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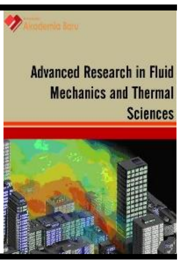

# Uncertainty of Temperature measured by Thermocouple

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**ABSTRACT**

Reliability of data is important for researchers to verify their research result. For temperature measurement involving thermocouple, uncertainty needs to be determined before deciding the reliability of data. In this research, four error sources were proposed to have contributed in the uncertainty of temperature measured by a thermocouple which were resolution limit of data acquisition device, error in temperature measurement based on voltage measurement, reference junction compensation error and data fluctuation. Experiments were carried out to obtain reference junction compensation error and data fluctuation using HIOKI data logger (LR8400-20). The procedure to obtain the uncertainty of the measured temperature including the reference junction compensation uncertainty is proposed. The uncertainty was obtained by combining all the error values with root-sum-square equation. The uncertainty for K thermocouple obtained from this research was 0.42 °C.

***Keywords:***
Uncertainty; thermocouple; reference junction compensation

## 1. Introduction

A thermocouple is a widely used temperature sensor consists of two different electrical conducting wires which shares two connecting junctions. The connecting junctions are known as reference junction (cold junction) and measuring junction (hot junction). Typical connections of a thermocouple are shown in Figure 1. The working principle of a thermocouple is based on Seebeck effect which is a phenomenon where the thermo-electromotive force (EMF) is induced when there is a temperature difference between two junctions [1]. The difference of the electrical potential produced by a thermocouple depends on the difference of the junction temperatures. Therefore, the reference junction temperature should be known to determine the measuring junction temperature. The reference junction used to be placed in an ice-water bath of 0 °C as shown in Figure 1(a). However, it is inconvenient to keep the temperature of the ice-water bath 0 °C for a long

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time. Therefore, a data logger has been developed in which the reference junction compensation (RJC) is automatically conducted measuring the terminal temperature in a data logger as shown in Figure 1(b).

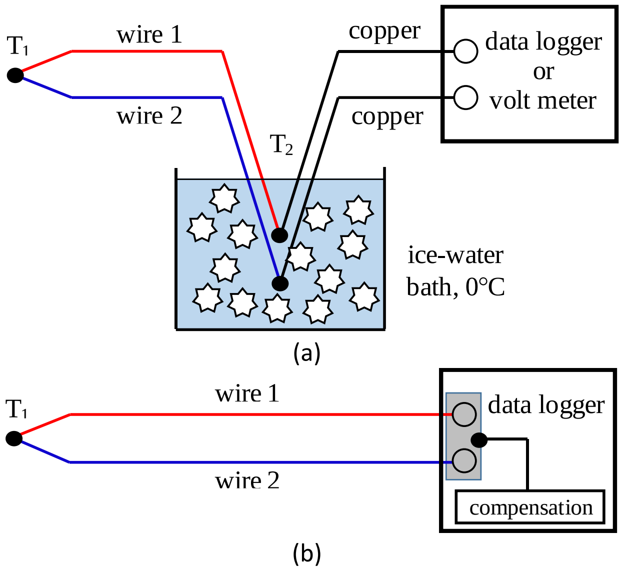


**Fig. 1.** Conceptual connection for thermocouple and data logger [2]

The accuracy of the temperature measurement by a thermocouple is provided in a product specification sheet of a data logger. Examples of manufacturers' reported accuracy of the temperature measurement with a type T thermocouple are tabulated in Table 1. The resolution is known as the least unit of data that can be obtained by a device and value smaller than that will not be able to record. The EMF of a thermocouple is measured by a voltage measurement unit and the measured voltage is interpreted to the temperature using the inverse polynomials. Therefore, the accuracy of the temperature measurement depends on the accuracy of the voltage measurement. When thermocouple wires are directly connected to the terminal of a data logger, the terminal becomes the reference junction. Therefore, it is necessary to measure the terminal temperature for the RJC. However, as shown in Table 1, the accuracy of the RJC is relatively low.

