Calibration of Thermocouple by Comparison against Standard Radiation Thermometer in a Blackbody Comparator

Beni Adi Trisna*, Suherlan, Asep Hapiddin*, Helmi Zaini**, Hidayat Wiriadinata and Ghufron Zaid

Temperature Laboratory, *Optical Frequency Laboratory, **Radiometry and Photometry Laboratory, Research Center for Metrology – LIPI (RCM – LIPI), Tangerang Selatan 15314, Indonesia

+E-mail: beni@kim.lipi.go.id or beni.ugm05@gmail.com

Abstract. A set-up to calibrate thermocouple up to 1500 °C by comparison against radiation thermometer is recently established in Research Center for Metrology – LIPI (RCM – LIPI). A blackbody cavity, made of silicon carbide, is put in a single-zone-controller furnace as a comparator block. A radiation thermometer standard (worked at λ = 650 nm) is employed to determine the reference temperature of the calibration. In this work, a type B thermocouple is calibrated in the range of 1000 – 1500 °C. The expanded uncertainty (k = 2) is evaluated to be 2.4 °C at 1500 °C. The uncertainty due to inhomogeneity of the thermocouple contributes more than 50% (1.4 °C) of the total uncertainty.

Keywords: thermocouple; calibration; radiation thermometer

1. Introduction

Among many types of temperature sensors, noble metal thermocouples are often used for high accuracy calibration work at a temperature above 1000 °C because platinum resistance thermometers can no longer work at this temperature. At a temperature below 1000 °C, low-uncertainty calibration can be achieved through calibration of thermocouples by fixed-points (1, 2). However, in the temperature range above 1000 °C, the traceability of thermocouple to the international temperature scale of 1990 (ITS-90) is limited by the lack of reliable high temperature fixed points (3) where only two available fixed points—the melting points of palladium and platinum. It can lead to the increasing of uncertainty value due to interpolation equation which, in turn, can have a severe impact on the total uncertainty of the thermocouple calibration.

A practical calibration technique to solve the problem about the number of reliable high temperature fixed points is by performing comparison calibration against a standard radiation thermometer in furnace (4-6). A direct traceability to ITS-90 can be established using this technique and the number of calibration points can be added to increase the degree of freedom of the calibration data. It is also offer affordable calibration system for developing NMI such as RCM-LIPI.

RCM-LIPI develops a set-up to calibrate thermocouple against a standard radiation thermometer using a blackbody comparator installed in a horizontal comparison calibration furnace. A type B thermocouple is calibrated using the set-up. This article describes the experimental details, calibration results and uncertainty calculation of the set-up. Some considerations are also provided to improve the set-up. This article adds new insights to existing scholarly discussions on the calibration of thermocouple at a temperature range above 1000 °C.
Fig. 1. Schematic diagram for calibration of noble-metal thermocouple against radiation thermocouple.

2. Experimental details

Fig. 1 shows a schematic diagram of the set-up for calibration of a thermocouple against standard radiation thermometer. A blackbody comparator, made of silicon carbide (SiC), is put in a single-zone-controller furnace, heated by six robust SiC heating elements (Landcal P1600B, Land Instruments, Meerbusch, Germany). It has about 100 mm cylindrical-conical cavity with a 50 mm diameter and the effective emissivity about 0.996 ± 0.001 at 650 nm. A type B thermocouple (SIMP 61889, Tempsens Instruments, Udaipur, India) is inserted 250 mm at the backside of the furnace, while at the rear side, a standard, monochromatic radiation thermometer (IKE LP4 80-58, PTB, Stuttgart, Germany), worked at $\lambda = 650$ nm, is directed on the aperture of the comparator at a distance about 1100 mm. The radiation thermometer is calibrated against the freezing point of copper of ITS-90 with the expanded uncertainty ($k=2$) of 0.52 °C at 1500 °C. The measuring junction of the thermocouple is placed at the position as closely as possible to the bottom part of the comparator to minimize the error due to axial temperature non-uniformity. Afterward, the output of the thermocouple and the radiation thermometer are read by a digital voltmeter (2182A, Keithley, Ohio, US) and a Pico ammeter (6485, Keithley, Ohio, US), respectively. All meters are traceable to SI units.

3. Results and Discussions

Traceability of thermocouple to ITS-90 is established by calculating the deviation of thermocouple emf and analysing the calibration uncertainty. In order to get these values, the comparison calibration is conducted at 11 set-points: 1000 °C, 1050 °C, 1100 °C, 1150 °C, 1200 °C, 1250 °C, 1300 °C, 1350 °C, 1400 °C, 1450 °C, and 1500 °C. First, to get the true surface temperature, the effective emissivity of the comparator is used to correct the radianc temperature reading obtained by the radiation thermometer. Second, the deviation of thermocouple emf is then calculated using the true temperature. Third, the uncertainty analysis is performed. The details of each step are explained hereafter.

