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Calibration values uninfluenced by the kind of pressure medium and the setting posture for quartz Bourdon-type pressure transducers

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ABSTRACT
The effects of the kind of gas medium and the setting posture on the calibration values of a quartz Bourdon-type pressure transducer mounted vertically are evaluated in this study. The transducer, at the upward and downward settings, was calibrated both with nitrogen and with helium. The difference between the calibration values of the transducer with nitrogen at the upward and downward settings was about 7.0 kPa at 100 MPa. At the same setting posture, the maximum difference in the calibration values between nitrogen and helium was 3.4 kPa. For precise pressure measurement, it is recommended that the transducers are used with the same pressure medium and the same setting posture with which they were calibrated. The methods of reducing the effects of both the kind of gas medium and the setting posture are discussed. The average of two calibration values at the upward setting and at the downward setting was not affected by the kind of gas medium. When the sensing elements of two pressure transducers arranged in point symmetry with each other, the average values of two transducers were independent of both the kind of gas medium and the setting posture.

Section: RESEARCH PAPER

Keywords: Pressure transducer; pressure medium; setting posture; high gas pressure

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1. INTRODUCTION

High gas pressure is measured in various contexts, such as hydrogen stations, natural gas pipelines, industrial plants, and scientific research [1]-[4]. For ensuring reliable measurements, the National Metrology Institute of Japan (NMIJ), AIST has developed a high gas pressure standard for pressures up to 100 MPa using a liquid-lubricated pressure balance [5]-[7]. A quartz Bourdon-type pressure transducer [8]-[10] is one of the highest precision pressure gauges in the high gas pressure range. The accuracy of these pressure transducers is about 0.01 % of the full scale. The characteristics of the pressure transducer have been evaluated in many institutes [11]-[14].

The quartz Bourdon-type pressure transducer is used as a transfer standard in some international comparisons of high gas pressure standards and hydraulic pressure standards [15]-[20]. In an international comparison of high gas pressure standards, we found that the calibration values of the quartz Bourdon-type pressure transducers are affected by the kind of gas medium used [15]. In this comparison, the transducers are previously calibrated both with nitrogen and with helium for the characterisation of the transducers, and the calibration values of the transducers depend on the kind of gas medium used. A recent article described the reason for these effects [21]. The indications of the transducers are affected by the weight of the pressure medium inside a sensing element. The calibration values of the horizontally mounted transducers also depend on the rotation angle around the central axis. It is found that the effects of the kind of gas medium can be reduced by adjusting the rotation angles of the transducers.

In this study, we investigate how to ensure that the calibration values are uninfluenced by the kind of gas medium and setting posture used. We evaluate the effect of the setting posture on the calibration values of transducers mounted horizontally [21]. In this paper, we evaluate the effects of both the kind of gas medium and setting posture used on the transducer mounted vertically. Using these evaluation results, the methods of reducing the effects of the kind of gas medium

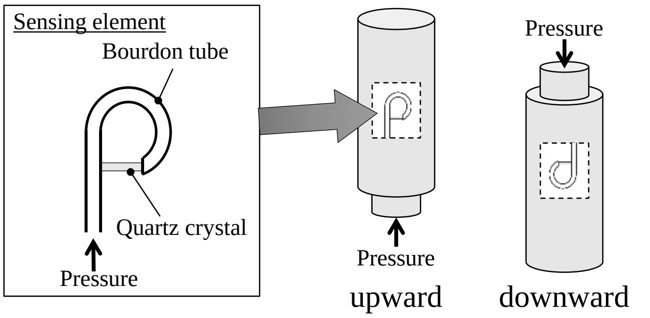

Figure 1. Quartz Bourdon-type pressure transducer, set at upward and downward settings.

