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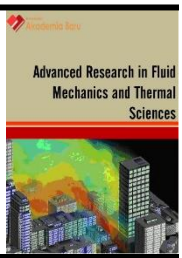

Testing a Calibration Method for Temperature Sensors in Different Working Fluids

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Reski Septiana[1], Ibnu Roihan[1], Raldi Artono Koestoer[1,*]

[1] Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Depok, Indonesia

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ABSTRACT

Temperature is one of the crucial parameters in every aspect of life; therefore, it is essential to be able to measure it accurately. Temperature data acquisition utilizing a K-type thermocouple and MAX6675 module as cold junction compensation is being increasingly used by researchers because of its availability and relative ease of use. K-type thermocouple and MAX6675 can be used as valid data acquisition if the sensors are properly calibrated. This research proposes a calibration method for K-type thermocouple and MAX6675 sensors based on Arduino microprocessor with DS18B20 thermistor as the reference, which has been previously calibrated with the ASTM-117C thermometer. Calibration was performed at ambient conditions utilizing the energy from the environment where four K-type thermocouple and MAX6675 sensors were calibrated alongside two DS18B20 sensors in ambient water for 24 hours. To increase the accuracy of the K-type thermocouple and MAX6675 sensors, simple mathematical methods were used in Arduino coding, thereby providing automatically calibrated values. After calibration using the proposed method, the sensors then were used in reading temperatures of ambient air and water. The result of this study is simple methods to improve the accuracy of K-type thermocouples and MAX6675 sensors to be used for reading temperature values in different working fluids using Arduino Microprocessor. The error value before calibration was 4.9% compared to 0.42% and 0.61% after calibration in ambient-water and ambient-air respectively.

1. Introduction

Temperature is an important parameter in every system. Because of its crucial role, the temperature measurement is needed in both academic and industrial field [1,2]. To measure the temperature or the temperature difference which is crucial in heat transfer [3], K-type thermocouple has been widely used because it is relatively low-priced, self-powered, and it has a wide range of measurements that can be applied to complex systems [2,4]. Long ago, to acquire data of measurement, researchers had to record the measurement results manually and periodically. To

* *Corresponding author.*
E-mail address: koestoer@eng.ui.ac.id (Raldi Artono Koestoer)

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ease the measurement nowadays, researchers commonly use data acquisition. However, the expense of commercial instruments is a significant obstacle to setting up important monitoring networks such as data acquisition [5]. Arduino, highly customizable open-platform electronics prototyping system [6], can be a valid data acquisition if the sensors are well-calibrated [7]. Therefore, Arduino has been selected for use in this study to test its efficacy for data acquisition and calibration.

To make a temperature data acquisition using Arduino and K-type thermocouple, a module to compensate for thermocouple cold junction is needed. MAX6675 is one of many modules compatible with Arduino that can compensate for the K-type thermocouple cold junction. The use of K-type thermocouple mounted on MAX6675 module is becoming more common among researchers [4, 8-10], but not many have tried to calibrate the sensor, especially in ambient conditions. In ambient conditions, where there is almost no temperature difference between cold junction and hot junction thermocouple, the reading from K-type thermocouple and MAX6675 is erratic and accuracy is compromised in comparison with readings taken from a DS18B20 sensor [11]. The purpose of this study is to calibrate the measurement value resulting from K-type thermocouple and MAX6675 sensor.

2. Methodology

The sensors used in this experiment are two DS18B20 waterproof thermistors as the calibrator and four K-type thermocouples which were mounted on MAX6675 module. K-type thermocouple has a wide range of measurement starting from -250°C to 1100°C [12], but when mounted on MAX6675 as a cold junction compensation module, the measurement range is limited from 0°C to 1024°C with a resolution of 0.25°C [13]. DS18B20 sensors were used as the calibrator because the sensors have been previously calibrated using an ASTM-117C thermometer [14] and have a great resolution of 0.0625°C [15]. The sensor's measurement range is from -55°C to 125°C [15-16] and the error between sensors after calibration varies from 0.23°C to 0.42°C [14]. The true value of the measured temperature is the average of the readings produced by two DS18B20 sensors each time taken, as this technique allows for compensation for the variations that exist between sensors after calibration.

