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Implementation of Uncertainty Analysis of Temperature Measurement

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ABSTRACT

Thermocouples is a common and widely used device in many industrial, scientific and OEM applications. As a temperature sensor, thermocouple is used in measuring temperature. 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. There are plenty of ways researchers have tried to get the uncertainty of thermocouple by using other equipment, but for data loggers an easier and faster way to obtain the RJC error is strongly required. Hence, a new easier and faster way to obtain the RJC error was proposed in this research. The purpose of this research was to obtain the result of reference junction compensation in parallel connection throughout 15 channels in a data logger with a shorter time taken, efficiently and accurately than series connection. Experiments were carried out by using HIOKI data logger (LR8400-20) connecting with thermocouple. Thermocouples consist of two wire legs made from different metals. The wires legs are welded together at one end, creating a junction. This junction is where the temperature was measured while the wire is connected to each other parallel on the data logger terminal. Three error sources were proposed to have contributed to the uncertainty of temperature measured by a thermocouple which were resolution limit of data acquisition device, reference junction compensation error and random error. The uncertainty was obtained by combining these three error values with the root-sum-square equation.

1. Introduction

Data collection is the primary and most important step for research [1], thus experiments will be carried out and experimental instruments will be used to measure data for further analysis so that data-driven decisions can be made for research [2].

An experiment which involve measuring instruments or data logging instruments might cause uncertainty in data or final result obtained [3]. Consequently, data obtained might vary from the true value of measurement. For temperature measurement, the uncertainty is dispersion of the measured temperatures.

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Thermocouples are a common and widely used device in many industrial, scientific and OEM applications [4]. It can be found in nearly all industrial markets, for example: Power generation, oil and gas, pharmaceutical, biotech and so on. Thermocouples are typically selected because of their low cost, high temperature limits, wide temperature ranges and durable nature. As a temperature sensor, thermocouple is used in measuring temperature. There are plenty of ways researchers have tried to get the uncertainty of thermocouple by using other equipment, but for data loggers that involves uncertainty.

Thermocouples consist of two wire legs made from different metals. The wires legs are welded together at one end, creating a junction. This junction is where temperature is measured. When the junction experiences a change in temperature, a voltage is created. The voltage can then be interpreted using thermocouple reference tables to calculate the temperature. It directly converts electric voltage into temperature or *vice versa* which is known as Seebeck effect.

There are two basic groups of thermocouples. One uses materials like iron, nickel, copper and constantan which are in group base metals that produce high thermoelectric voltages when paired. The other group has more expensive noble metals such as rhodium, platinum, rhenium and tungsten, which are used at much higher temperatures. For this research we applied Omega type T as thermocouple.

However, when thermocouples are unable to produce readings for the temperature difference e.g. between the junctions, a data acquisition system is needed. Therefore, a data logger which is a portable measurement instrument that is capable of autonomously recording temperature over a defined period of time; reads temperature, voltage, resistance and humidity. The digital data can be retrieved, viewed and evaluated after it has been recorded. When the same condition for measuring instruments in a data logger was applied, it might cause instrument error and lead to uncertainty in measurement.

1.1 Reference Junction Compensation

The thermocouple is a differential device rather than an absolute temperature measurement device, so, the reference junction temperature must be known to get an accurate absolute temperature reading. This process is known as reference junction compensation as shown in Figure 1 [5].

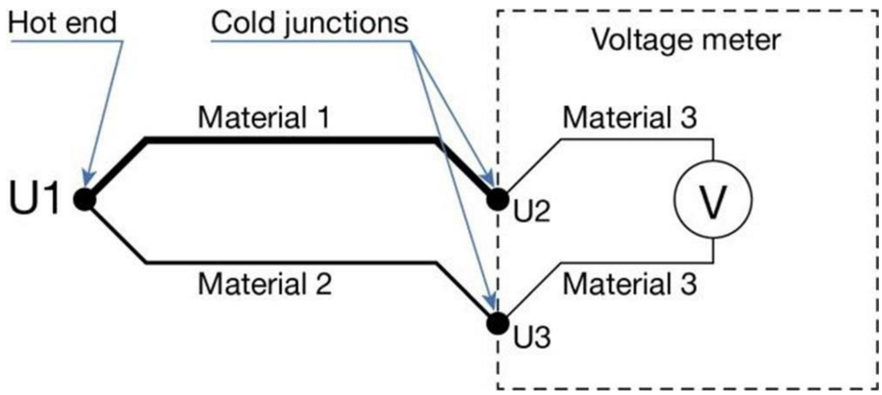

Fig. 1. Reference junction in thermocouple

In order to eliminate this error, cold-junction compensation needs to be established to ensure the accuracy of the experiment. The shaved ice-bath temperature measured by resistance temperature detector (RTD) is used for temperature measurement. The shaved ice-bath temperature starts from 0°C and slightly increases.