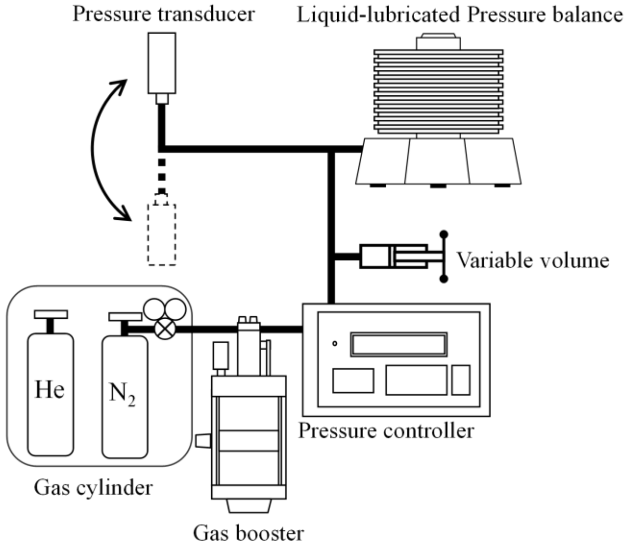

Figure 2. Schematic drawing of a high gas pressure calibration system.

used are discussed. We also propose an appropriate arrangement for two transducers, with which the effects of both the kind of gas medium and the setting posture are highly reduced.

2. REASON FOR THE EFFECTS OF THE KIND OF GAS MEDIUM AND SETTING POSTURE USED

The sensing element of a quartz Bourdon-type pressure transducer [8]-[10] mainly consists of a Bourdon tube and a quartz crystal oscillator. In the sensing element, the quartz crystal oscillator is attached across the root and tip of the Bourdon tube, as shown in Figure 1. Pressure applied to the Bourdon tube generates an uncoiling force that applies tension to the quartz crystal. The change in the frequency of the quartz crystal oscillator as a function of the tension is a measure of the applied pressure.

The reason for the effects of the kind of gas medium used has been described in a recent article [21]. The indications are affected by the weight of the pressure medium inside the Bourdon tube. The weight of the pressure medium can cause the extensional or compressional deformation of the Bourdon tube, thereby affecting the oscillating frequency and, hence, the pressure indication. In this case, the indication of the transducer can be expressed as the sum of two contributions: the force acting on the Bourdon tube purely from the applied pressure and an extensional (or compressional) gravitational force arising from the weight of the pressure medium inside the Bourdon tube. Since the gas density largely varies depending on the kind of gas medium used [22], [23], the second term depends on both the kind of gas medium and the relationship between the directions of the gravitational force and the deformation of the Bourdon tube.

Therefore, it is thought that the indication of the pressure transducer, I_p, mounted vertically, is expressed by the following equation:

$$I_p = I'_p \pm \Delta I_p. \quad (1)$$

Here, the first term I'_p represents the contribution purely from the applied pressure, and ΔI_p represents the effect of the weights of pressure medium inside the Bourdon tube. ΔI_p depends on both the kind of gas medium and the setting posture used. ΔI_p depends on the relationship between the directions of the gravitational force and the deformation of the Bourdon tube. When the transducer is set at the upward setting, as shown in Figure 1, the sign of ΔI_p is negative because the gravitational force arising from the weight of the pressure medium causes the compressional deformation of the Bourdon tube. Conversely, when the transducer is set at the downward setting, ΔI_p is positive because the gravitational force causes extensional deformation.

In the next section, the above assumption was experimentally confirmed by calibrating the vertically mounted pressure transducer, both with nitrogen and with helium.

3. THE EFFECTS AT VERTICAL SETTINGS

3.1. Calibration methods

Figure 2 shows a schematic drawing of a high-gas pressure calibration system in NMIJ [5]. A pressure supply source is gas cylinder. A gas booster with a maximum compression ratio of 25:1 pressurises the gas to about 100 MPa. Pressurised gas is supplied to the pressure controller, which is used to accurately adjust the gas pressure and supply a sufficiently stable pressure to a liquid-lubricated pressure balance and the pressure transducer. A variable volume is also used to manually adjust the piston's floating position. The liquid-lubricated gas pressure balance is used as a standard device.

