Real-time correction of self-heating effect of capsule-type SPRTs used in gauge block calibration at KRISS

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Abstract. Standard Platinum Resistance Thermometer (SPRT) is the most accurate temperature sensor directly calibrated by the fix point cells given in the International Temperature Scale 1990 (ITS-90). However, when it is used for temperature measurement of an object in high precision dimensional metrology, self-heating effect may cause error in the measured temperature, and thus also in the measured length. The two-current method, which is the well-known method to compensate the self-heating effect of SPRTs is not practical for dimensional metrology because it takes several tens of minutes to measure temperature. A new method has been proposed by the authors which can enable a real time correction of the self-heating effect of SPRTs. The method utilizes the fact that the resistance of SPRT is linear with respect to its temperature within the short range around 20 °C. The correction value for the AC bridge resistance ratio corresponding to the self-heating effect is measured in advance by using the two currents of 1 mA and 1.414 mA. This correction value can be directly added to the AC bridge readout in real time to compensate for the self-heating value in length measurement applications. Since no current change is required during actual length or temperature measurements, there is no need to wait several tens of minutes like in the case of using the two-current method during the length measurement. In this paper, we present the measurement results of the self-heating effect of Minco’s capsule type SPRTs used in the gauge block interferometer of KRISS.

1. Introduction
Length of an object changes as its temperature changes. Thus, the international standard ISO 1:2016, states that all length measurements should be referred to the reference temperature 20 °C. This means that for all precise dimensional measurements including the measurement of length of gauge blocks, a correction for the thermal expansion must be applied through temperature measurement. During the calibration of gauge blocks, precise measurement of temperature is crucial. To measure the temperature of a gauge block with the highest accuracy, a standard platinum resistance thermometer (SPRT) calibrated by using fixed point cells given in the ITS-90 [1], may be attached to the measuring face of the gauge block.

The operating principle of the SPRT is based on the temperature sensitivity of the resistance of platinum wire, used in the SPRT sensing element. Therefore, to measure the temperature of an object with an SPRT, one must measure the electrical resistance of the SPRT sensor. Electrical resistance of the SPRT can only be measured by applying an electrical current to the sensor and observing the consequent
voltage drop. The current passing through the sensing element of the SPRT causes heat dissipation in the sensor and will eventually increase the measured temperature. The measurement is therefore intrinsically affecting the measurand. This temperature increase due to the heat dissipation is known as the self-heating effect [2]. Although the self-heating effect is basically a temperature phenomenon, it can be measured as a resistance difference by applying the two-current method. If $R_1$ and $R_2$ are resistances determined at currents $i_1$ and $i_2$ respectively, $R_0$, the resistance of SPRT at “zero current” could be found from the equation (1).

$$R_0 = R_1 \frac{i_1^2 (R_2 - R_1)}{i_2^2 - i_1^2}$$ \hspace{1cm} (1)

However, this two-current method is not practical for dimensional metrology application such as gauge block calibration, because it takes several tens of minutes to use this two-current method to measure temperature. One method to reduce the self-heating effect other than using the two-current method is to apply a lower current (e.g. 0.1 mA) than the usual current of 1 mA to the SPRT. In this case however, the fluctuation noise of the AC bridge increases resulting in bigger measurement uncertainty. We have proposed a practical and effective method of correcting the self-heating effect of SPRTs in gauge block measurement [3]. In this proposed method, the correction value for the resistance ratio of the SPRT and the reference resistor read by the AC-bridge is measured by analyzing the readouts obtained when the applied current is altered between 1 mA and 1.414 mA. The difference of the bridge readouts corresponds to the self-heating effect.

In this paper, we present the actual measurement results of the SPRTs being used in the gauge block interferometer of the Korea Research Institute of Standards and Science (KRISS). The temperature sensors evaluated are the capsule type SPRTs manufactured by Minco.

2. Obtaining Self-Heating Effect Correction Value of SPRT for gauge block measurement

In measuring temperature of a gauge block the SPRT sensor must be brought in close contact with the measuring face of the gauge block. This is realized by inserting the capsule type SPRT into a hole made within a copper block. To investigate the self-heating effect of SPRT attached on a gauge block, we periodically switched the applied current to the SPRT between 1 mA and $\sqrt{2}$ mA while the temperature inside the gauge block interferometer of KRISS was kept almost constant to the reference temperature of 20 °C by using cooled water circulation [4]. Figure 1 shows the variation of AC bridge readout during 22 hours.

To estimate accurately the average value of the bridge output difference, the least squares curve fitting method was used. During this process, the raw data was classified and divided into two groups. The first group consist of data obtained with 1 mA and the second group with 1.414 mA. Next, the data in each group were fitted to a polynomial of degree of 8 using MATLAB. Figure 2 shows the two groups of data fitted to polynomials. If we denote the functions of each fitted curve as $f_1$ and $f_2$ respectively, the average difference was obtained as the average of the difference of the two functions over the whole measurement range.
3. Calculating Temperature of Gauge Blocks during Calibration
Once the self-heating effect of each SPRT is analyzed and correction value for the AC bridge output is found, the self-heating compensated temperature is calculated using equation (2) and equation (3).

\[ W(T) = \frac{B_c(T)}{B(TPW)} = \frac{B(T) - \Delta B}{B(TPW)} \]  

(2)

Here, \( B_c(T) \) is corrected AC Bridge reading, \( B(T) \) is the readout of the AC bridge with a current of 1 mA, \( \Delta B \) is pre-measured correction for self-heating, and \( B(TPW) \) the zero-current resistance ratio at the triple point of water, which is measured during SPRT calibrations.

Finally, temperature of the gauge block or air is calculated by

\[ T = 273.15 + \sum_{i=1}^{9} \frac{D_i}{1.64^i} \left[ \frac{(W(T) - 1)(W_f(T_{Ga}) - 1)}{W(T_{Ga}) - 1} - 1.64 \right] \]  

(3)

where, \( W(T_{Ga}) \) is measured during calibration with zero current, \( W_f \) is the reference function and \( D_i \) \((i=1,\ldots,9)\) is a constant and that are given in ITS90 [1].

### 4. Summary and Conclusions

The new method of pre-measuring the necessary correction value of the AC-bridge output to compensate for the self-heating effect of SPRT, proposed by the authors was applied to the capsule type SPRTs used in gauge block interferometer at KRISS. The bridge ratio was monitored and recorded while current was altered between 1 mA and 1.414 mA. The data were grouped and separated into two groups and each was fitted to polynomials to obtain the function of each curve. The average value of the two functions over the whole measured data was taken as the correction value. Utilizing such obtained correction value for each SPRT, the self-heating effect could be directly corrected during the temperature measurement without the need of changing the current. Correction values for SPRTs used to measure temperature of gauge block and air were measured. Since in the precision dimensional metrology, the environment temperature is kept nearly constant at 20 °C, once the correction value is determined, it can be simply applied for any further temperature measurements. By experiment, it was found that without the proper correction for the self-heating effect, the measurement error of about 5.2 mK for the temperature of the gauge block and 5.1 mK for the air temperature will occur, which corresponds to the length error of 15 nm and 1.3 nm, respectively, for a gauge block having nominal length of 250 mm. This method is practical and very efficient for measuring gauge blocks.

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