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Research Paper

Humidity Calibration for a Pressure Gauge Using a Temperature-Stable Quartz Oscillator

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Abstract Humidity calibration for a temperature-stable quartz oscillator (TSQO) was investigated to exclude the influences of relative humidity on the TSQO output in order to use the corresponding devices outdoors. The TSQO output is a voltage that is inversely proportional to the electric impedance of the quartz oscillator, which depends on the viscosity and density of the measured gas. The TSQO output was humidity calibrated using its humidity dependence, which was obtained by varying the relative humidity (RH) from 0 to 100 RH% while other conditions were kept constant. The humidity dependencies of the TSQO output were fit by a linear function. Subtracting the change in the TSQO output induced by the change in humidity, calculated with the function from the experimentally measured TSQO output for a range of 0-100RH%, eliminated the influence of humidity on the TSQO output. The humidity calibration succeeded in reducing the fluctuations of the TSQO output from 0.4-3% to 0.1-0.3% of the average values for a range of 0-100RH%, at constant temperatures. The necessary stability of the TSQO output for application in hydrogen sensors was below one-third of the change observed for a hydrogen leakage of 1 vol.% hydrogen concentration, corresponding to 0.33% of the change in each background. Therefore, the results in this study indicate that the present humidity calibration effectively suppresses the influence of humidity, for the TSQO output for use as an outdoor hydrogen sensor.

Keywords: Quartz oscillator, Humidity calibration, Pressure gauge, Hydrogen sensing, Viscosity measurement

I. Introduction

Outdoor temperature and humidity fluctuations affect the pressure reading from a quartz oscillator pressure gauge (Q-gauge) because the reading from the Q-gauge depends on the temperature and humidity outside.

It has been shown that the electrical impedance (Z) of a quartz oscillator depends on the viscosity (η) and molecular weight (M) of the measured gas [1]. This is based on the theory that the dissipation energy from the surface of a fork-type quartz oscillator, generated by collision with a detected gas, affects the electrical energy supplied from the electric power supply, thereby altering the value of Z. The difference (ΔZ) between Z and the value at vacuum in a viscous flow region can be expressed as follows:

$$\Delta Z = C3\pi R^2\ (2\eta\rho\omega)^{1/2} \tag{1}$$

Here, R, ω, ρ, and C are the thickness and the resonant frequency of the quartz oscillator, density of the gas measured, and a constant, respectively. In addition, ρ can be expressed as a product of the molecular weight (M) and pressure (P) of the gas. Therefore, the output from a quartz oscillator depends on ç and M. This means that the Q-gauge can detect not only the change in pressure, but also the content of the gas, making it applicable to hydrogen sensing, hydrogen concentration measurements, partial concentration measurements of binary gases, and plasma diagnostics [2-20].

Because temperature affects the resonant frequency of the quartz oscillator, the Q-gauge pressure is affected by temperature through the resonant frequency [21]. On the other hand, humidity affects the Q-gauge pressure by reducing the average viscosity and molecular weight of air, because the viscosity and molecular weight of water vapor (12.6×10^{-6} Pa · s and 18.0), the source of the humidity, are smaller than those of air (17.08×10^{-6} Pa · s and 29.0). Thus, the relative humidity can change the Q-gauge pressure [22].

Hydrogen sensing, an application of the Q-gauge, can detect the change in viscosity and molecular weight induced by the introduction of hydrogen into air because the corresponding values of hydrogen (8.9×10^{-6} Pa · s and 2.0) are drastically smaller than those of air [22].

Concerning this outdoor application, other conditions apart from hydrogen, such as the temperature and humidity, should be stable against changes in the Q-gauge pressure. If the temperature or humidity change induces a

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Q-gauge pressure change, such changes may result in an error in hydrogen sensing. From this point of view, the fluctuation of the Q-gauge pressure should be suppressed below one-third of the minimum detection level of the hydrogen concentration, which is 1 vol.% in air for hydrogen sensing.

In order to suppress the influence of the temperature, a noble temperature-stable quartz oscillator (TSQO) has been developed (Vacuum Products Co.) [20]. The change in the TSQO output for a typical room temperature of 15–50°C is below 0.2% of the TSQO output, sufficiently smaller than the necessary stability. In addition, the TSQO output depends on the absolute pressure in the pressure range of 0.5-100 kPa. Therefore, it can be used as a pressure gauge.

