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VOLUME CHANGE MEASUREMENT OF DIAPHRAGM DEFORMATION IN DIFFERENTIAL TYPE CAPACITANCE DIAPHRAGM GAUGE

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Abstract: A deformation of a diaphragm inside a differential type capacitance diaphragm gauge is investigated as a function of the differential pressure applied to the gauge. Below its full scale of 133 Pa, the volume change of the gauge is proportional to the applied pressure as predicted by the elastic theory. The volume change rate of the gauge is calculated to be 0.00012 ml/Pa at a line pressure of atmosphere pressure of about 100 kPa. When the pressure is more than its full scale, the response of the diaphragm volume change is linear to the applied pressure until 500 Pa. The response is changed to one-third power of the applied differential pressure as predicted by the membrane theory above 500 Pa until 3000 Pa.

Keywords: Diaphragm gauge, diaphragm deformation, elastic theory, constant pressure flowmeter, stressed diaphragm

1. INTRODUCTION

Several types of diaphragm gauges (DGs) are widely used because of the independent sensitivity of the kind of gases and the high resolution reached to 10^{-3} Pa [1]. Diaphragm gauge consists of two rooms separated by a thin diaphragm. The deformation of the diaphragm $w_{\max}$ is proportional to the applied differential pressure P, as given by

$$w_{\max} = \frac{3a^4(1-\nu^2)}{16Eh^3}P, \qquad (1)$$

where a, h, ν, and E are a radius of the diaphragm, a thickness, the Poisson's ratio and the Young's modules, respectively. In case of capacitance diaphragm gauges (CDGs), the deformation is detected by the change of the capacitance between the diaphragm and an electrode inside the CDG.

The volume change of the deformed diaphragm δV_{DIA} is obtained by the integral of Eq. (1) and given by,

$$\delta V_{\mathrm{DIA}} = \frac{\pi a^6(1-\nu^2)}{16Eh^3}P. \qquad (2)$$

The volume change is a factor of the uncertainty of exact volume required equipment, such as a constant volume type flow meter [2]. A diaphragm deformation as a function of the applied pressure should be analysed for precise flow rate measurements and its uncertainty analysis.

In this study, an amount of the diaphragm deformation in a differential type CDG was investigated at a line pressure of about 100 kPa. The sensitivity of the volume change against the applied differential pressure was derived. The volume change as a function of the applied differential pressure until 100 kPa, about 750 times as high as its full scale was also investigated.

2. EXPERIMENTAL SETUP

An experimental setup is shown in Fig. 1. Both ends of a differential type CDG (G_1, target gauge, FS: 133 Pa) were connected to chamber A and B, respectively. Those chambers were also connected via valve #1. Chamber A connected to Chamber C (inner volume: about 6×10^{-3} m^3) via a crimped metal capillary type leak artefact. The chamber C was evacuated by a turbo molecular pump and a diaphragm pump. The pressure in chamber C was set by introducing a gas from a gas cylinder. Chamber B was connected to chamber D via valve #3. Chamber D was connected to the pump and the gas cylinder via valve #4. The pressure in chamber B and C were measured by a

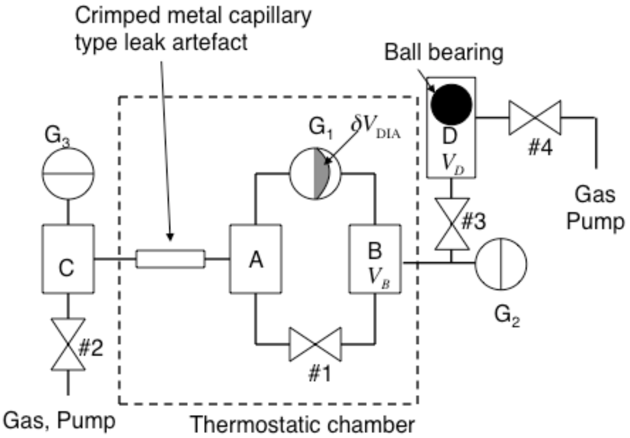

Figure 1: Schematic diagram of an experimental setup. A, B, C, and D: chambers. G_1: differential type capacitance diaphragm gauge (Target gauge, Full scale: 133 Pa), G_2: resonant silicon pressure gauge (FS: 130 kPa), G_3: pressure gauge (FS: 500 kPa), #1, #2, #3, #4: valves. V_B, V_D and δV_{DIA} are the volume of chamber B, D and volume change of the G_1 induced by the deformation of the diaphragm, respectively.