The calibration is conducted by comparing the applied pressure from the liquid-lubricated pressure balance with the indication of the pressure transducer. The target pressure was changed from 0 MPa to 100 MPa in steps of 10 MPa. At each target pressure, the indication of the pressure transducer was sampled 18 times at 10 s intervals, after waiting 7 mins following the establishment of a steady pressure. The difference between the pressure applied by the standard and the indication of the pressure transducer after offset correction at nominal gauge pressure p MPa, R_p, is calculated as

$$R_p = (I_p - S_p) - (I_0 - S_0). \quad (2)$$

Here, S_p is the pressure applied by the standard. The mean value of R_p in three ascending processes is used as the calibration value.

The quartz Bourdon-type pressure transducer (Paroscientific Inc., Model 9000-15K, pressure range 100 MPa) [8] was calibrated at the upward and downward settings as shown in Figure 1. The reference level for each pressure transducer was determined as the level at the end face of the inlet port. Nitrogen and helium were used as the pressure media.

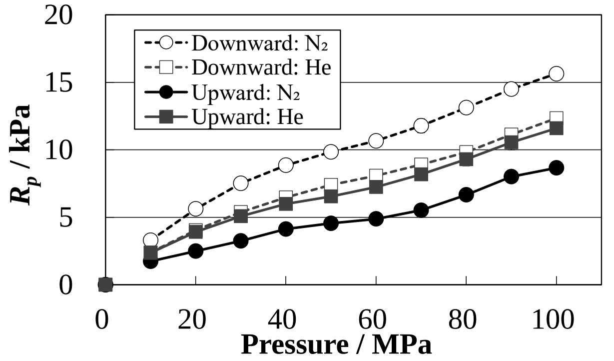

Figure 3. Calibration results R_p at the upward and downward settings, both with nitrogen and with helium.

3.2. Calibration results

The calibration results of the pressure transducers at the upward and downward settings are shown in Figure 3. R_p depends on both the pressure medium and the setting posture. The standard deviation of R_p in the three ascending processes was less than 0.6 kPa in all measurement pressure. The difference between R_p at the upward and downward settings was larger than the standard deviations. The same difference with nitrogen at 100 MPa was about 7.0 kPa, relatively 7.0×10^{-5} of the full scale. When the transducer is set at the downward setting, the gravitational force arising from the weight of the pressure medium causes the extensional deformation of the Bourdon tube, and when the transducer is set at the upward setting, the gravitational force causes compressional deformation. Therefore, R_p at the downward setting was larger than R_p at the upward setting. The effects of the setting posture with helium were smaller than that with nitrogen because the density of helium is smaller than that of nitrogen. At the same setting posture, the maximum difference between R_p with nitrogen and R_p with helium was 3.4 kPa, relatively 3.4×10^{-5} of the full scale.

4. METHODS FOR REDUCING THE EFFECTS

4.1. Using a single pressure transducer

Since the quartz Bourdon-type pressure transducer was affected by the kind of gas medium and the setting posture, it is recommended that the transducers are used with the same pressure medium and the same setting posture with which they were calibrated.

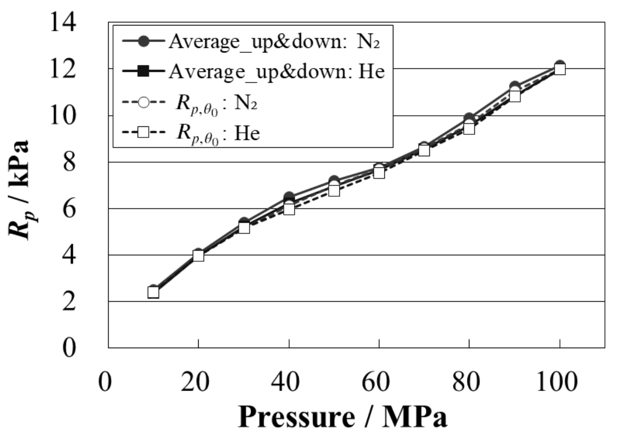

Figure 5. Average values of calibration values at the upward and downward settings. Calibration values at horizontal settings with rotation angle θ_0.