In order to improve accuracy of data and decide the reliability of data, uncertainty [6-8] of measured temperature needs to be determined in a more concise and accurate way. Therefore, in this research, the uncertainty of temperature measured by a thermocouple would directly be connected to a data logger. The wire was connected to each terminal in parallel form. At the reference junction point, an ice bath was set to maintain 0°C and to ensure accurate data was obtained. After determining the reference junction compensation effect, random error and instrumentation error, the uncertainty of thermocouple measurement was calculated.

This research's main focus was on uncertainty generated by different channels in data logger which was connected all in parallel condition. Hence a new, easier and faster way to obtain the RJC error was proposed by this research.

1.2 Parallel Connection

Components connected in parallel are connected along multiple paths, and each component has the same voltage across it, equal to the voltage across the network connecting in data logger. The current through the network is equal to the sum of the currents through each resistor. A lower resistance is obtained during parallel connection. Besides the parallel connection was beneficial to raise current but the voltage remained unchanged [9].

2. Methodology

The process flow starting from simulation, examining the effect of reference junction compensation, resolution limit error and random error until the calculation of overall uncertainty in temperature is illustrated in Figure 2. Table 1 also lists the coefficient values needed for the inverse polynomials calculation.

2.1 Inverse Polynomials Voltage-Temperature Conversion

When voltage was measured with data logger, conversion for voltage to temperature was carried out with thermocouple inverse polynomial equation below,

$$t_{90} = c_0 + c_1E + c_2\mathrm{E}^2 + \cdots + c_i\mathrm{E}^{\mathrm{i}} \quad (1)$$

where, t_{90} is the coefficient of approximate inverse functions giving temperature in degree Celsius (°C), E is measured thermoelectric voltage in microvolts (μV). Remaining coefficients, ci, depends on the thermocouple. Thermocouples used in this project was thermocouple T. The value of coefficients for respective thermocouple is listed in Table 1.

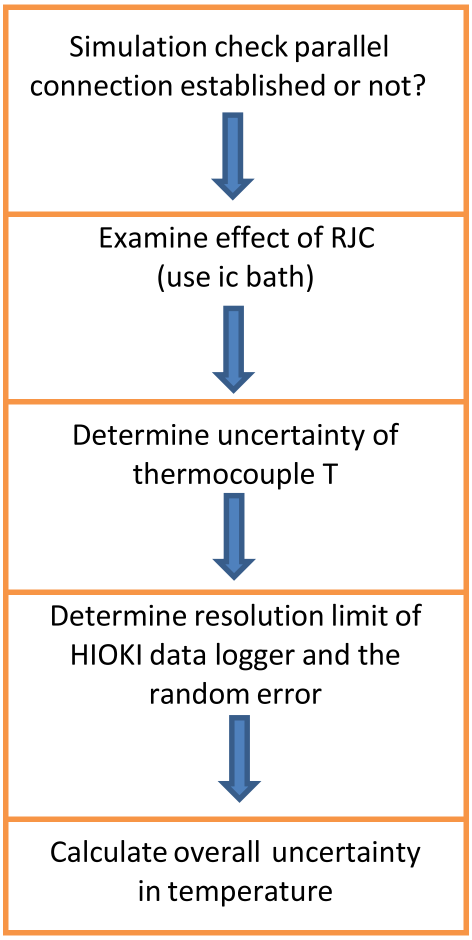

Fig. 2. Flow chart showing the process of determining temperature uncertainty

Table 1
Coefficient value for inverse polynomials calculation

Constant	Thermocouple T
Temperature Range:	0 to 400 °C
Voltage Range:	0 to 20872 μV
$c0$	0.000000
$c1$	2.592800 × 10−2
$c2$	−7.602961 × 10−7
$c3$	4.637791 × 10−11
$c4$	−2.165394 × 10−15
$c5$	6.048144 × 10−20
$c6$	−7.293422 × 10−25