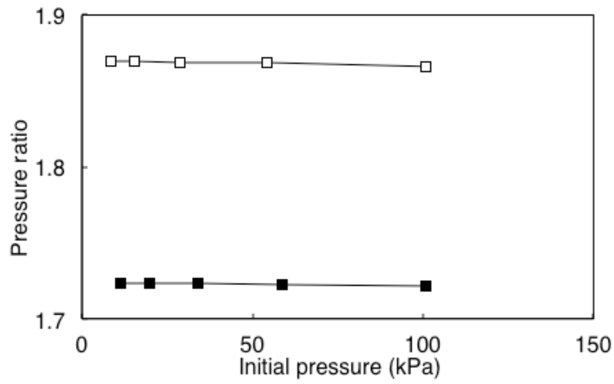

Figure 2: Pressure ratios between before and after the opening of a valve connecting chambers B and D as a function of the pressure in the chamber B. Open and closed squares represent the results obtained without and with 8 ball bearings in chamber D.

resonant silicon pressure gauge (G_2, FS: 130 kPa) and a digital pressure gauge (G_3, FS: 500 kPa), respectively. Chambers A and B, DG G_1, and the leak artefact were set in a thermostatic chamber. Eight ball bearings, whose diameter were 14.288 mm, were used to fill chamber D. Temperatures of the experimental setup were measured by four platinum thermal resistances with a digital multi meter. Nitrogen gas was used as a gas medium for experiments. Leak rate of the whole system was below 10^{-8} Pa m^3/s.

3. VOLUME MEASUREMENT

Prior to the volume change measurements of the diaphragm, a volume of chamber B including the inside volume of gauge G_1 and pipes were measured by the combination of the Boyles's law, as follows. (i) Pressures in chamber A, B, and D were equalized at about atmosphere pressure by the opening of valves #1 and #3. (ii) Valves #1 and #3 were closed and the pressure in chamber B was set at an initial pressure of P_1. Chamber D was evacuated by the pump. A typical pressure in chamber D was below 10^{-4} Pa after the 30 minutes evacuation. (iii)Valve #4 was closed, then valve #3 was opened. A relation based on the Boyle's law between before and after the opening of valve #3 was given by,

$$P_1 V_B = P_1'(V_B + V_D)\ , \tag{3}$$

where V_B, V_D and P_1' are the volumes of chambers B and D, and the pressure after the opening of the valve, respectively. (iv) Ball bearings were set in chamber D and then the process from (i) to (iii) was repeated. A relation between before and after the opening of valve #3 was given by,

$$P_2 V_B = P_2'(V_B + V_D - V_R), \tag{4}$$

where P_2, P_2', and V_R represent an initial pressure in chamber B and the pressure after connecting chambers B and D, and the sum of the volume of the ball bearings. From the Eqs. (3) and (4), the volume of chamber B, V_B, was

$$V_B = \frac{V_R}{\frac{P_1}{P_1'} - \frac{P_2}{P_2'}}\ . \tag{5}$$

Pressure ratios of P_1/P_1' and P_2/P_2' are plotted as a function of initial pressures P_1 and P_2 in Fig. 2, respectively. When the ball bearings were not in chamber D, tpressure ratio P_1/P_1' was 1.8661 at initial pressure P_1 of 100 kPa. When P_1 decreased from 60 kPa to 20 kPa, pressure ratio P_1/P_1' increased from 1.8686 to 1.8695. When the ball bearings were set in chamber D, pressure ratio P_2/P_2' was 1.7211 at P_2 of 100 kPa. Pressure ratio P_2/P_2' increased from 1.7228 to 1.7233 when P_2 decreased from 60 kPa to 20 kPa.