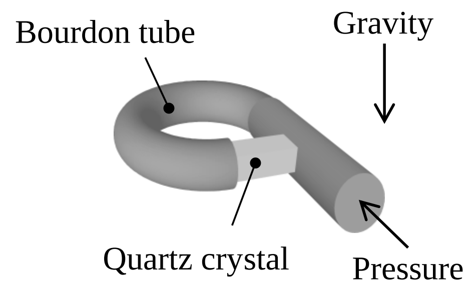

Figure 4. Setting posture of sensing element, θ_0. Direction of deformation of Bourdon tube is perpendicular to direction of gravitational force.

The two methods for reducing the effect of the kind of gas medium are discussed. When the transducer is mounted vertically, the deformation of the Bourdon tube by the gravitational force arising from the weight of the pressure medium at the upward setting is opposite to that at the downward setting. Therefore, it is thought that the effect of the weight of the pressure medium can be eliminated by averaging the calibration values at the upward and downward settings.

When the transducer is mounted horizontally, there is a particular rotation angle, θ_0, where there is no effect of the gas medium. The method of identifying the rotation angle θ_0 by the experiment has been reported in other studies [21]. At the rotation angle θ_0, the direction of the deformation of the Bourdon tube is perpendicular to the direction of gravitational force, as shown in Figure 4.

Figure 5 shows the average value of R_p at the upward and downward settings both with nitrogen and with helium. The calibration values of the horizontally mounted transducer at the rotation angle θ_0, R_{p,θ_0}, both with nitrogen and with helium are also shown. Each value showed good agreement within 0.6 kPa in all measurement pressures. 0.6 kPa was comparable to the standard deviations of the calibration value. The average value of the R_p at the upward and downward settings agreed well with R_{p,θ_0} because both values only included the contribution purely from the applied pressure. The effect of the kind of gas medium on the calibration value can be reduced by averaging the calibration values at the upward and downward settings or by adjusting the setting posture of the transducers.

4.2. Using two pressure transducers

In the international comparison, two pressure transducers are used as the transfer standard for securing redundancy. We discuss here the case in which two transducers can be used for measurements. It is thought that the effect of the kind of gas medium used can also be reduced by averaging the calibration values of two transducers at the upward setting and at the downward setting. In addition, when the sensing elements of the two pressure transducers are arranged in point symmetry with each other, the deformations of the two Bourdon tubes by the gravitational force arising from the weight of the pressure medium are opposite to each other in any setting posture. Therefore, it is thought that the effects of both the kind of gas medium and the setting posture used can also be reduced by averaging the calibration values of the two arranged transducers.

Figure 6 shows a point-symmetry arrangement of two transducers. The inlet port of two transducers A and B at

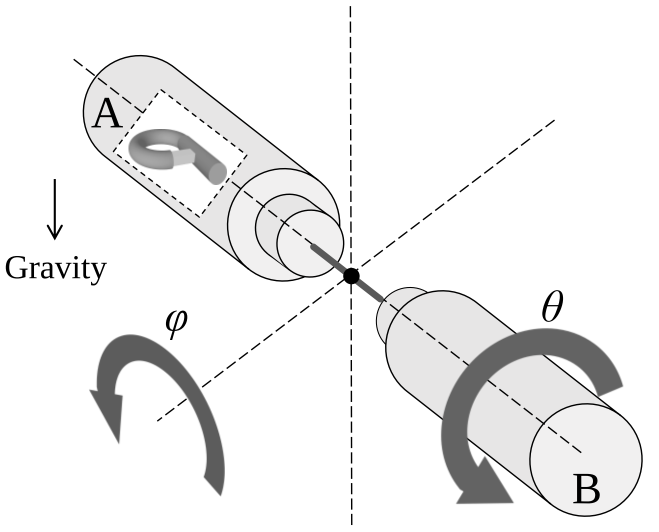

Figure 6. Two pressure transducers at rotation angle θ_0 are positioned in point symmetry with each other. This posture is defined as θ = 90°, φ = 90°.

rotation angle θ_0 were arranged face to face with each other. This posture was defined as $\theta = 90°$, $\varphi = 90°$.

