Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 23-24, 2019

Review of Error Sources for Application of Thermocouples in RCS Temperature Measurement for an Integrated Reactor

Inkoo Hwang [a*], Sewoo Cheon [a], Gwisook Jang [a], Wonman Park [a], Changhwoi Kim [a]
[a] *Division of Nuclear ICT Research, Korea Atomic Energy Research Institute, Daejeon, Korea*
[*] *Corresponding author: ikhwang@kaeri.re.kr*

1. Introduction

As the temperature of a Reactor Coolant System (RCS) needs to be measured by thermocouple (TC) elements rather than Resistance Temperature Detectors (RTDs) for an integrated reactor, an important issue in using TCs is accuracy deterioration. This paper presents an analysis review on the accuracy effect when applying TCs for such industrial high temperature measurement of reactor coolant.

2. Selection for RCS Temperature Sensors

It is essential to measure the temperature of the reactor coolant flowing in and out of steam generators for monitoring and controlling the reactor thermal output in pressurized nuclear power plants. Among several types of temperature sensors available for industrial process applications, only RTDs and TCs are regarded as being able to be used to measure high temperatures above 300℃ in liquid-based process plants such as nuclear power plants [1].

Owing to their excellent accuracy and stability performance, RTDs are used for measuring the RCS temperature in most current Pressurized Water Reactors (PWRs). However, TCs need to be used for an integrated reactor system in which Steam Generators (SGs) are contained in the reactor pressure vessel because K-type TCs are regarded more tolerant than RTDs in neutron flux [1, 2].

Compared with RTDs, one of the disadvantages of using TCs for temperature measurement is the issue of inaccuracy or uncertainty. This paper presents an analysis result estimating the extent of accuracy deterioration when TCs are used instead of RTDs for RCS temperature measurement.

3. Analysis of Accuracy

3.1 Key Error Factors Affecting Accuracy of a TC-based Temperature Instrumentation Channel

The main sources of error in a temperature measurement loop with a TC are:

(1) Error in the TC itself,
(2) Extension wire error,
(3) Measurement device error including non-linearity,
(4) Cold junction sensing error,
(5) Drift error,
(6) Mounting error,
(7) Electric noise ingress.

Among the above factors, (1), (2), and (5) are mainly caused by material inhomogeneity in the manufacturing process or crystallographic change with long time usage under high temperature. Factors (3) and (4) are issues of measurement circuits, and they can be minimized by utilizing a precise instrument circuit. Factors (6) and (7) are related to the physical installation methods, dimensions, or locations.

3.2 Uncertainty Analysis

The circled numbers in Fig. 1 illustrate the error terms in a TC circuit loop for temperature measurement for Instrumentation and Control (I&C) systems in industrial process plants such as nuclear plants.

① indicates the mounting error, which means a deviation between the true process temperature, T_T, and the temperature transferred to the measurement junction of TC, T_m. This type of error is related to the installation and junction types of TCs. It may be large or small depending on the situations. However, for this calculation, it is assumed to be negligible.

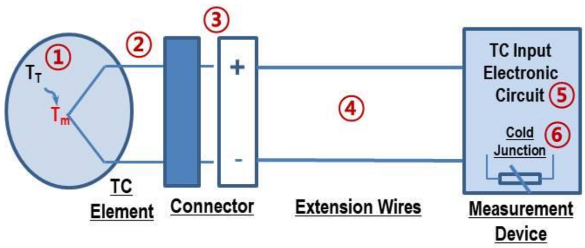

Fig. 1 Thermocouple (TC) connection circuit

② implies the error in the TC element itself. The ranges of industrial TC accuracy are classified in the national standards [3]. For a K-type TC, which is widely used in industrial plants, its error limit of Class 2 is specified as ±2.5℃.

③ shows an error created from the temperature difference, ΔT, along the TC connector pins. It is anticipated that the proximity between the connector pins would not make the ΔT more than ±0.5℃.

④ is another error source of the extension wires which must be compatible to the installed TC materials. The uncertainty limits of each type of extension and compensation wires are also defined in the national standards [4]. For a K-type extension wire, its error limit of Class 2 is specified as ±2.5℃.

⑤ represents the total uncertainty of a TC analog input module of the plant instrumentation system, which converts a millivolt signal of the TC to a corresponding temperature value. The uncertainty range of industrial TC input modules is generally ±0.1~0.5% full scale. Thus it will be reasonable to take ±0.3% with calibration, which is the performance of an instrumentation device currently used in nuclear power plants [5]. Assuming the scale range is set as 0~400℃ for RCS temperature instrumentation, the uncertainty will be within ±1.2℃.

⑥ indicates the error of reference junction temperature, which must be precisely measured for translating the process temperature. It is measured by a high-resolution thermometer such as a thermistor. Therefore, it is reasonable to regard its uncertainty within ±0.5℃.