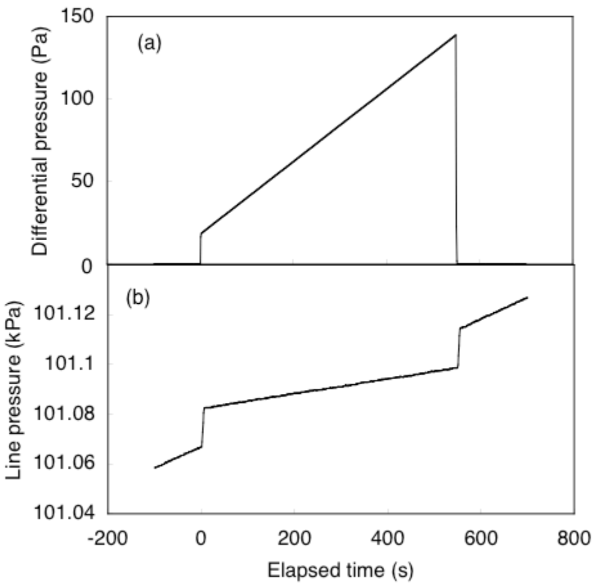

Figure 3: (a) Differential pressure applied to the target capacitance diaphragm gauge and (b) the pressure in chamber B as a function of the elapsed time.

The initial pressure was changed from 100 kPa to 20 kPa, while the pressure in chamber A was set always at 100 kPa. In process (iii), the pressure in chamber B was changed, for example from 100 kPa to 60 kPa, while the pressure in chamber A remained at 100 kPa because no operation was performed to the chamber. The applied differential pressure to G_1 increased from 0 kPa to 40 kPa during process (iii). The diaphragm in the gauge is deformed and the volume of the room of the gauge to chamber B side is reduced. The volume of chamber B is reduced in the process (iii). The applied differential pressure to G_1 increases with a decrease of the initial pressure. The volume of the deformed diaphragm of the gauge increases with the decrease. The volume of the room is reduced with the decrease. Thus, the pressure ratio depends on the initial pressure.

However, in the initial pressure ranging from 60 kPa to 20 kPa, the change of the pressure ratio was about 0.009, which is equivalent to the volume reduction of 0.03 ml. Therefore, in this study, the pressure ratios obtained below the initial pressure of 60 kPa are used for the estimation of the volume of chamber B.

The calculated volume V_R is 12.22 ml by adding the volume of the ball bearings. Volume of the chamber B was 83.63 ml by using Eq. (5).

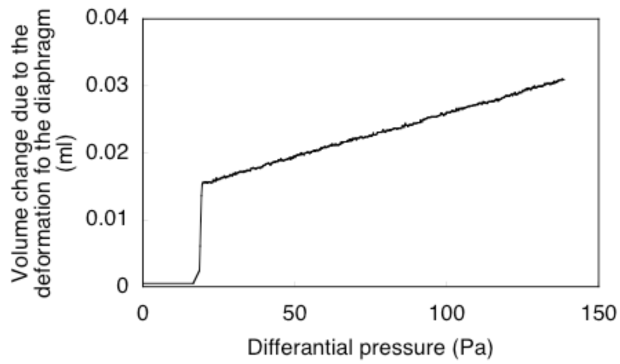

Figure 4: Calculated volume change of capacitance diaphragm gauge G_1 induced by the deformation of the diaphragm as a function of the applied differential pressure.

4. VOLUME CHANGE MEASUREMENT

A differential pressure between chambers A and B measured by G_1 and a pressure in chamber B by G_2 are plotted as a function of the elapsed time in Figs. 3(a) and (b), respectively. Both pressures were acquired at every 1 s. Valves #2, #3, and #4 were closed. At the elapsed time of 0 s, valve #1 was closed to separate chambers A and B.

Before the elapsed time of 0 s, valve #1 was opened and the pressures in chambers A and B were equalized at about 101 kPa (atmosphere pressure). The pressure in chamber C was set at 200 kPa. A gas was flown from chamber C to chambers A and B via the leak artefact by the applied pressure difference of 99 kPa. The differential pressure measured by G_1 was 0 Pa.

When valve #1 was closed, the indication of G_1 increased from 0 Pa to 14 Pa within 6 s due to the volume reduction inside valve #1. The differential pressure increased from 14 Pa to 138 Pa in the next 544 s, since the gas was flown from chamber C to chamber A. At the elapsed time of 550 s, valve #1 was opened to re-connect chambers A and B. Then, the differential pressure was returned to 0 Pa.