All objects with temperature above absolute zero (0 K) emit electromagnetic radiation generated by the vibration of charged particles. The radiation thermometer measures the spectral radiation emitted by the object surface, and then converts it to the radianc temperature (apparent temperature). In fact, the real surface temperature (kinetic temperature) of the object is not the same as the radianc temperature $T_e$. The real surface temperature $T$ is calculated using Wien’s approximation (7). In some writings, the term effective spectral emissivity is used rather than the spectral emissivity because the emissivity of a surface depends not only on the wavelength but also on the nature of the surface, such as roughness, shape and angle. Two objects made of the same material with the same value of $T$ could have different $T_e$, when measured by a radiation thermometer simply because their emissivity is different due to their difference in surface nature. In our experiment, the effective spectral emissivity of the comparator is about 0.996 ± 0.001 at 650 nm which corresponds to the radianc temperature corrections ranging between −0.30 °C (at ~1000 °C) and −0.57 °C (at ~1500 °C).
The reference thermocouple-emf is obtained from converting $T$ with respect to the type of type B thermocouple. The deviation of thermocouple-emf $dT$ is calculated by subtracting the reference emf from the measured emf at each calibration point. In order to obtain the values of $dT$ on the other points, a deviation function is created using a least square fit procedure.

Table 1 gives the values for each uncertainty components in the calibration of type B thermocouple. The uncertainties due to calibration and drift of indicator contribute to a value of 0.004 °C and 0.0005 °C, respectively. The repeatability of thermocouple is estimated from the maximum value of standard deviation for 15-time measurements of the thermocouple reading at each calibration points. SEE of the deviation function and indicator correction is calculated to be 0.17 °C and 0.001 °C, respectively. The calibration of standard radiation thermometer is estimated from the maximum value of uncertainty in the calibration range of (1000-1500) °C. The calibration and drift of the radiation thermometer add values of 0.26 °C and 0.03 °C, respectively. The repeatability of standard radiation thermometer is calculated from the maximum value of standard deviation for 15-time measurements of the thermometer reading at each calibration points. The assessment of temperature non-uniformity and instability on the comparator shows that these components contribute not exceed a value of 0.033 °C and 0.028 °C, respectively. SSE of the comparator contributes to 0.029 of uncertainty from Ref. (6). The uncertainty due to determination of the comparator emissivity is calculated to not exceed a value of 0.23 °C. The uncertainty due to thermocouple inhomogeneity is estimated from the Ref. (8) for a new fabricated thermocouple. The others sources with a contribution value of 0.34 °C to the combined uncertainty are from parasitic emfs, measurement hysteresis, and noise.

Fig. 2 shows the comparison of thermocouple calibration with the limit of tolerance in ASTM E230 (red line) (9). There are two interesting regions in the graph: the outlier and the inlier regions. The outlier region, at temperature ranges approximately (1000-1075) °C and (1250-1500) °C, is the region where there is exist a part of calibration data—summation between the deviation of emf and the uncertainty—falls beyond the limit of tolerance. On the other hand, the inlier region, at temperature ranges approximately (1075-1250) °C, is the region where all calibration data show a good agreement within the tolerance. For best performance, the thermocouple shall be used in the inlier region.

**Table 1.** Sources and estimates of the uncertainty components in the calibration of type B thermocouple against standard radiation thermometer on a blackbody comparator

| No. | Uncertainty Sources                                      | Standard Uncertainty $(k=1)$, °C |
|-----|---------------------------------------------------------|---------------------------------|
| 1   | Calibration of indicator                                | 0.004                           |
| 2   | Drift of indicator                                      | 0.000                           |
| 3   | Repeatability of thermocouple                           | 0.034                           |
| 4   | SEE of deviation function                               | 0.170                           |
| 5   | SEE of indicator correction equation                    | 0.001                           |
| 6   | Calibration of standard radiation thermometer           | 0.260                           |
| 7   | Drift of standard radiation thermometer                 | 0.030                           |
| 8   | Repeatability of standard radiation thermometer         | 0.019                           |
| 9   | Temperature non-uniformity of blackbody comparator      | 0.033                           |
| 10  | Temperature instability of blackbody comparator         | 0.028                           |
| 11  | SSE of the blackbody comparator                         | 0.029                           |
| 12  | Determination of blackbody comparator emissivity        | 0.258                           |
| 13  | Inhomogeneity of thermocouple                           | 0.00046*t                      |
| 14  | Other sources                                           | 0.338                           |
|     | Combined standard uncertainty $(k=1)$, °C               | $(0.53±0.00046*t)$ °C           |
Fig. 2. The comparison between results of thermocouple calibration and limit of tolerance listed in ASTM E230.

4. Conclusions and Future Works
A set-up to calibrate thermocouple against radiation thermometer has been established and tested in RCM-LIPI. One type B thermocouple has been calibrated using the set-up. The results show that the set-up generates a calibration and measurement capability (CMC) value of 2.4 °C (k=2) at 1500 °C, which is appropriate for the most usual applications of high-temperature measurement using thermocouples. Assessment of the inhomogeneity of type B thermocouple in various temperature range is required for further experimental study. In addition, validation of the set-up with a eutectic fixed-points is also important.

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