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COMPARISON BETWEEN GAS AND HYDRAULIC PRESSURE BALANCES USING A LIQUID-LUBRICATED PRESSURE BALANCE

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Abstract – A method for comparing pressures of different mediums generated by gas and hydraulic pressure balances is examined to improve consistency between gas and hydraulic pressure-standards. The pressure range compared is 0.5 MPa to 7 MPa. In the method, a liquid-lubricated pressure balance was used and a precise pressure transducer was applied as a comparator to determine the equilibrium state between the two pressure balances. In this paper, the comparative result and the uncertainty obtained from the method are presented. From the results, it was shown that the method adopted in this study could be used to compare gas and hydraulic pressure balances accurately.

Keywords: pressure standard, pressure balance, pressure transducer

1. INTRODUCTION

Pressure balances are available in many applications [1, 2]. They can be classified by their structure, usage, etc. They are classified also by the medium used. Then they are roughly classified into a gas pressure balance, which uses gas and a hydraulic pressure balance which uses liquid. Usually, gas pressure standard and hydraulic pressure standard are maintained by gas pressure balance and hydraulic pressure balance, respectively.

This paper describes an accurate method to compare the pressure generated by gas and hydraulic pressure balances with different medium, in order to improve harmonization between a gas pressure standard and a liquid pressure standard. Concretely, we pay attention to the effective cross-sectional area of a piston-cylinder assembly, which is a device constant of pressure balances. We make comparative measurements and examine a high-precision method to determine the effective area ratio, including the pressure dependence of both gas and hydraulic pressure balances. If the effective area of either pressure balance used is known as a function of pressure, then the effective area ratio including pressure dependence determined, can give the unknown effective area of another pressure balance as a function of pressure. In order to reduce uncertainty of the effective area to be sought, it is necessary to reduce uncertainty of the effective area ratio that is determined by comparative measurement. A couple of methods have been examined to seek the effective area ratio of both gas and hydraulic pressure balances. One method using a gas-liquid pressure exchanger was already reported [3].

A method adopted in this study uses a liquid-lubricated pressure balance as a transfer device. In the method, we made our measurement by the comparator method [4], where we used, as a comparator, a high-precision pressure transducer. The pressure range compared was 0.5 MPa to 7 MPa. This paper indicates the result of the effective area ratio obtained from the method, along with its uncertainty. It can be confirmed that the method can compare, with high reliability, both gas and hydraulic pressure balances.

2. PRESSURE BALANCE

The main constituent elements of a pressure balance are the piston-cylinder and the weights.

If a pressure is applied to float the piston with the weights up to an appropriate position, then the pressure P generated is given by equation (1).

$$P = \frac{W}{A(P,t)} + (\rho_f - \rho_a) \cdot g \cdot h \qquad (1)$$

where, $A(P, t)$ is the effective area at pressure P and temperature t which are determined by the piston-cylinder. $(\rho_f - \rho_a) \cdot g \cdot h$ is the pressure corrected by head difference. ρ_f is the density of medium used. ρ_a is air density. g is gravity acceleration at the location where a measurement was made. h is the perpendicular distance between the measurement position and the reference level of pressure balance, with the measurement position is relatively lower being positive. W is the force applied to the piston, which is expressed with equation (2).

$$W = M \cdot g \cdot (1 - \frac{\rho_a}{\rho_m}) + \gamma \cdot C \qquad (2)$$

where, M is the sum of the total mass of weights including the piston mass. ρ_m is the average density of the piston and weights. γ is the surface tension of medium. C is the circumference of piston.

Positive free deformation type or negative free deformation type piston-cylinders are easy to handle and highly reproducible. If their dependence on pressure is assumed to be linear, their effective area is given by equation (3).

$$A(P,t) = A(0,t_r) \cdot (1 + b \cdot P) \cdot \{1 + \alpha_s \cdot (t - t_r)\} \qquad (3)$$

where, $A(0,t_r)$ is the effective area at the reference temperature under atmospheric pressure. b is a pressure distortion coefficient. α_s is the sum of α_p, which is thermal expansion coefficient of the piston and α_c, which is that of the cylinder. This study used pressure balances: a negative free deformation type gas pressure balance and a positive free deformation type hydraulic pressure balance. Therefore, the above-mentioned equations give the pressure generated.

3. COMPARISON USING A LIQUID-LUBRICATED PRESSURE BALANCE AS A TRANSFER DEVICE

This section describes the method to obtain the effective area ratio of gas and hydraulic pressure balances, by using a liquid-lubricated pressure balance as a transfer device.