The pressure in chamber B increased by the rate of 0.085 Pa/s before closing valve #1, since the gas was flown via the leak artefact to chambers A and B. Just after closing valve #1, the pressure increased from 101.065kPa to 101.082 kPa within 6 seconds due to the volume reduction in valve #1. After the pressure rising, the pressure continuously increased from 101.082 kPa to 101.095 kPa with a pressure increasing rate of 0.030 Pa/s meanwhile no gas was

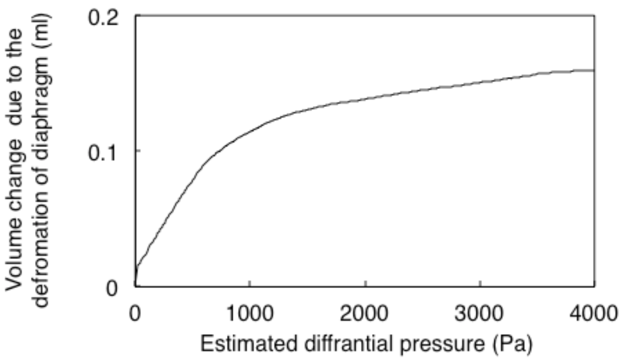

Figure 5: Calculated volume change of the diaphragm deformation as a fuction of the estimated differential pressure.

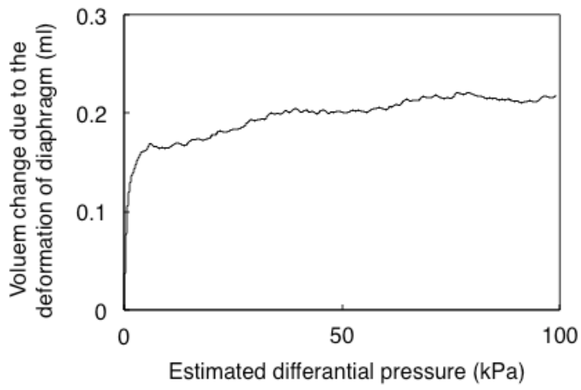

Figure 6: Same as Fig. 5.

introduced into chamber B. The pressure increased from 101.095 kPa to 101.115 kPa in a second, after the opening of valve #1 at the elapsed time of 550 s. This pressure increase is caused by the accumulated gas in chamber A during the close of valve #1. Once chambers A and B were re-connected by the open of valve #1, the pressure increasing rate was 0.030 Pa/s and was same value as before the elapsed time of 0 s.

The temperature stability of the whole system is one of the important factors for small pressure measurements at the atmosphere pressure in a closed chamber. In particular, the change of the temperature difference between chambers A and B will cause a quasi-differential pressure between those chambers. The temperature of chamber A and B were 22.990 ˚C and 23.020 ˚C, respectively. The changes of the temperature fluctuation at each point were about 1 mK, which was equivalent to fluctuation of 0.3 Pa at the pressure in chamber B of 100 kPa. The temperature inside the thermostatic chamber was at 23.025 ˚C.

The volume change of chamber B, δV, is given by,

$$\delta V = \delta V_{\mathrm{DIA}} + \delta V_{\mathrm{VAL}} \tag{6}$$

where δV_{VAL} represents the volume change caused by the volume reduction of the valve itself at the closing. According to the Boyle's law, a relation between before and after closing valve #1 is given by,

$$V_{\mathrm{B}} P_{\mathrm{i}} = (V_{\mathrm{B}} - \delta V) P_{\mathrm{f}} \ , \tag{7}$$

where P_{i} and P_{f} are the pressure in chamber B before and after the close of valve #1, respectively. The volume change δV was given by

$$\delta V = \left(1 - \frac{P_{\mathrm{i}}}{P_{\mathrm{f}}}\right) V_{\mathrm{B}}. \tag{8}$$

The volume change of chamber B derived from the results shown in Fig. 3(b) and Eq. (8) is plotted as a function of the differential pressure in Fig. 4. Below the differential pressure of 20 Pa, the plotted value was not reflected the exact volume change due to the transition of the valve #1 closing. When the differential pressure increased from 31.0 Pa to 130.6 Pa, the total volume change of the chamber B is varied from 0.017 ml to 0.020 ml. The volume change sensitivity of differential pressure type CDG G_1 was 0.00012 ml/Pa at the line pressure of 100 kPa.