**Table 1**
Examples of accuracy of the temperature measurement (T thermocouple)

| | Accuracy of voltage measurement | Re-solution | Accuracy of temperature measurement | Accuracy of RJC | Total accuracy | Ref. |
|---|---|---|---|---|---|---|
| O | ±20μV | - | ±0.1% of rdg | ±0.5°C | ±(0.1% of rdg+0.5°C) | [3] |
| K | ±10μV | 0.01°C | - | ±0.5°C | - | [4] |
| H | ±10μV | 0.01°C | ±0.6°C | ±0.5°C | ±1.1°C | [5] |
| E | ±(0.02% of rdg+6μV) | 0.1°C | ±(0.02% of rdg+0.2°C) | ±0.3°C | ±(0.02% of rdg+0.5°C) | [6] |

An uncertainty analysis of experimentally measured value is necessary for results to be used to their fullest value. In the temperature measurement with a thermocouple, a few factors contribute in the uncertainty of the measured temperature. Four factors are considered in this research which are the resolution of a data logger, the accuracy of temperature measurement caused by the accuracy of the voltage measurement, the accuracy of the RJC and the fluctuation of data [2]. The uncertainty based on the resolution and the accuracy of the temperature measurement caused by the voltage measurement is the instrument uncertainty. The uncertainty based on the RJC is the RJC uncertainty. The uncertainty based on the data fluctuation is the random uncertainty. As mentioned earlier, the accuracy of the RJC listed in Table 1 ranges from 0.3 to 0.5 °C and is low comparing with other accuracy. Therefore, measuring the terminal temperatures and the internal terminal temperature, which is used for the RJC, the accuracy of the RJC is assessed. Also, the procedure to obtain the uncertainty of the measured temperature including the RJC uncertainty has not been reported yet. Therefore, in this paper, the procedure to obtain the uncertainty of the measured temperature including the RJC uncertainty is proposed.

## 2. Experimental Setup

In this research, a HIOKI data logger (LR8400-20) with a voltage/temperature unit (LR8500) is used to assess the RJC error. The LR8500 unit has terminals of 15 channels. The connection of the thermocouples is also shown in Figure 2. As shown in Figure 2, two type T thermocouples, a and b which are connected to the terminal 2 and 3, respectively, are used to measure the temperatures of the (+) and (-) terminals of channel 12. To avoid the RJC error, an ice-water bath is used. The temperatures of the (+) and (-) terminals of other channels are measured in the same way.

LR8400-20 measures an internal temperature, $T_{internal}$, in the LR8500 unit which is used for the RJC. When the (+) and (-) terminals of a channel are shunted by a copper wire, the EMF of the channel becomes zero and the internal temperature which is used for the RJC, is displayed since the EMF is zero when the hot junction temperature is equal to the internal temperature. As shown in Figure 2, the (+) and (-) terminals of the channel 1 are shunted by a copper wire to know the $T_{internal}$. All the measurements are conducted after 30 minutes of warming-up.

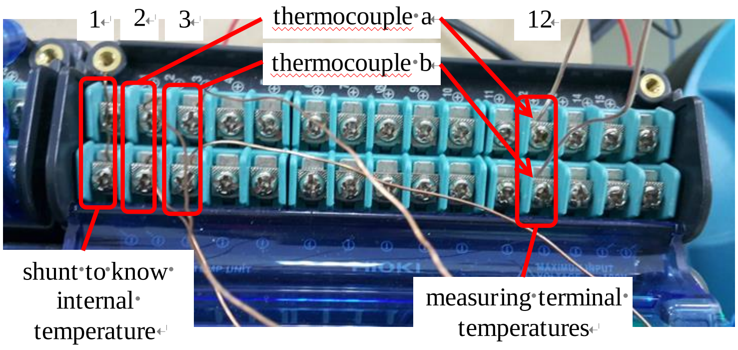


**Fig. 2.** Temperature measurement of (+) and (-) terminals

## 3. Results

### *3.1 Accuracy of Reference Junction Compensation*

Before measuring the terminal temperatures, the internal temperatures, $T_{internal}$, are obtained by shunting all the (+) and (-) terminals of each channel. The results are shown in Figure 3. The $T_{internal}$ of all channels except channels 14 and 15 are identical. The $T_{internal}$ at the channel 14 and 15 are 0.1 °C and 0.2 °C lower than that at the channel 13. Note that LR8400-20 measures the temperature at somewhere in the LR8500 unit and make it the internal temperature, $T_{internal}$ and the internal temperatures of each channel of the LR8500 unit are not measured individually. The manufacturer just assumed that the $T_{internal}$ at the channels 14 and 15 are 0.1 °C and 0.2 °C lower than that at the channel 13 considering the heat loss from the LR8500 unit since the channel 15 locates at the edge of the unit.