The set of two transducers arranged in point symmetry were mounted vertically ($\varphi = 0°$ and 180°), and both were calibrated with nitrogen and with helium. The rotation angle θ was fixed to 90°. When $\varphi = 0°$, transducer A was set at the upward setting and transducer B was set at the downward setting. When $\varphi = 180°$, transducer A was set at the downward setting, and transducer B was set at the upward setting. The R_p of the two transducers were averaged. Figure 7 shows the average value of the two transducers, $R_{p,\mathrm{ave}}$, both with nitrogen and with helium at $\varphi = 0°$ and 180°. At the same setting posture, $R_{p,\mathrm{ave}}$ with nitrogen and $R_{p,\mathrm{ave}}$ with helium showed good agreement within 0.7 kPa in all measurement pressures, relatively 7.0×10^{-6} of the full scale. 0.7 kPa was comparable to the standard deviations of the calibration value. In addition, $R_{p,\mathrm{ave}}$ at $\varphi = 0°$ and 180° showed good agreement.

Two transducers A and B, arranged as shown in Figure 7, were calibrated at different setting postures. The pressure medium was nitrogen. In the first experiment, the rotation angle φ was fixed to 90°. The rotation angle θ was changed in order of 90°, 45°, 0°, 90°, 135°, 180°, 90°. Figure 8(a) shows the calibration values at 100 MPa, R_{100}, of transducer A and B at each rotation angle θ. The average values of the two transducers are also shown. The three R_{100} at $\theta = 90°$ showed good agreement within 0.5 kPa in both transducers A and B. Although the maximum difference by the rotation angle θ of transducer A was 7.2 kPa and transducer B was 7.0 kPa, the average values were 0.5 kPa. The average values were not affected by the rotation angle θ.

In the second experiment, the rotation angle θ was fixed to 90°. The rotation angle φ was changed in order of 90°, 45°, 0°, 90°, 135°, 180°, 90°. Figure 8(b) shows the R_{100} of transducers A and B at each rotation angle φ. The average values of the two transducers are also shown. The three R_{100} at $\varphi = 90°$ showed good agreement within 0.5 kPa in both transducers A and B. Although the maximum difference of rotation angle φ of transducer A was 7.8 kPa and transducer B was 9.5 kPa, the average value was 1.0 kPa. In both cases, the effect of the setting posture on the calibration value can be reduced by averaging the calibration values of the two transducers.

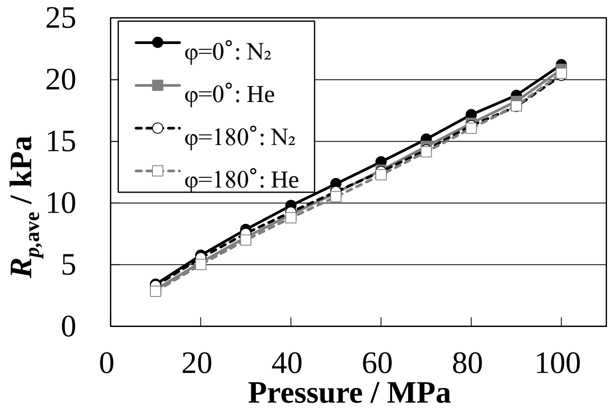

Figure 7. Average value of two transducers, $R_{p,\mathrm{ave}}$, at φ = 0° and 180° both with nitrogen and with helium.

When the sensing elements of the two pressure transducers were arranged in point symmetry, their average values were almost independent of both the kind of gas medium and the setting posture used. If two transducers that have the same effects are used, the average values would be completely independent of both the kind of gas medium and the setting posture used. In this study, the inlet ports of the two transducers were arranged face to face with each other. However, the same results can be obtained as long as the sensing elements are arranged in point symmetry with each other.