A fluctuation of the volume was about 2.8 %, which is larger than the repeatability of 0.01 % shown on a catalogue of the diaphragm gauge tested here. Because the volume estimation is based on the small pressure measurements of 0.3 Pa at 100 kPa.

An intercept of the curve (0.013 ml) is a volume change at no differential pressure and is to be the volume change of valve δV_{VAL}.

5. OVER PRESSURE

In order to estimate the volume change of the diaphragm above the full scale of differential pressure gauge G_1 of 133 Pa, the gas was introduced from the chamber C to the chamber A over 2 days, while the valve #1 had been closed. The differential pressure above the full scale of G_1 was estimated by using the extrapolating the rising rate of the indicated differential pressure of G_1 against the elapsed time. The volume change estimation in G_1 was the same as described in Sec. 4. The pressure in chamber C was set at 300 kPa for this measurement. The volume change in G_1 as a function of the estimated differential pressure on G_1 is plotted in Figs. 5 and 6. The volume change was changed from 0 ml to 0.22 ml with an increase of the estimated differential pressure from 0 Pa to 100 kPa. In detail, the behavior of the volume change induced by the differential pressure was divided into seven regions.

(I: 0 Pa to 500 Pa) The volume change increased from 0 ml to 0.08 ml. In the region, the volume change was proportional to the estimated differential pressure.

(II: 500 Pa to 1400 Pa) The volume change increased from 0.08 ml to 0.13 ml. The slope of the volume change against the differential pressure was not constant.

(III: 1400 Pa to 3000 Pa) The volume change increased from 0.13 ml to 0.16 ml. The volume change was proportional to about one-third power of the estimated differential pressure.

(IV: 3 kPa to 30 kPa) The volume change increased from 0.16 ml to 0.20 ml. Above 3 kPa, the fluctuation of the volume change was larger than that below 3 kPa.

(V: 30 kPa to 55 kPa) The volume change was almost constant about 0.20 ml.

(VI: 55 kPa to 76 kPa) The volume change increased again from 0.20 ml to 0.22 ml.

(VII: 76 kPa to 100 kPa) The volume change was almost constant about 0.22 ml.

In this measurement, the differential pressure of 100 kPa, which was 750 times as high as its full scale, was applied to G_1 for 4 times. The repeatability of the volume change was below 2.8%, which was determined by the small pressure measurements at the atmosphere pressure of about 100 kPa.

The CDG tested here had a linear response to the pressure below 500 Pa, which is about four times as high as its specified full scale.

The deformation of a circular plate such as a diaphragm of a capacitance diaphragm gauge is proportional to the applied pressure in the elastic theory for the deformation is smaller than its thickness, while the deformation is proportional to the one-third power of the applied pressure in the membrane theory when the deformation is much larger than its thickness, like a balloon [3]. Above the differential pressure higher than 500 Pa, the diaphragm is still deformed as a function of the differential pressure. In the region III, the deformation of the diaphragm is obeyed on the membrane theory.

Above the differential pressure higher than 3 kPa (beyond region IV), the volume change is saturated at 0.20 or 0.22 ml. However, the volume change is not constant. Most CDG has a guard electrode serves as a protective overpressure stop, to prevent damage to the diaphragm [4]. At regions ranging from V to VII, the diaphragm seems to be partially touched to the guard electrode.

6. SUMMARY

The relation between the applied differential pressure and the volume change induced by the diaphragm deformation of the differential type CDG has been investigated by means of the Boyle's law. Prior to the diaphragm volume change of the measurements, the method to measure the volume including the inside volume in a pressure gauge and pipes by means of the Boyle's law and ball bearings were developed. By using this method, the test volume of 83.63 ml was evaluated. When the differential pressure to the target gauge, G_1, was changed from 31.0 Pa to 130.6 Pa, the volume of the gauge was changed by 0.012 ml. The sensitivity of the volume change is 0.00012 ml/Pa at the lien pressure of 100 kPa. Above the full scale of the gauge tested here, the linear response to the applied pressure was obtained till 500 Pa, 4 times as high as its full scale. Above the applied pressure of 3000 Pa, the volume change was almost constant and in the range from 0.20 ml to 0.22 ml, reflecting the contact of the diaphragm to the guard electrode, partially.

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