2.2 Simulation

Hot junction was put into the ice-water bath of 0°C and reference junction compensation worked correctly; the reading of the thermocouple was 0°C. Therefore, the indicated temperature of the data logger is the uncertainty of the reference junction compensation. The same measurement was carried out in each channel to find out the difference uncertainty but it is connected in parallel form. To measure the uncertainty of the reference junction compensation at the same time in each channels of data logger, a simulation was required to know the voltage drops based on the internal resistance which obtained by Open Modelica as shown in Figure 3, to see whether could correctly measure the electromotive force of thermocouple in each channel when the electromotive force is 1 V. Although the actual electromotive force of the thermocouple at 25°C is about 1 mV.

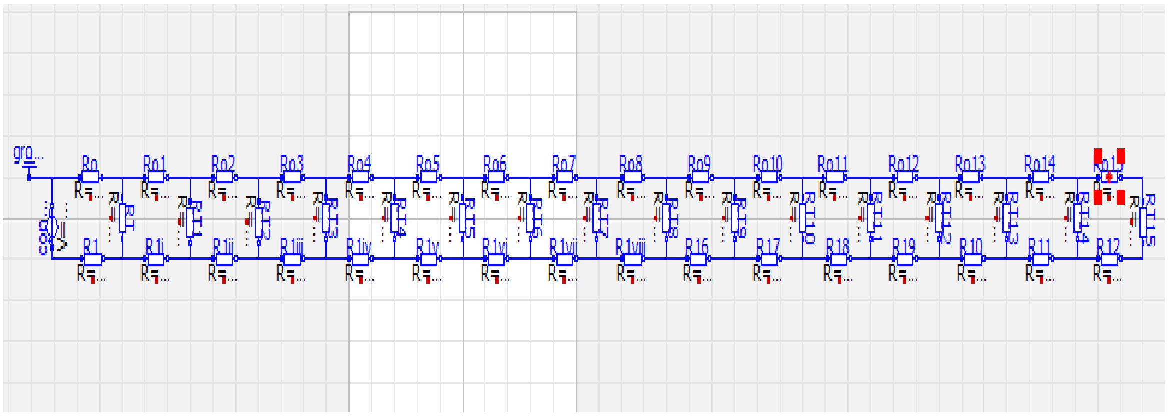

Fig. 3. Simulation drawing in Open Modelica

A ground and a voltage source are connected to the terminals. The upper row of resistors (Ro) represent the upper row terminals of the data logger which is the positive terminal, the resistance as lower row of resistors (R1) represent the lower row terminals of data logger which is the negative terminal and the resistor at the center row (RT) indicates when the connection is in parallel. After setting up all the resistance and the electronic devices, the simulation was started and the electromotive force was obtained.

2.2.1 Resistivity and conductivity

The resistance was calculated using resistivity and conductivity formula. To achieve a desired voltage in parallel connection, the wire length between each terminal must be shorter than the resistance, if not it will become low. Therefore, the resistance for the first resistor Ro, R1 and RT were set as 0.19 Ohm, 5.4 Ohm and 1 M Ohm respectively with 1 metre wire length. It is longer than other wires due to the extra length of wire needs to connect to the ice bath. But from the second until the fifteen resistor Ro, R1 and RT was set as 0.0038 Ohm, 0.108 Ohm and 1 M Ohm respectively with 0.02 metre wire length.

2.3 Experimental Setup

Tools and equipment to be used in this experiment were thermocouple T, resistance temperature detector (RTD), HIOKI data logger (LR400-20), metal block, copper wire, constantan wire, ice bath and screwdriver. Data obtained using RTD was treated as true value for that quantification and hence data of RTD will be used to compare with data obtained by thermocouple. Besides, cover of copper and constantan wire were removed. The ice bath and setting of data logger were then ready for experiment reference junction compensation part.