The Arduino microprocessor was used to perform this calibration. Although Arduino is mostly used as a controller [17-19], it also can be used as data acquisition tool, which can be upgraded as data logger [5,16, 20-21]. The output of Arduino, which can be engineered, is beneficial for calibration [22]. The engineered output then can be saved to SD Card [16, 23]. SD Card and Arduino compatibility reduce power consumption for computers, but it is extremely difficult to monitor the data directly without the help of the Liquid Crystal Display.

To achieve calibration, all sensors are connected to Arduino which is connected to the computer to input the commands for measuring temperature. Temperature data retrieval from six sensors is done every 100 milliseconds. The measured temperatures then were engineered in Arduino to be saved in SD Card as a .txt file.

The stabilization and calibration process were carried out in ambient conditions, utilizing the environment's energy and environmental heat-transfer. The calibration process must be done in a steady-state condition where the temperature is constant in order to get the true value of the temperature being measured. Environmental heat-transfer in ambient condition provides natural steady-state conditions, which is beneficial for the purpose of calibration.

To test whether K-type thermocouples mounted on MAX6675 can be calibrated with DS18B20 sensors, it is first necessary to observe their patterns by reading the water-ambient temperature. Four K-type thermocouples, each mounted on MAX6675 (TC_i) were immersed in an open vessel containing ambient water for 24 hours with two DS18B20 thermistors (DS_i), as shown in Figure 1. The ambient water medium was chosen to see the initial measurement of the sensors because water has a high specific heat capacity; therefore, a change in temperature of the surrounding environment would have little effect on the temperature of water.

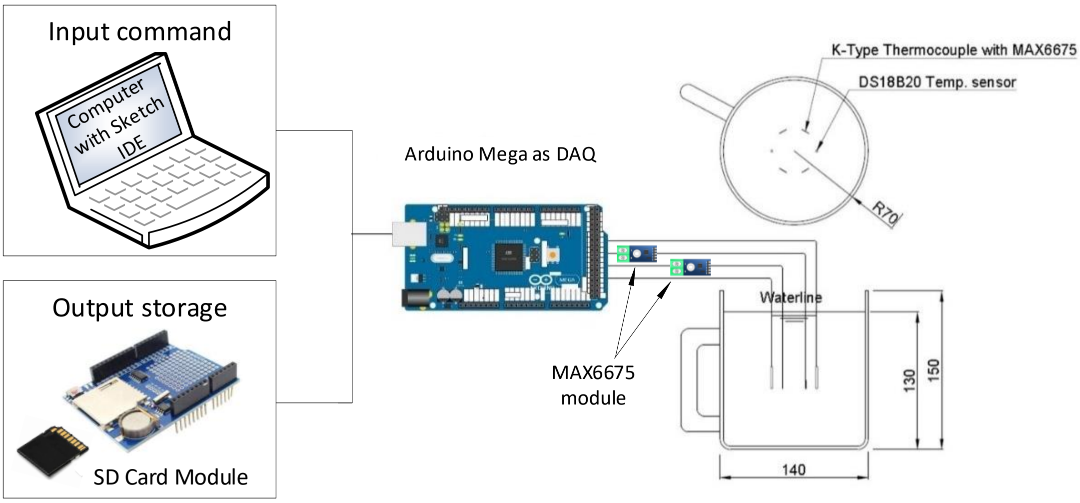

Fig. 1. Experimental set-up

If the patterns of both sensors in reading water-ambient temperature are the same, then the next step is to calibrate the sensors. Simple mathematical methods were chosen to calibrate the K-type thermocouple mounted on MAX6675 sensors, such as averaging, filtering, and fitting. Averaging all measured data generated every second by each K-type thermocouple and MAX6675 using Eq. (1) can reduce the noise of the sensors. The filtering process using Eq. (2), based on MAX6675 resolution, 0.25°C, can reduce the fluctuation so that the data will be distributed in the range of ±0.25°C. The fitting process using Eq. (4), can boost the accuracy of K-type thermocouple in reading temperature values.