Measurements on temperatures at the (+) terminal and the (-) terminal, $T_+$ and $T_-$, and the internal temperature, $T_{internal}$, were repeated few times. The measured temperatures are plotted in Figure 4. Temperature differences among the $T_+$, $T_-$ and the terminal temperatures, $T_{internal}$ are observed and also there is the temperature difference between the $T_+$ and $T_-$. However, the maximum difference between the $T_-$ and $T_+$ is less than 0.3 °C as seen in Figure 4. Note that the internal temperatures in Figure 3 are obtained at the same time, however, the terminal temperatures and the internal temperature of each channel in Figure 4 are obtained at different times. Therefore, the internal temperature at each channel is different in Figure 4.

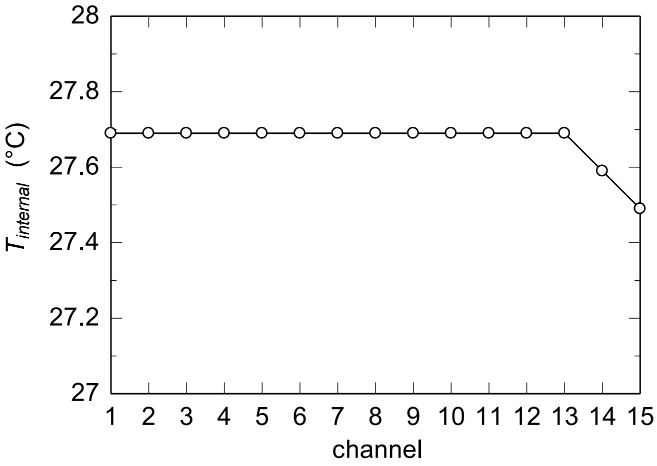


**Fig. 3.** Internal temperatures at each channel

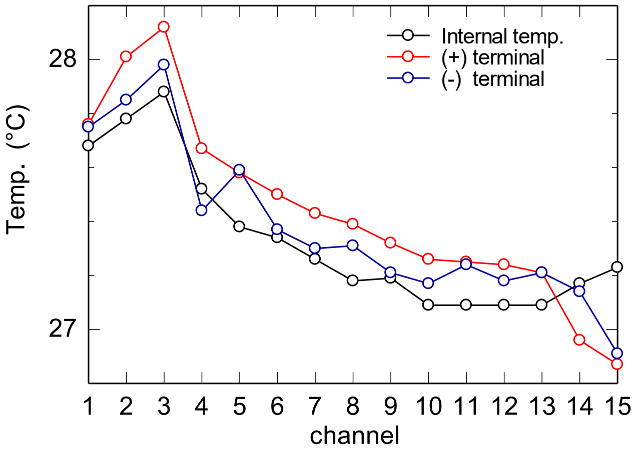


**Fig. 4.** Terminal temperatures and internal temperatures

Here we consider a case where the $T_-$ is higher than the $T_+$ as shown in Figure 5(a). In such a case, the EMF is expressed as Recktenwald [7]

$$E = \int_{T_-}^{T_H} S_{12}\, dT + \int_{T_+}^{T_-} S_1\, dT \tag{1}$$

where $S_{12}$ and $S_1$ are the relative Seebeck coefficient of the thermocouple and absolute Seebeck coefficient of the wire 1, respectively. Since the maximum difference between the $T_-$ and $T_+$ is less than 0.3 °C, we assume that the $S_1$ between the $T_-$ and $T_+$ is constant. Then, Eq. (1) can be rewritten as

$$E \approx \int_{T_-}^{T_H} S_{12}\, dT + S_1(T_- - T_+) \tag{2}$$

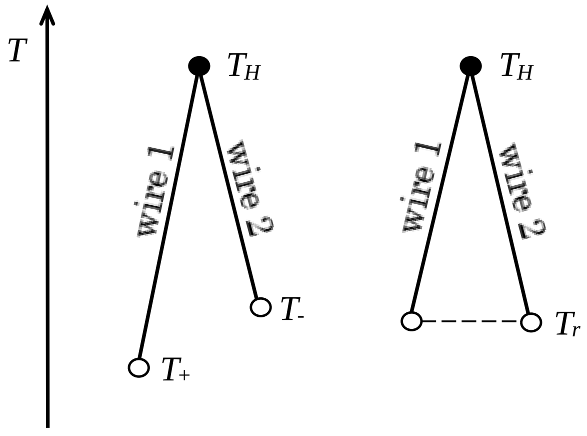
The $T_r$ in Figure 5(b) is the reference temperature under a situation that the EMF is equal to the EMF calculated from Eq. (2). In such a case, the EMF of the thermocouple is expressed as

$$E = \int_{T_-}^{T_H} S_{12}\, dT + \int_{T_r}^{T_-} S_{12}\, dT \approx \int_{T_-}^{T_H} S_{12}\, dT + S_{12}(T_- - T_r) \tag{3}$$

Substituting Eq. (3) into Eq. (2), the following equation is obtained.

$$T_r = T_- - \frac{S_1}{S_{12}}(T_- - T_+) \tag{4}$$

Note that the values of $S_{12}$ and $S_1$ depend on the materials of the thermocouple, therefore, the $T_r$ also depends on the type of the thermocouple. Values of $S_{12}$ and $S_1$ of the K and T thermocouples at a room temperature are listed in Table 2 [8-9].