2.4 Resolution Limit of HIOKI Data Logger (LR8400-20)

Experiment was carried out using thermocouple and it was connected with copper wire and the ice bath. With ice bath thermocouple connection, voltage was measured instead of temperature difference between reference junction and measuring junction. The measurement range of HIOKI data logger (LR8400-20) was between -10mV - 10mV and the accuracy given in product specification was ± 10 μV. By conducting inverse polynomials in section 2.1, the resolution limit of data logger in temperature was obtained.

2.5 Random Error

Experiments were carried out to determine data fluctuation of thermocouple temperature measurement. Temperature of metal block in controlled temperature room was measured with both thermocouple and RTD at the same time.

Thermocouple measuring junction was attached closely to RTD probe as shown in Figure 4 so that temperature gradient in metal block would affect lesser. The true value to be compared between data both from RTD and the thermocouple.

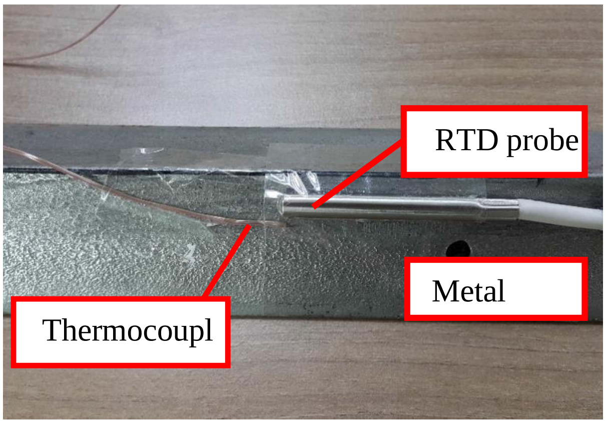

Fig. 4. Thermocouple and RTD probe arrangement

The measurement was recorded at channel 4 in data logger with copper extension wire connecting thermocouple and data logger in ice bath cold junction, experiment set up was as in Figure 5. Two seconds interval reading in a total 15 mins was recorded for both thermocouple and RTD, yet, only 5 mins reading was extracted and used in data analysis. A longer period of time was used to eliminate data fluctuation due to change in surrounding temperature.

Fig. 5. Experiment set up for data fluctuation experiment

The constant surrounding temperature is important in ensuring fluctuation in measurements measured was not caused by changes in room temperature but data fluctuation. Hence, RTD and thermocouple were affixed to metal block few mins before commencing in recording the readings with data logger. This is to ascertain these temperatures achieved thermal equilibrium with metal block. Moreover, experiment was set up early in air-conditioned room to make sure room temperature remain in constant state and it will not affect temperature of metal block. Data readings were taken after thermal equilibrium was achieved. Value of random error was obtained from standard deviation calculation computed on data from thermocouple T.

2.6 Reference Junction Compensation Error in Data Logger (LR8400-20)

Experiment was carried out to examine the effect of reference junction compensation (RJC). Figure 6 shows a situation where a hot junction of a thermocouple is immersed in an ice bath and each of the terminal of data logger are connected in parallel. Ice-bath temperature is almost 0°C when the ice-bath was filled with the shaved ice and water. If there is no RJC error, 0 °C will be displayed in the data logger when the measuring junction is put in the ice-bath. Therefore, the RJC error of each channel will be displayed when the measuring junction is put in the ice-bath. The RJC error was obtained by putting the measuring junction in the ice-bath.

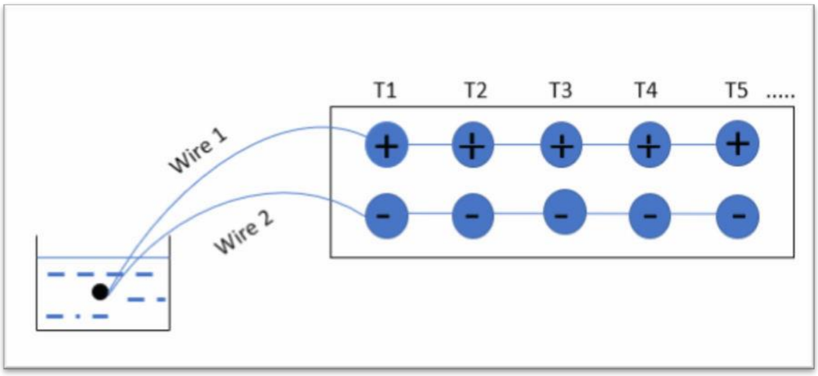

Fig. 6. Situation of an immersed thermocouple in a hot junction

The connected channel of the data logger acted as the reference junction. The hot junction of thermocouple was connected to the copper wire and constantan wire then immersed in ice bath. The results then was directly obtained from the data logger.

