Effects on calibration values of quartz Bourdon-type pressure transducers caused by density of pressure medium

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Abstract. We have found that the calibration values of a quartz Bourdon-type pressure transducers are affected by the kind of pressure medium and the setting conditions. The effect comes from an additional gravitational force arising from the weight of the pressure medium inside a Bourdon tube at sensing element. In this study, the amount of the effect was evaluated quantitatively by comparing the calibration values of the pressure transducer at upward and downward settings. To investigate the relationship between the effect and the density of pressure medium, the amount of the effect was evaluated at pressures up to 100 MPa for using nitrogen, helium and argon. The amount of the effect has a linear relationship with the density regardless of the pressure and the kind of pressure medium.

1. Introduction
High gas pressure is measured in various situations, such as hydrogen stations, natural gas pipelines, industrial plants and scientific research. For ensuring reliable measurements, National Metrology Institute of Japan (NMIJ), AIST has developed a high gas pressure standard for pressures up to 100 MPa [1]. NMIJ has confirmed the international equivalence of high gas pressure standard up to 100 MPa through international comparison [2]. A quartz Bourdon-type pressure transducer [3] is used for the high precision pressure measurement. The sensing element of the quartz Bourdon-type pressure transducer 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. Pressure applied to the Bourdon tube generates an uncoiling force that applies tension to the quartz crystal. The change in frequency of the quartz crystal oscillator is a measure of the applied pressure. The accuracy of these pressure transducers is about 0.01 % of full scale.

Recently, we have found that the calibration values of the quartz Bourdon-type pressure transducers are affected by the kind of pressure medium [4–7]. It is thought that the calibration values are affected by the weight of the pressure medium inside a Bourdon tube. The weight of pressure medium can cause additional or compensatory deformation of the Bourdon tube, affecting the pressure indications. In this case, the indication of the transducer can be expressed by a sum of two contributions. The first one comes from the force which the Bourdon tube receives purely from the applied pressure, and the second one comes from an additional (or compensatory) gravitational force arising from the weight of the pressure medium inside the Bourdon tube. It is thought that the second term depends both on the density of the pressure medium, and the relationship between the directions of the gravitational force and the deformation of the Bourdon tube. The gas density largely differs

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depending on the kind of gas medium and its pressure, the indication of the quartz Bourdon-type pressure transducers can be significantly affected by the kind of gas medium. The effect of the setting condition and the method for reducing the effect by kind of pressure medium were reported [5-7].

It is expected that the amount of the effect by kind of pressure medium is correlated with the density of pressure medium. In this study, the relationship between the amount of the effect and the density of pressure medium was evaluated quantitatively by measuring the amount of the effect by multiple gas media. From the relationship, the calibration values by using any gas medium can be estimated if the gas density is known.

2. Method

Figure 1 shows a schematic drawing of high gas pressure calibration system [1] in NMIJ. Calibrations for a high gas pressure transducer is conducted by comparing the applied pressure from the liquid-lubricated pressure balance [8] 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 sec intervals, after waiting seven minutes following establishment of a steady pressure. Difference between the pressure applied by the standard and the indication of the pressure transducer at nominal pressure \( p \), \( D I_p \), is calculated as

\[
D I_p = I_p - S_p. \tag{1}
\]

Here, \( S_p \) is the pressure applied by the standard. Subscript \( p \) means gauge pressure. The difference after offset correction, \( R_p \), is calculated as

\[
R_p = DI_p - DI_0. \tag{2}
\]

Here, \( DI_0 \) is \( DI_p \) at \( p = 0 \). 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) [3] was calibrated at the upward and downward settings, as shown in figure 2. Nitrogen, helium and argon were used as the pressure medium in this study. The reference level of each pressure transducer was set at a position of 100 mm apart from the edge of the case, as shown in figure 2.

The indications of the pressure transducer, \( I_p \), at the upward and downward settings are expressed by the following equation,

\[
I_p = I_p' \pm \Delta I_p. \tag{3}
\]

Here, the first term \( I_p' \) represents the contribution purely from the applied pressure, and \( \Delta I_p \) represents the effect of weights of pressure medium inside the Bourdon tube. The sign of \( \Delta I_p \) 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, the sign of \( \Delta I_p \) is negative because the gravitational force arising from the weight of pressure medium causes compensatory deformation of the Bourdon tube. Conversely, when the transducer is set at the downward setting, the sign of \( \Delta I_p \) is positive because the gravitational force causes additional deformation.

![Figure 1. Schematic drawing of high gas pressure calibration system in NMIJ.](image)
Sensing element
Quartz crystal
Bourdon tube
Pressure
upward downward
Pressure
Pressure
100 mm
100 mm
Reference level
Reference level

Figure 2. Quartz Bourdon-type pressure transducer.

\[ R_p = R_p' \pm (\Delta I_p - \Delta I_0). \]  
(4)

Here, \( R_p' = DI_p' - DI_0' \), \( DI_p' = I_p' - S_p \). \( R_p' \) is the calibration value not including the effect of weights of pressure medium. The gas density at more than 10 MPa is about 100 times larger than the density at atmospheric pressure. When the pressure medium is gas, \( \Delta I_0 \) can be neglected and \( (\Delta I_p - \Delta I_0) \approx \Delta I_p \). \( \Delta I_p \) is expressed by the following equation,

\[ \Delta I_p = (R_{p,down} - R_{p,up})/2. \]  
(5)

Here, \( R_{p,down} \) and \( R_{p,up} \) are \( R_p \) at the downward and upward settings, respectively.

3. Result

\( R_{p,down} \) and \( R_{p,up} \) of the quartz Bourdon-type pressure transducer were evaluated with using nitrogen, helium and argon. Then \( \Delta I_p \) was calculated from equation (5). Figure 3 shows \( \Delta I_p \) versus pressure. Error bars indicate the combined standard deviations at the upward and downward settings. \( \Delta I_p \) has positive correlation with the pressure on each pressure medium. \( \Delta I_p \) with using nitrogen was larger than that with using helium and was smaller than that with argon. When target pressure is 100 MPa, the difference between \( \Delta I_p \) of argon and \( \Delta I_p \) of helium is 8 kPa, relatively \( 8 \times 10^{-5} \) of the target pressure. \( \Delta I_p \) has a larger value as the density of pressure medium is larger at the same pressure.

In the next, the horizontal axis of figure 3 is changed to the density of pressure medium. Figure 4 shows \( \Delta I_p \) versus the density of pressure medium. For the density of pressure medium, the literature values [9 - 11] were used. The gas density largely differs depending on the kind of gas medium and its pressure. \( \Delta I_p \) has a linear relationship with the density regardless of the kind of pressure medium. A coefficient obtained by linear approximation is 8.6 Pa kg^{-1} m^{3}.

Figure 3. \( \Delta I_p \) versus pressure by using different pressure medium.
4. Summary
We have found that the calibration values of a quartz Bourdon-type pressure transducers are affected by the kind of pressure medium and the setting conditions. The effect comes from an additional gravitational force arising from the weight of the pressure medium inside a Bourdon tube at sensing element. In this study, the amount of the effect was evaluated quantitatively by comparing the calibration values of the pressure transducer at upward and downward settings. To investigate the relationship between the effect and the density of pressure medium, the amount of the effect was evaluated at pressures up to 100 MPa for using nitrogen, helium and argon. The amount of the effect has a linear relationship with the density regardless of the pressure and the kind of pressure medium. From the relationship, the calibration values by using any gas medium can be estimated if the gas density is known.

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