(a) (b)

**Fig. 5.** Conceptual diagram to calculate EMF

**Table 2**

Relative and absolute Seebeck coefficients of thermocouple K and T [8-9]

| Thermocouple | $S_{12}$ (μV/K) | $S_1$ (μV/K) |
|---|---|---|
| K | 40.5 | 22.2 |
| T | 40.2 | 1.9 |

The temperature difference, $T_r - T_{internal}$, expresses the error of the RJC. The temperature difference, $T_r - T_{internal}$, is plotted in Figure 6. The $T_r - T_{internal}$ ranges from -0.31 to 0.21 °C for the T thermocouple and from -0.34 to 0.20 °C for the K thermocouple. Therefore, the accuracy of the RJC is ±0.31 °C for the T thermocouple and ±0.34 °C for the K thermocouple. The accuracy of the RJC provided by the manufacturer is ±0.5 °C. The measured accuracy of the RJC are in the range of the accuracy provided by the manufacturer. Note that Eq. (4) is also available in the case that the $T_+$ is higher than the $T_-$.

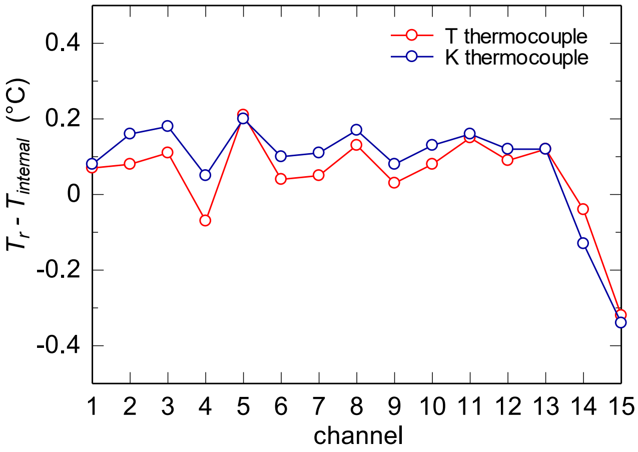


**Fig. 6.** Temperature difference between reference and internal temperatures

### 3.2 Uncertainty of Measured Temperature

Four factors are considered for the uncertainty of measured temperature which are the resolution of a data logger, the accuracy of temperature measurement caused by the accuracy of the voltage measurement, the accuracy of the RJC and the fluctuation of data.

### 3.2.1 Uncertainty of instrument

The uncertainty of the instrument consists of the resolution of a data logger, the accuracy of temperature measurement caused by the accuracy of the voltage measurement. Since the HIOKI's resolution is 0.01 °C based on the specification of the LR8400-20, the uncertainty of the resolution is ±0.005 °C. The EMF produced by a thermocouple is measured by the voltage measuring unit and the measured voltage is interpreted to the temperature using the inverse polynomials. The accuracy of the voltage measurement is ±10μV based on the specification of the LR8400-20. The inverse polynomials are almost the linear function. Therefore, the conversion coefficients are 0.0251 for the K thermocouple and 0.0259 for the T thermocouple [10]. The uncertainty of temperature measurement is tabulated in Table 3. The uncertainty of the resolution is much smaller than the uncertainty of temperature measurement. Therefore, the uncertainty of the instrument is equal to the uncertainty of temperature measurement.

**Table 3**
Uncertainty of temperature measurement caused by accuracy of voltage measurement

| Accuracy of voltage measurement | Thermocouple K | Thermocouple T |
|---|---|---|
| ±10 μV | ±0.25 °C | ±0.26 °C |

### 3.2.2 Uncertainty of fluctuation

The uncertainty of fluctuation was obtained by measuring temperature of a metal block under controlled surrounding temperature. The 50/60 Hz cut-off filter setting is selected. The measured temperature was plotted in Figure 7. Although the room temperature is controlled, the metal block temperature slightly increases or decreases with time like a temperature drift. Therefore, the temperature drift is expressed by a linear function (a red dashed line in Figure 7) and the temperature fluctuation, $T'$, is calculated from the following equation. The linear equation of the temperature drift is obtained by a curve fitting.