3. Results and Discussion

3.1 Simulation Results

The thermocouple to the input terminal and the output of the thermocouple was 1 V and the measured voltage was 0.9999 V and above. The percentage error was 0.01 %. Since the resolution of the data logger was at 0.1 %, then the percentage error of 0.01 % was small enough. The desired value of the voltage from the resistor was 0.9999 V. The outcome with first RT resistor from top left side was 0.999914 V and the first RT from the top right, 0.999901 V. Results were near to 1 V, so it has been shown that this parallel connection was established as shown in Figure 7.

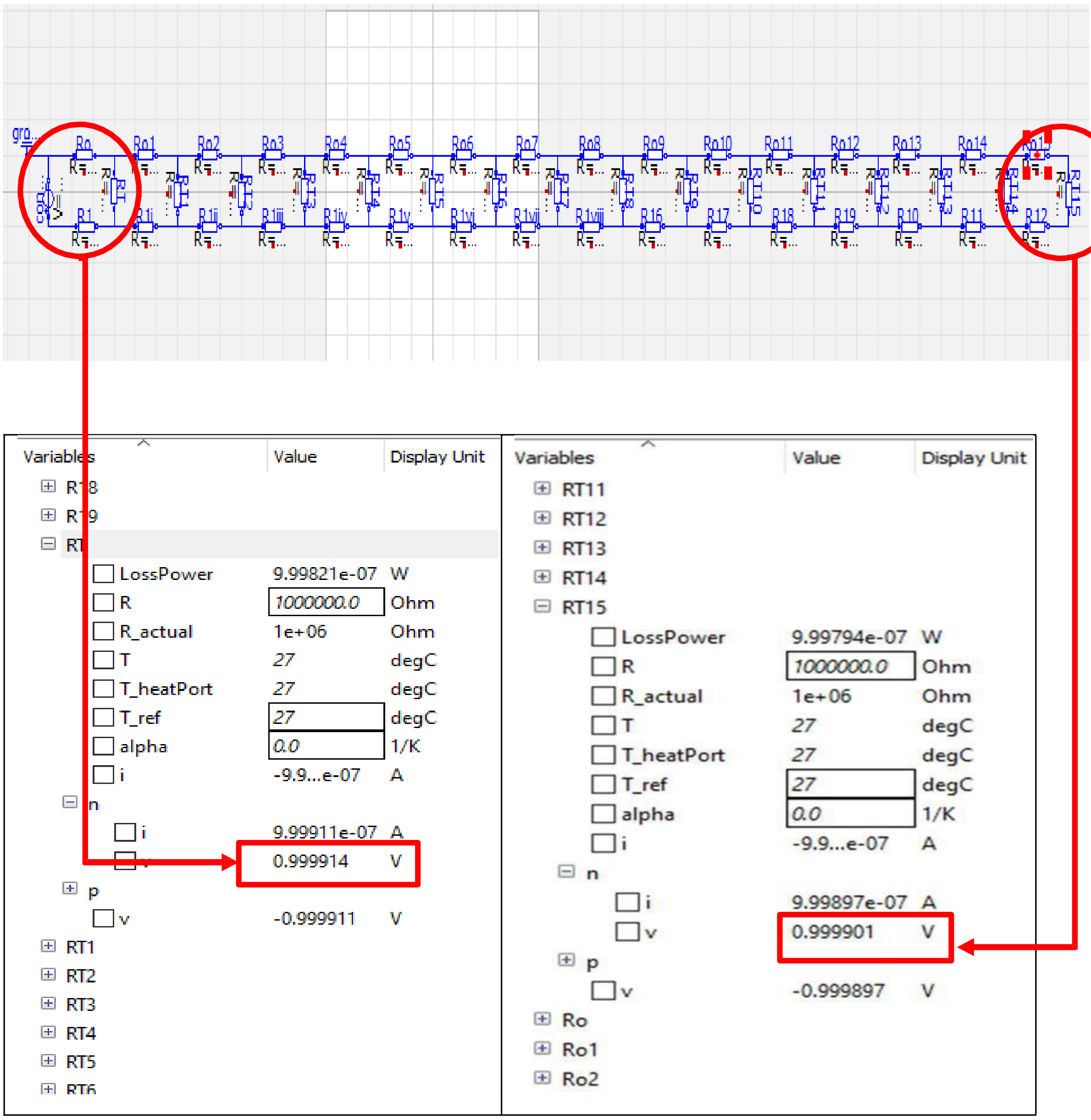

Fig. 7. Simulation results

3.2 Resolution Limit of Data Logger

Resolution limit of data logger which was ± 10 μV was converted using inverse polynomials thermocouple T coefficients as summarized in Table 2.

Table 2
Resolution limit in degree Celsius (°C)

Resolution limit	Thermocouple T
10 µV	± 0.259204

3.3 Random Error

The temperature of the metal block was measured under controlled surrounding temperature. Results were tabulated in Table 3 and shown in graph as in Figure 8. The temperature of metal block was measured with thermocouple K and it resulted in 27.21°C while RTD was 27.80°C. The temperature difference between thermocouple and RTD was predicted as the value of uncertainty.

Table 3
Random error obtained in different days

Standard deviation in degree Celsius (°C)	