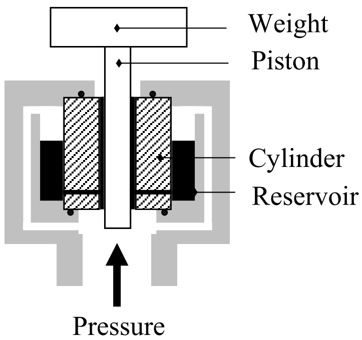

Fig. 1. Piston-cylinder assembly of a liquid-lubricated pressure balance.

3.1. Liquid-lubricated pressure balance and measurement principle

Fig. 1 is the schematic diagrams of the piston-cylinder and peripheral housing of a liquid-lubricated pressure balance (made by DH Instruments Inc. PG7202) [5]. 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. The pressure generated at the piston bottom is applied, as shown in the figure, 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. So, the piston-cylinder gap will be filled with liquid. The structure of this piston-cylinder is of negative free deformation type, and the generating pressure is applied also to the outer surface of cylinder. Therefore, higher pressure results in a smaller piston-cylinder gap. If the medium below the piston bottom is replaced, then this pressure balance can generate pressure with either gas or liquid. If the pressure medium below the piston bottom is gas, the piston-cylinder gap is filled with liquid unless the medium in the reservoir is drained. So, its effective area is theoretically the same as the liquid medium [5].

In this method, firstly, we made comparative measurement by using gas as a medium. If the pressure P_G generated by the gas pressure balance is at equilibrium with the pressure P_O generated by the liquid-lubricated pressure balance, then equation (4) is given.

$$P_G = P_O \tag{4}$$

where, P_G and P_O are represented by the following equations, respectively, using the equation (1).

$$P_G = \frac{W_G}{A_G(P,t_G)} + (\rho_{fG} - \rho_a)\cdot g \cdot h_G \tag{5}$$

$$P_O = \frac{W_O}{A_O(P,t_O)} + (\rho_{fO} - \rho_a)\cdot g \cdot h_O \tag{6}$$

where, the meaning of each parameter is as explained in the foregoing paragraph. The subscripts G and O refer to parameters of the gas side and the liquid-lubricated side, respectively. W_G and W_O are the sum of gravity due to all weights mass including the small weight and the force due to surface tension. They are calculated from the equation (2). h_G and h_O are the perpendicular distance to the measurement position from the reference levels of the gas and liquid-lubricated pressure balances, respectively. From the equations (4), (5) and (6), the effective area ratio of piston-cylinder of both pressure balances is given by equation (7).

$$\frac{A_G(P,t_G)}{A_O(P,t_O)} = \frac{W_G}{W_O} + \Delta R(P,t_G) \tag{7}$$

where, ΔR is the term to correct the effect of head difference between each reference level as mentioned above. It is given by equation (8).

$$\Delta R(P,t_G) = \frac{A_G(P,t_G)\cdot g}{W_O} \times \{(\rho_{fG} - \rho_a)\cdot h_G - (\rho_{fO} - \rho_a)\cdot h_O\} \tag{8}$$

where, if $A_G(P, t)$ is presumed to be known, then the effective area ratio at the reference temperature, is obtained, from equation (3), by equation (9).

$$\frac{A_G(P,t_r)}{A_O(P,t_r)} = \frac{A_G(P,t_G)}{A_O(P,t_O)} \times \frac{1+\alpha_{sO}\cdot(t_O - t_r)}{1+\alpha_{sG}\cdot(t_G - t_r)} \tag{9}$$

We obtained the effective area ratio, $A_G(P, t_r)/ A_O(P, t_r)$, of the gas pressure balance and the liquid-lubricated pressure balance. Here, $A_O(P, t_r)$ is the effective area at the reference temperature t_r, including pressure dependence of the liquid-lubricated pressure balance. Next, we made comparative measurements by using a liquid medium, and obtained the effective area ratio of a hydraulic pressure balance and the liquid-lubricated pressure balance $A_L(P, t_r)/ A_O(P, t_r)$. From the two comparative measurements mentioned above, we obtained two values of the effective area ratio. From these values, we obtained the effective area ratio of the gas pressure balance and the hydraulic pressure balance, at the reference temperature, by equation (10).

$$R_2(P) = \frac{A_G(P,t_r)}{A_L(P,t_r)} = \frac{A_G(P,t_r)/A_O(P,t_r)}{A_L(P,t_r)/A_O(P,t_r)} \tag{10}$$

As shown in equation (10), when we intend to obtain the effective area ratio of the gas and hydraulic pressure balances, we need not know the absolute effective area $A_O(P, t_r)$ of a liquid-lubricated pressure balance.

