpiration effect [15]	-	0.2 % / $\sqrt{3}$
		Long-term stability	0.006 % / $2\sqrt{3}$	0.2 % / $\sqrt{3}$
	CDG_N-10Torr	Fluctuation of p_I	< 0.03 %	1.1 % – 0.03 %
		Resolution (3.9×10^{-2} Pa / $2\sqrt{3}$)	< 0.011%	< 1.1 %
	Calibration system	Pressure distribution	0.1 %/ $\sqrt{3}$	0.3 %/ $\sqrt{3}$
		Height	< 0.01 %	
	Reputability		0.26 % – 0.01 %	0.88 % – 0.01 %
	Combined standard uncertainty		2.6 % – 0.24 %	1.8 % – 0.29 %
Relative expanded uncertainty with k=2			5.1 % – 0.48 %	3.6 % – 0.58 %

The two results by methods (1) and (2) also show in good agreement within their claimed uncertainties, although the calibration uncertainty of CDG_N-10Torr was larger than that of CDG_H-10Torr due to larger repeatability, fluctuation of p_I, and its resolution. The S(CDG_N-10Torr) has a liner characteristic within ± 0.7 % without compensation for thermal transpiration.

4. DISCUSSION ON REFERENCE GAUGE FOR DIRECT COMPARISON

A calibration by direct comparison is widely used for many users. In the case that RSG with 130 kPa full scale (absolute) is used as a reference gauge, the lowest calibration pressure may be limited at several hundred Pa if the calibration uncertainty is desired to be within several %. CDGs with 133 Pa or 1333 Pa full scale are useful as a reference gauge under the pressure of 100 Pa. In that case, however, the thermal transpiration effect should be compensated if CDG with a heated sensor head is used. A wide calibration pressure range is realized by combining RSG and CDG as reference gauges and evaluating the uncertainty arising from the linearity of the sensitivity, the correction of thermal transpiration effect, the resolution, the influence of temperature, attitude, and so on.

5. CONCLUSION

Two capacitance diaphragm gauges with 1333 Pa full scale were calibrated by the following three methods; (1) direct comparison to a resonant silicon gauge with 130 kPa full scale absolute from 100 Pa to 1300 Pa, (2) direct comparison to a capacitance diaphragm gauge with 133 Pa full scale from 1 Pa to 130 Pa, and (3) static expansion method from 1 Pa to 1300 Pa. These results by three methods show in good agreement within their claimed uncertainties, which mean these calibration methods and the uncertainty analyses are validated. It is demonstrated that calibrated pressure points by the pressure balance and the static expansion system are linearly interpolated by measuring zero point certainly, compensating the thermal transpiration effect if heated sensor head is used, and considering the calibration uncertainty of CDG with 1333 Pa full scale appropriately.

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