Thermocouple K	Thermocouple T
0.02	0.03
0.01	0.01
0.01	0.01
0.06	0.02

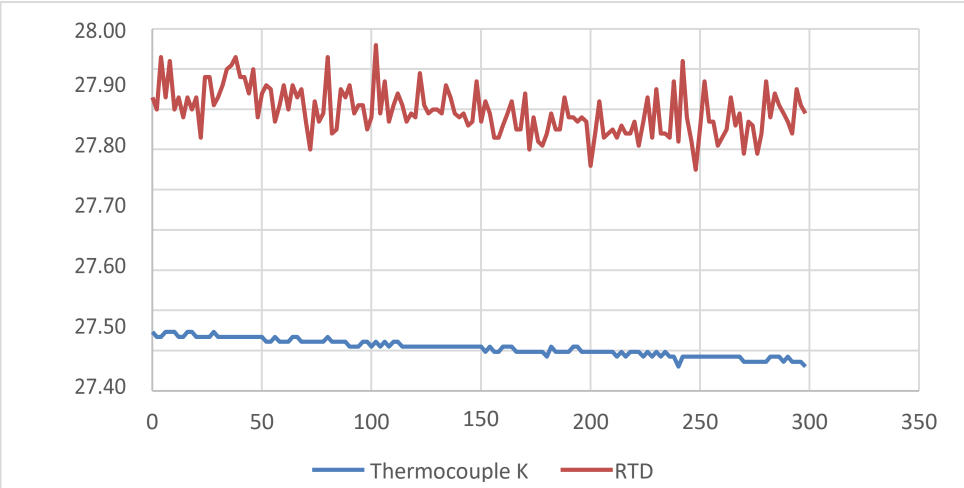

Fig. 8. Thermocouple K measurement

3.4 Reference Junction Compensation Error in Data Logger (LR8400-20)

Based on the data obtained, channel 1 to channel 15 of data logger depicted that there had almost the same trend, the only difference was the temperature in each of the channel. The temperature decreased from channel 1 until 8, but increased from channel 8 until 15 as depicted in Figure 9.

1	File name	WATER00:	V 1.28													
2	Title comr	GRAPHENE 0.2%														
3	Trigger Tir	21-04-30 16:43:37														
4	Ch	A 1- 1	A 1- 2	A 1- 3	A 1- 4	A 1- 5	A 1- 6	A 1- 7	A 1- 8	A 1- 9	A 1-10	A 1-11	A 1-12	A 1-13	A 1-14	A 1-15
5	Mode	Tc	Tc	Tc	Tc	Tc	Tc	Tc	Tc	Tc	Tc	Tc	Tc	Tc	Tc	Tc
6	Range	100 C	100 C	100 C	100 C	100 C	100 C	100 C	100 C	100 C	100 C	100 C	100 C	100 C	100 C	100 C
7	Comment															
8	Scaling	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
9	Ratio	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00
10	Offset	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	Time	1-1[C]	1-2[C]	1-3[C]	1-4[C]	1-5[C]	1-6[C]	1-7[C]	1-8[C]	1-9[C]	1-10[C]	1-11[C]	1-12[C]	1-13[C]	1-14[C]	1-15[C]
12	0	-0.37	-0.54	-0.53	-0.58	-0.59	-0.66	-0.72	-0.74	-0.72	-0.69	-0.67	-0.67	-0.66	-0.64	-0.56
13	5	-0.37	-0.54	-0.54	-0.59	-0.59	-0.65	-0.72	-0.74	-0.72	-0.69	-0.66	-0.67	-0.66	-0.65	-0.56