3.2. Measuring method

For this measurement, we used the gas pressure balance whose effective area was about 0.49 cm^2. Mounting of a 35 kg weights enables the pressure balance to generate stably gas pressure of about 7 MPa. The hydraulic pressure balance has the effective area of about 1.42 cm^2. Mounting of a 101.5 kg weights enables the pressure balance to generate stably hydraulic pressure of about 7 MPa. Accordingly, the effective area ratio (A_G / A_L) is about 0.345. We also used a liquid-lubricated pressure balance whose effective area of piston-cylinder was 0.98 cm^2. Mounting a 70 kg weights on this piston-cylinder enables the pressure balance to stably generate gas or hydraulic pressure of about 7 MPa. As the medium in the reservoir, we used Sebacate for hydraulic pressure. When gas is used as the pressure medium under the piston bottom, careful preparation is necessary in order to prevent exhaustion of the medium in the reservoir. When liquid is used as the pressure medium under the piston bottom, careful preparation is necessary in order not to introduce air bubbles into pipes and the reservoir. When liquid is used, if a significant amount of bubbles are present in the pipes and liquid, they cause a large error as mentioned in the previous section. In order to compare the gas pressure balance with the liquid-lubricated pressure balance, we used a gas high-precision pressure transducer and gas switching valves. In order to compare the hydraulic pressure balance with the liquid-lubricated pressure balance, we used a hydraulic high-precision pressure transducer and hydraulic switching valves. Fig. 2 is a schematic diagram of the apparatus for hydraulic medium. In the figure, CVV is a constant volume valve, which opens or closes without changing the volume inside, and to keep the position of floated piston almost constant irrespective of valve switching. The apparatus for gas medium is almost similar to that for hydraulic medium.

The calculation method is mentioned in section 3.1. The resulting equations should be used to calculate the effective area ratio, $A_G(P, t_r)$/ $A_O(P, t_r)$. For hydraulic comparison, the subscript G should be changed to L. The resulting equations should be used to calculate the effective area ratio, $A_L(P, t_r)$/ $A_O(P, t_r)$. However, when the generating pressure of a liquid-lubricated pressure balance is calculated, it is necessary to note whether the medium under the piston bottom is gas or liquid, and to pay attention to the values of the surface tension value γ and the medium density value ρ_f. The piston-cylinder gap of this type of pressure balance is, as mentioned previously, filled with liquid. So, it is necessary to consider the surface tension of the liquid.

When the piston bottom is filled with gas, it is necessary to consider the surface tension of the bottom of the piston-cylinder contact surface, in addition to the top. These surface tensions cancel each other. So, when the piston bottom is filled with gas, γ_O which is included in W_O is zero, i.e. γ_O = 0. On the other hand, when the piston bottom is filled with liquid, it is sufficient to consider only the surface tension on the top of piston-cylinder contact surface. So, $\gamma_O = \gamma_L$. For the medium density, if the piston bottom is filled with gas, then $\rho_{fO} = \rho_{fG}$. If the piston bottom is filled with liquid, then $\rho_{fO} = \rho_{fL}$.

For this measurement, we used nitrogen with more than 99.9999% purity as the gas medium, and Sebacate (Di-2-Ethyl Hexyl Sebacate) as the liquid medium. The surface tension of nitrogen is negligibly small. So, γ_G = 0 N/m. For the surface tension of Sebacate, γ_L = 0.031 N/m. The density of both medium, ρ_{fG} and ρ_{fL} was obtained as a function of pressure P and temperature t in the pressure range compared from the following equations [6].

$$\rho_{fG}(\mathrm{kg/m^3}) = \frac{28.01348 \cdot (P\,/\,\mathrm{MPa} + 0.101325)\cdot 10^3}{0.9967 \cdot 8.31451 \cdot (t\,/\,^\circ\mathrm{C} + 273.15)} \qquad (11)$$

$$\begin{aligned}\rho_{fL}(\mathrm{kg/m^3}) = \{&912.67 + 0.7521 \cdot P\,/\,\mathrm{MPa} \\ &- 1.6448 \cdot 10^{-3}(P\,/\,\mathrm{MPa})^2 \\ &+ 1.45625 \cdot 10^{-6}(P\,/\,\mathrm{MPa})^3\} \\ &\cdot \{1 - 7.8 \cdot 10^{-4}(t\,/\,^\circ\mathrm{C} - 20)\}\end{aligned} \qquad (12)$$

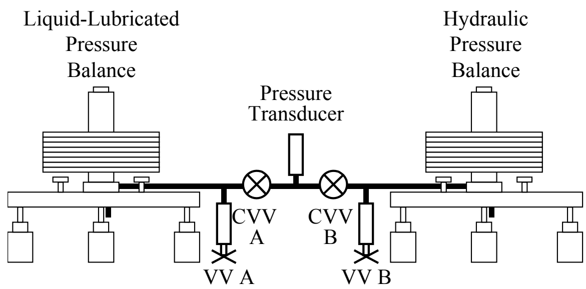

Fig. 2. Apparatus for comparing hydraulic and liquid-lubricated pressure balances using the comparator method. VV: variable volume, CVV: constant volume valve.