5. CONCLUSIONS

A quartz Bourdon-type pressure transducer is one of the highest precision pressure gauges in a high gas pressure range. This study found that the calibration values of the quartz Bourdon-type pressure transducers are affected by the kind of

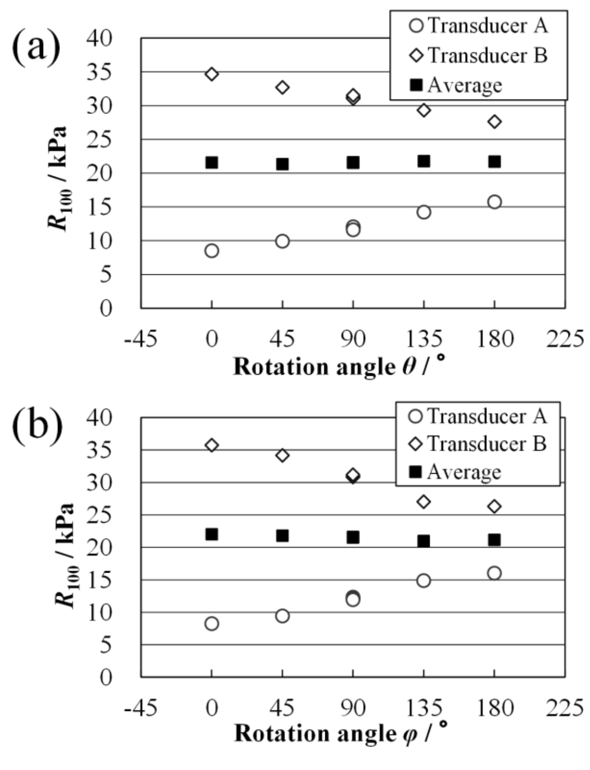

Figure 8. Calibration values at 100 MPa, R_{100}, of transducers A and B (a) at different rotation angles θ; (b) at different rotation angles φ. The average values of the two transducers are also shown.

gas medium used. This is because the indications of the transducers are affected by the weight of the pressure medium inside a sensing element. The weight of the pressure medium can cause extensional or compressional deformation of the Bourdon tube in the sensing elements, affecting the oscillating frequency and, hence, the pressure indications. The indications depend on both the kind of gas medium and the setting posture used. In this study, the effects of the kind of gas medium and the setting posture on the vertically mounted transducer were evaluated. The transducer at the upward and downward settings was calibrated both with nitrogen and with helium. The difference between the calibration values of the transducer at the upward and downward settings was about 7.0 kPa, relatively 7.0×10^{-5} of full scale. At the same setting posture, the maximum difference in the calibration values between nitrogen and helium was 3.4 kPa, relatively 3.4×10^{-5} of the full scale. For precise pressure measurement, it is recommended that the transducers are used with the same pressure medium and the same setting posture with which they were calibrated.

The methods of reducing the effects of the kind of gas medium used have been discussed. Since the deformation of the Bourdon tube due to the gravitational force arising from the weight of the pressure medium at the upward setting is opposite to that at the downward setting, it was found that the effect of the kind of gas medium used can be reduced by averaging the calibration values at the upward and downward settings. The average value of the calibration values at the upward and downward settings with nitrogen agreed well with the average value with helium.

In addition, the effects of the kind of gas medium used were reduced by averaging the calibration values of two transducers at the upward setting and at the downward setting. When the sensing elements of the two pressure transducers are arranged in point symmetry with each other, the deformations of the two Bourdon tubes by the gravitational force arising from the weight of the pressure medium are opposite to each other in any setting posture. Therefore, it was thought that the effect of both the kind of gas medium and the setting posture used can also be reduced by averaging the calibration values of the two arranged transducers. The two arranged transducers were calibrated at different settings with nitrogen. The maximum difference in the transducer's calibration values due to the setting posture was 9.5 kPa. However, the maximum difference of the average values of the two arranged transducers was 1.0 kPa. When the sensing elements of the two pressure transducers were arranged in point symmetry, the average values of the two transducers were independent of both the kind of gas medium and the setting posture used.

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