Another key error factor for a TC system is the drift error that occurs at high temperature exposure during a long period of usage. This is caused by atomic crystal structure change, known as the Short Range Ordering (SRO) phenomenon, between 150~600℃ and oxidation progress over 500℃ [6]. Therefore, the range of drift is highly variable depending on the exposed temperatures, TC structures (bare-wire or mineral-insulated sheath types), and manufacturers. One experiment for a K-type mineral-insulated sheathed TC shows a 2℃ shift at 500℃ over 1,000 hours [7].

3.3 Overall Uncertainty Calculation of a Thermocouple (TC) Measurement Circuit

With the typical uncertainty values addressed in Section 3.2, the overall uncertainty of the entire TC measurement channel can be calculated via the Root-Sum-Square (RSS) method [8-9]. For simplicity, mounting errors and drift errors are not included in this calculation because they are one-sided (positive or negative side), and it is not easy to define typical error boundaries. Thus, the overall uncertainty will be

$$U_{TC} = \pm(2.5^2 + 0.5^2 + 2.5^2 + 1.2^2 + 0.5^2)^{\frac{1}{2}} \approx \pm 3.8\ ℃. \quad (1)$$

When we use a typical RTD element in an RCS loop outside the reactor pressure vessel in a conventional nuclear plant, the tolerance of class B will be ±1.8℃ at 300℃[10]. And, if we modify or set the input rage of an RTD analog module to be 300 ~ 400℃ to narrow the uncertainty, then the accuracy will be ±0.3℃ when regarding the uncertainty as a typical ±0.3% full scale. Thus, assuming that the drift error is ±0.5℃ per 2 years and other factors such as installation, wire resistance effect compensation, and self-heating errors are properly confined and managed to be negligible, the overall uncertainty of an RTD circuit will be

$$U_{RTD} = \pm(1.8^2 + 0.5^2 + 0.3^2)^{\frac{1}{2}} \approx \pm 1.9\ ℃ \quad (2).$$

Comparing the TC uncertainty in Eq. (1) to this RTD example in Eq. (2), the uncertainty has increased twice to almost ±2℃. If we consider mounting error and drift factors for TCs, the deviation will expand further.

Therefore, usage of TCs instead of RTDs for measuring RCS temperatures in an integrated reactor will present a sacrifice in set-point determination for a reactor protection system.

4. Conclusions and Suggestions

As K-type TCs are required to be used for RCS temperature measurement in an integrated reactor, we have estimated the effect of uncertainty for the measurement channel, and have compared this to a conventional RTD-based instrumentation method.

Even though we disregarded the drift factor of TCs, which is one of the concerns for high temperature measurement, the accuracy loss for average class TCs has been estimated to be considerably higher than that of RTDs (class 2 for TCs and class B for RTDs).

In addition, one of the concerns is that it is not easy to confine drift error tolerance for TCs because the drift mechanism is complicated and variant depending on the exposed temperatures and the manufactured mechanical properties. In contrast, RTDs generally have a small drift value.

Based on our review and analysis, it is recommended that top class TCs as well as extension wires should be selected for RCS temperature measurement for an integrated reactor, and an experiment should be conducted to identify the drift amount of the selected TCs for the normal operating temperature to be exposed to during their required operation period.

ACKNOWLEDGMENT

This research is supported by a nuclear research and development project funded by the Korea Atomic Energy Research Institute.

REFERENCES

[1] I. Hwang, et al., Considerations regarding Temperature Measurement using RTDs for Industrial Process Plants, KNS Autumn Meeting, Yeosu, Korea, Oct. 25-26, 2018

[2] R. V. Nieuwenhove and L. Vermeeren, Irradiation effects on temperature sensors, R-3693, ref. INSTR/1248/03-02, March 2003.

[3] KS C IEC 60584-2, Thermocouples – Part 2: Tolerances, 2004.

[4] KS C IEC 60584-3, Thermocouples – Part 3: Extension and compensation cables – Tolerances and identification system, 2004.
[5] Operating Instruction Manual for APC, 2016.
[6] E. S. Webster, Drift in Type K Bare-Wire Thermocouples from Different Manufactures, Int. J Thermophys. (2017) 38:70, Mar. 2017.
[7] R. E. Bentley, Long-term Drift in Mineral-insulated Nicrosil-sheathed Type K Thermocouples, Sensors and Actuators A, 24(1990) 21-26, 1990.
[8] ASME PTC 19.1-1998, Test Uncertainty, Instruments and Apparatus, Supplement to the ASME Performance Test Codes, 1998.
[9] J. T. Nakos, Uncertainty Analysis of Thermocouple Measurements Used in Normal and Abnormal Thermal Environment Experiments at Sandia's Radiant heat Facility and Lurance Canyon Burn Site, Sandia Report, Apr. 2004.
[10] KS C 1616, Resistance Temperature Detector, 1992(2017 Reaffirmed), Dec. 1992.