3.3. Measurement results

Fig. 3 (a) shows the effective area ratio $A_G(P, t_r)$/ $A_O(P, t_r)$ and its standard deviation, which were obtained from comparative measurement of the gas pressure balance and the liquid-lubricated pressure balance, where gas medium was used. As shown in the figure, the difference between the ascending pressure and the descending pressure was relatively 3 × 10^{-6} or less even at maximum. The standard deviation of the measured value at each pressure was relatively 2 × 10^{-6} or less at the pressure 2 MPa or higher. Fig. 3 (b) shows the effective area ratio $A_L(P, t_r)$/ $A_O(P, t_r)$ and its standard deviation, which were obtained from comparative measurement of a hydraulic pressure balance with the liquid-lubricated pressure balance, where liquid medium was used. As shown in the figure, the difference between the ascending pressure and the descending pressure was relatively 1 × 10^{-6} or less. The standard deviation of the measured value at each pressure was relatively 2 × 10^{-6} or less at the pressure 1 MPa or higher. We obtained two values of ratio: $A_G(P, t_r)$/ $A_O(P, t_r)$ and $A_L(P, t_r)$/ $A_O(P, t_r)$. From these values, we can obtain the effective area ratio $R_2(P)$ of the gas pressure balance and the hydraulic pressure balance at the reference temperature by equation (10). The calculated average of $R_2(P)$ of the effective area ratio is shown in Fig. 3 (c). The combined standard uncertainty [7] of $R_2(P)$ is estimated by equation (13).

$$u(R_2) = R_2 \times \sqrt{\left\{\frac{u(A_G / A_O)}{A_G / A_O}\right\}^2 + \left\{\frac{u(A_L / A_O)}{A_L / A_O}\right\}^2} \quad (13)$$

where, two values of standard uncertainties, $u(A_G / A_O)$ and $u(A_L / A_O)$, evaluated. The combined standard uncertainty obtained by equation (13) is shown in Fig. 3 (c) as an error range.

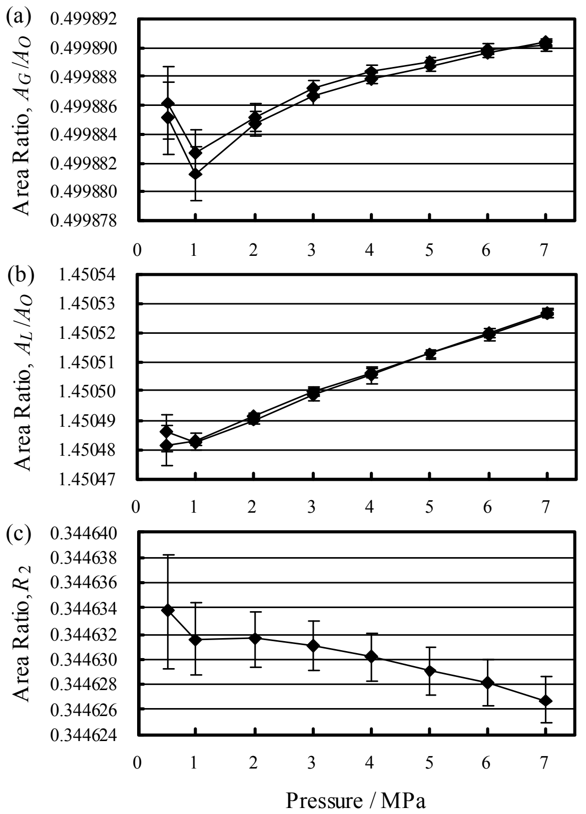

Fig. 3. The effective area ratios obtained by method using a liquid-lubricated pressure balance: (a) ratio of gas pressure balance to liquid-lubricated pressure balance, (b) ratio of hydraulic pressure balance to liquid-lubricated pressure balance, (c) calculated ratio of gas pressure balance to hydraulic pressure balance and its combined standard uncertainty (k = 1).

4. CONCLUSIONS

In order to precisely compare gas pressure with hydraulic pressure, we studied how to compare the effective area ratio between gas and hydraulic pressure balances. In this study, we used liquid-lubricated pressure balance as a transfer device. In the method, we firstly compared the gas pressure balance with the liquid-lubricated pressure balance. Next, we compared the hydraulic pressure balance with the liquid-lubricated pressure balance. From those results, we calculated the effective area ratio of both gas and hydraulic pressure balances. The measurement result by the method showed no noticeable hysteresis. Uncertainty of the method is relatively small compared with that by the method using a gas-liquid exchanger especially in the lower pressure range [3]. The results shown in this article suggest that the method compares gas pressure balance with hydraulic pressure balance with high definition. NMIJ/AIST researches to ensure consistency of a gas pressure standard and a hydraulic pressure standard in a wider pressure range with a smaller uncertainty.

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