As above, the influence of temperature on a quartz oscillator is mostly eliminated using a TSQO. Next, in this study, the humidity calibration for the TSQO output was investigated. One method investigated is the humidity calibration using the humidity dependence of the TSQO output and humidity measurement, and the other uses a filter, which excludes the water vapor. Finally, these results were compared to each other to investigate the suppression of the influence of humidity.

II. Experiment and Procedure for the Humidity Calibration

1. Measurement for humidity dependence of the TSQO output

The experimental setup to study the humidity dependence of the TSQO output is mostly identical to the previous reports for the measurement of the temperature dependence of a quartz oscillator output [19]. The humidity dependence of the TSQO output was obtained by changing the relative humidity while maintaining a constant temperature using a temperature and humidity chamber with an atmospheric environment. Here, the TSQO output used is a voltage, which is inversely proportional to Z and depends on not only pressure, viscosity, and molecular weight, but also temperature and humidity.

2. Humidity calibration using the humidity dependence of the TSQO output

One approach to suppress the influence of humidity for the TSQO output is a procedure including some calculation. If the degree of the change in the TSQO output with the change in humidity is calculated, then the influence of humidity can be eliminated from the TSQO output by subtracting the change in the TSQO output with the change in humidity. The change in the TSQO output induced by the change in humidity can be derived from the humidity dependence of the TSQO output and the change in humidity.

As seen in the proceeding section, the humidity dependence of the TSQO output can be obtained by measuring the TSQO output with varying humidity while maintaining other conditions such as pressure, temperature, and gas content constant. The change in humidity can be obtained by simultaneous humidity measurements. These measurements of humidity dependence of the TSQO output and humidity enable humidity calibration for the TSQO output.

3. Filtering water vapor from air

Another method to suppress the influence of humidity on the TSQO output is the use of a filter, which only evacuates water vapor from air. One such device used in this study is an "air dryer," which is made of a hollow fiber membrane (Koganei Co.). This was installed at the head of the TSQO.

III. Results and Discussion

1. Humidity dependence of the TSQO output

The results of the humidity dependence of the TSQO output at constant temperatures of 10, 20, 30, 40, and 50°C are shown in Fig. 1. As seen in Fig. 1, the TSQO output increases with relative humidity at each constant temperature. The TSQO output increases with decreasing viscosity and molecular weight of air because the TSQO output is inversely proportional to Z. Therefore, the tendency in Fig. 1 is to qualitatively agree with the reduction in viscosity and molecular weight of air mixed with vapor.

Here, in order to evaluate the outside fluctuation level of the TSQO output quantitatively, the following parameter was defined as the stability:

Stability (%)=Maximum change in TSQO output /
Average TSQO output
=(Maximum TSQO output Minimum TSQO output) /
Average TSQO output (2)

The stability of the TSQO output is defined as the difference between the maximum and minimum of the TSQO output divided by the average TSQO output for the humidity range measured. This "stability" means the assumed change induced by the change in relative humidity

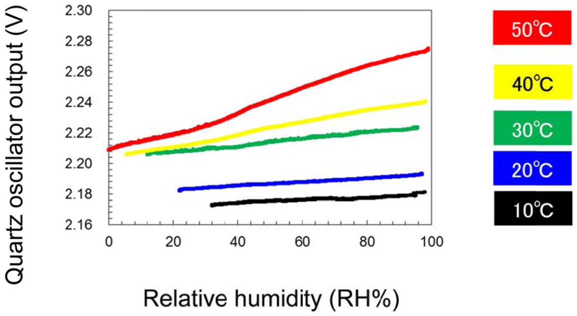

Figure 1. Humidity dependence of the TSQO output measured at 10, 20, 30, 40, and 50°C.

in this study, and is not the uncertain error in the measurement. Previous works presented that this stability value is quantitatively identical to the hydrogen concentration in air measured by the hydrogen sensor using the Q-gauge [20]. For example, if the stability is equal to 1%, then the same change in the TSQO output is seen when the hydrogen sensing with the Q-gauge detects 1 vol.% hydrogen concentration in air.