$$T' = T_{measured} - T_{drift} \tag{5}$$

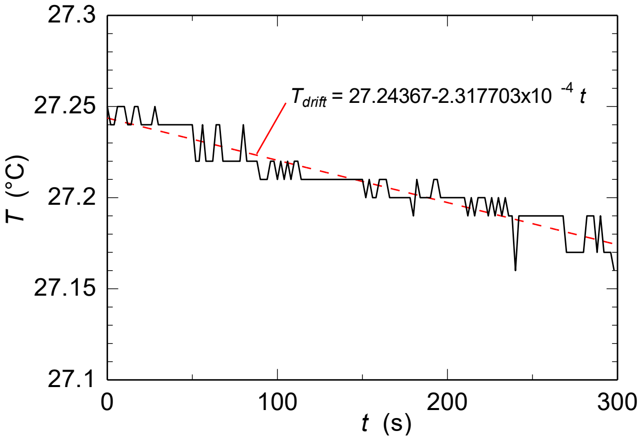


**Fig. 7.** Temperature of a metal block

The temperature fluctuation is plotted in Figure 8 as a function of time. The range of the uncertainty of the resolution is also plotted in Figure 8. The uncertainty of the resolution is smaller than the fluctuation. The temperature measurements were repeated on different days. The standard deviation of the fluctuation, $\sigma$, is calculated and $\pm 2\sigma$ is chosen for the uncertainty due to the fluctuation and the result is tabulated in Table 4. The uncertainty of random fluctuation is not constant. However, it is much smaller than the uncertainty of the instrument and the uncertainty of the reference junction compensation. This is because the 50/60 Hz cut-off filter setting is selected.

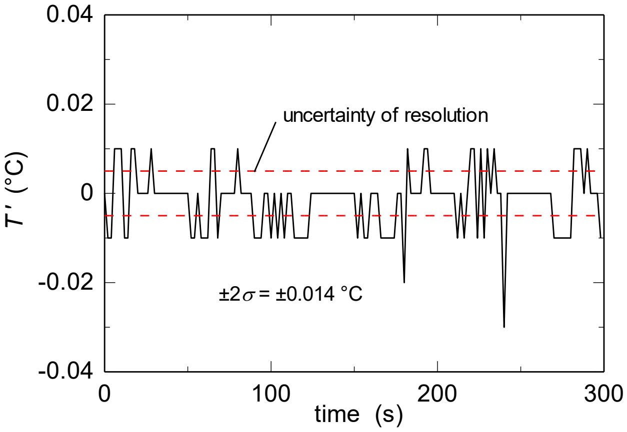


**Fig. 8.** Graph showing fluctuating data and temperature gap of thermocouple data

**Table 4**
Uncertainty of random fluctuation obtained on different day

| Date | $2\sigma$ (°C)<br>Thermocouple K | Thermocouple T |
|---|---|---|
| 25/4/2019 | 0.0150 | 0.0286 |
| 6/5/2019 | 0.0137 | 0.0148 |
| 7/5/2019 | 0.0129 | 0.0149 |
| 9/5/2019 | 0.0122 | 0.0156 |

### *3.2.3 Overall uncertainty of measured temperature*

Overall uncertainties obtained with root-sum-square, Eq. (6), are listed in Table 5. The overall uncertainties for the K thermocouple and the T thermocouple are ±0.42 °C and ±0.40 °C, respectively. Random error is too small, and it does not affect overall uncertainty value. The uncertainty of the reference junction compensation is relatively large, the usage of the ice-water bath is recommended in an academic purpose.

$$u_{total} = \sqrt{u_{inst}^2 + u_{RJC}^2 + u_{rand}^2} \tag{6}$$

**Table 5**
Overall uncertainty

| Thermocouple | $u_{inst}$ °C | $u_{RJC}$ °C | $u_{rand}$ °C | $u_{total}$ °C |
|---|---|---|---|---|
| K | ±0.25 | ±0.34 | ±0.012 ~ ±0.015 | ±0.42 |
| T | ±0.26 | ±0.31 | ±0.015 ~ ±0.029 | ±0.40 |

## 4. Conclusion

i. Uncertainty of measured temperature by the HIOKI data logger (LR8400-20) is 0.42 °C for the thermocouple K and 0.40 °C for the thermocouple T when the RJC is used. This value is much less than 1.1 °C which is reported by the manufacturer and data logger is reliable.
ii. The uncertainty of the reference junction compensation is relatively large, the usage of the ice-water bath is recommended in an academic purpose.

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