Fig. 9. Results of all channels

This is because the wire was inserted in the ice bath then the thermocouple start to detect the temperature of the wire. The initial temperature detected was slightly lower until the coldest temperature, then it bounced back to thermal equilibrium temperature which was the temperature between room and ice bath temperature.

The thermo-electromotive force of the thermocouple was generated according to the temperature difference between the hot and cold junctions. If the cold junction temperature fluctuates, the measurement data will fluctuate even if the hot junction temperature remained stable. The terminal connected to the thermocouple was used to monitor any changes in the cold junction and the controller automatically compensates for these changes to keep the cold end of the device at 0°C. This is called cold junction compensation or reference junction compensation. If the terminal temperatures of all channels were identical, the RJC errors of all channels would be identical.

The lowest temperature of each channel is plotted in the following Figure 10. The true temperature is 0°C, therefore the lowest temperature of each channel indicates the RJC error. The lowest temperature of the channel 8 was -0.77 °C. -0.77°C is the RJC error of channel 8. Note that the terminal temperature was affected by the room temperature and also air flow. If we conduct the same measurement under the different surrounding conditions, the RJC error will change and we will obtain the uncertainty of the RJC of each channel. Figure 10 shows the reference junction compensation error occurred in channel 8.

Fig. 10. Graph of reference junction compensation error

Based on this channel 8 graph, it is shown that the temperatures at each time were not stable. For state 1, the temperature of thermocouple inserted into the ice bath was -0.74°C, then the temperature kept increasing until the accurate temperature was -0.66°C. Lastly, the temperature sudden fluctuate with a huge gap. This condition happened because of the water temperature around the TC junction rose with time and the space around TC junction increased. When the space fits a certain size, it breaks and the temperature around the TC junction returned to the lower temperature.

For state 2, the trend of graph was the same with state 1. The only difference was the final temperature in state 2 that is quite lower than state 1. This was because the temperature around the TC junction reached the coldest point. For state 3, the same trend of the graph repeated again. But the time taken was longer than state 1 and 2. This was because the temperature of ice water slowly become higher due to the heat loss to the surrounding. The final temperature was different compared to state 1 and 2 since the temperature almost become average and went up and down twice due to there were no space to break. The ice slowly melts and temperature slowly become steady. For state 4, the condition repeated and from the graph, the temperature was lower than state 3, and was more stable starting from 3000s at temperature of -0.72°C.

In a nut shell, the ice bath temperature fluctuated and its lowest temperature was considered as 0°C. Since channel 8 had the lowest temperature among the 15 channels, therefore RJC error occurred at channel 8. The greatest temperature difference obtained was -0.77°C occurred at terminal of channel 8. Hence, the error from reference junction compensation was -0.77°C because it had the lowest temperature.

3.5 Calculation of Uncertainty Value

The uncertainty value of thermocouple T was calculated and the results are listed in Table 4.

Table 4
Error value from each source and the combined uncertainty value

Thermocouple	$u_{x_{inst}}$, °C	$u_{x_{rjc}}$, °C	$u_{x_{rand}}$, °C	u_x, °C
T	0.259	± 0.77	0.03	± 0.8129
			0.01	± 0.8125
			0.01	± 0.8125
			0.01	± 0.8125

4. Conclusions

Based on the simulation, the parallel connection was established. We have shown that it was a better way to get the uncertainty of reference junction compensation measuring the temperature by the HIOKI data logger (LR8400-20) with ± 0.77°C for the thermocouple T when the RJC was applied. The results were taken at 5 seconds interval long 3600 seconds, therefore the value was more precise compared to previous researches.

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