As described in the introduction, the stability needs to be kept below 0.33% in order to avoid error in hydrogen sensing because 0.33% is one-third of the minimum detected hydrogen concentration level, which is 1 vol.%. From this point of view, the stability seen in Fig. 1 for each temperature seems to be larger than that particularly at relatively higher temperatures. Therefore, the stability for the TSQO output on relative humidity needs to be more improved.

Fig. 1 also indicates that the stability increases with temperature, which should be attributed to the change in the actual density of the water vapor with temperature.

2. Humidity calibration using the humidity dependence of the TSQO output

The humidity dependence of the TSQO output in Fig. 1 at each temperature can be fitted by a linear function. The linear dependence of the TSQO output on humidity means that the change in the TSQO output resulting from the humidity change can be calculated from the humidity dependence of the TSQO output and humidity. Finally, the TSQO output can be humidity calibrated by subtracting the calculated change in the TSQO output induced by the change in humidity.

The result of humidity calibration for the results at 30°C is indicated in Fig. 2. For comparison, the TSQO outputs before the humidity calibration in Fig. 1 are also plotted. According to the results of the humidity calibration, as seen in Fig. 2, the stability of the TSQO output was improved by a factor of four.

The temperature dependence of the stability of the TSQO with a humidity change with and without humidity calibration is summarized in Fig. 3. The stability of the TSQO output increases, which means that it becomes worse, with temperature. As seen in Fig. 3, the saturated steam pressure derived from Tetens's equation well agrees with the tendency of the stability of the TSQO output without humidity calibration, thereby, this temperature dependence of the stability of the TSQO output without humidity calibration is probably attributed to amount of vapor in air, related to the saturated steam pressure [23].

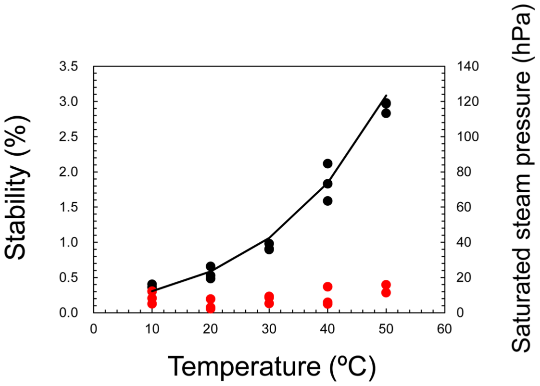

Figure 3. Temperature dependence of the stability of the TSQO output before (black) and after (red) humidity calibration and saturated steam pressure (line) calculated by Tetens's equation.

The stability of the TSQO output can be improved by the present humidity calibration up to the acceptable stability of about 0.33% at almost all temperatures. Therefore, it can be concluded that the present procedure of humidity calibration is sufficiently effective at suppressing the influences of humidity from the TSQO output.

3. Filtering water vapor from air

Humidity dependence plots of the TSQO output with and without the air dryer are shown in Fig. 4. Clearly, the stability of the TSQO output induced by the change in humidity is drastically suppressed using the air dryer.

Fig. 5 shows temperature dependence of the stability of the TSQO output with the humidity change with the air dryer and with the humidity calibration for comparison. As seen in Fig. 3 and 5, the air dryer used in this study is effective to improve the stability for all temperatures

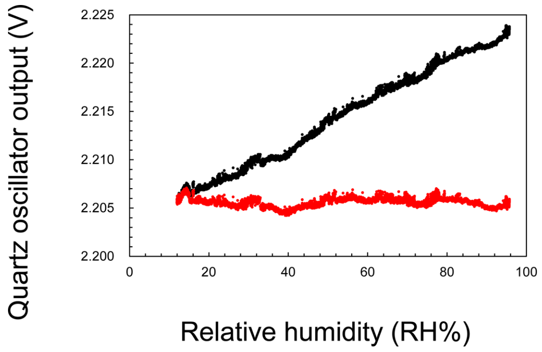

Figure 2. Humidity dependence of the TSQO output measured at 30°C before (black) and after (red) humidity calibration.

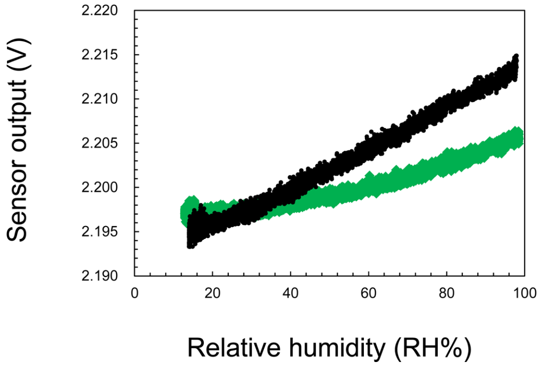

Figure 4. Humidity dependence of the TSQO output measured at 30°C with (green) and without (black) an air dryer.

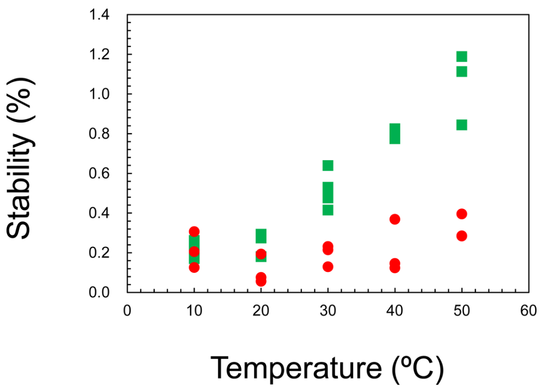

Figure 5. Temperature dependence of the stability of the TSQO output with the humidity change with the air dryer (green) and with the humidity calibration for comparison (red).

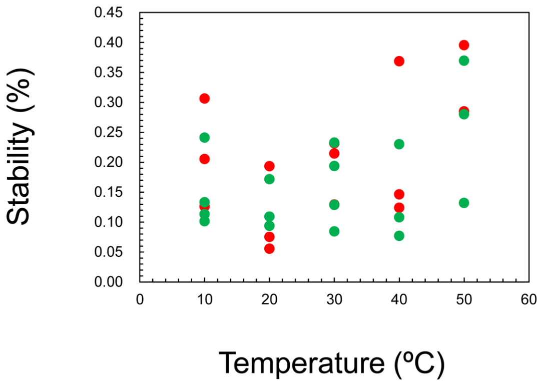

Figure 6. Temperature dependence of the stability of the humidity-calibrated TSQO output with (green) and without an air dryer for comparison (red).

measured in this study compared to those without humidity calibration using the humidity dependence of the TSQO output and measured humidity; however, it was less effective than those with humidity calibration as shown in Fig. 5. Therefore, it can be noted that the present calibration on humidity for the TSQO output can improve the stability more than the air dryer.

4. Humidity calibration for the results of filtering water vapor from air

The humidity calibration presented in this study is applicable to the results of the air dryer. Fig. 6 shows the temperature dependence of the stability resulting from the humidity calibration for the results with and without the air dryer. The humidity dependence of the TSQO output with the air dryer was separately measured from those of the TSQO output without the air dryer. The humidity dependence of the TSQO output with the air dryer is also assumed to be linear as well as the TSQO output without the air dryer. Finally, it shows that the present humidity calibration is also effective for the stability of the TSQO output with the air dryer by comparison of Fig. 5 and 6. However, the stability of the TSQO output with the air dryer and humidity calibration was comparable to those of the TSQO output without the air dryer for all temperatures in Fig. 6, and was not drastically improved over those.

IV. Summary

The TSQO output was humidity calibrated to improve stability using humidity dependence and humidity, which were simultaneously measured. The stability was improved to be typically less than 0.33% at constant temperatures, which is acceptable for application to hydrogen sensing. Humidity calibration is better than the air dryer to improve stability and is also effective when used with the results with the air dryer, but comparable to those without it. Humidity calibration makes outdoor hydrogen sensing possible using TSQO by improving stability to reduce the influence of humidity. In future work, an outdoor test of the TSQO output will be achieved to confirm the stability in order to make hydrogen sensing using TSQO a practical application.

Acknowledgements

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