Fitting process or *line translation* is an important process to reduce the systematic error of the sensors. Factor of translation or later will be described as fitting value (FV) is calculated by averaging the delta of measurements between DS18B20 sensors and K-type thermocouple mounted on MAX6675's sensors at steady condition.

$$\overline{TC_i} = \frac{\sum_{j=1}^{4} TC_{i,j}}{4} \quad (1)$$

Data will be printed if

$$TC_i = \left|\overline{TC_{i,j+1}} - \overline{TC_{i,j}}\right| < 0.25°\text{C} \quad (2)$$

Otherwise, "$\overline{TC_{i,j}}$"

$$TC = \frac{\sum_{i=1}^{4} TC_i}{4} \quad (3)$$

$$TC^* = TC - FV \quad (4)$$

Between 08 PM and 11 PM; $08PM \le t \le 11PM$

$$FV = \frac{TC_t - DS_{AV_t}}{j_t} \tag{5}$$

$$DS_{AV_t} = \frac{\sum_{i=1}^{2} DS_i}{2} \tag{6}$$

where
TC = the data of measurement from the K-type thermocouple and MAX6675 (°C)
Subscript i = the order of sensor
Subscript j = the data of measurement at each time
TC^* = the measured data after calibration (°C)
j_t = the data of measurement at each time for a predetermined hour
FV = Fitting value (°C)
DS_{AV} = The true value indicated by the average measurements taken from two DS18B20 sensors (°C)

The above methods were written in the form of code (coding) and uploaded in Arduino's Sketch, resulting in automatically calibrated values. These methods will be used in reading not only water-ambient temperature but also air-ambient temperature. The results from reading water-ambient and air-ambient temperature with the proposed methods will then be compared. The standard deviation (°C) and error value (%) before and after calibration will be calculated using Eqs. (7) to (10).

$$\text{Standard deviation} = \sqrt{\frac{\sum_{j=1}^{n}(TC_i - DS_{AV})^2}{n-1}} \tag{7}$$

$$\text{Systematic Error} = \left|\frac{TC_{i,j} - DS_{AV,j}}{DS_{AV,j}}\right| \times 100\% \tag{8}$$

$$\text{Average Standard deviation} = \frac{1}{n}\sqrt{\frac{\sum_{j=1}^{n}(TC_i - DS_{AV})^2}{n-1}} \tag{9}$$

$$\text{Average of Systematic Error} = \frac{1}{n}\left(\sum_{j=1}^{n}\left|\frac{TC_{i,j} - DS_{AV,j}}{DS_{AV,j}}\right|\right) \times 100\% \tag{10}$$

where
n = total data measured per sensor

3. Results

3.1 Before Calibration

The measurements taken by each K-type thermocouple sensor mounted on MAX6675 (TCi) compared to the true value shown by the average of DS18B20 sensors (DSAv) in reading the water ambient temperature are shown in Figure 2. Since each K-type thermocouple sensor has the same patterns with the average of DS18B20 sensors, the calibration of K-type thermocouple to DS18B20 sensor can be done.

Based on Figure 2 and Table 1, K-type thermocouple mounted on MAX6675 is relatively precise in reading the ambient temperature but not so accurate. The range of ambient temperature on that day (24 hours) as shown by the average of DS18B20 sensors was from 27.7°C to 28.7°C; different readings were produced from the K-type thermocouple and MAX6675 sensors. The temperature measured by K-type thermocouples and MAX6675 sensors were not the same even though they have the same specifications and were purchased from the same manufacturer. The average deviation between sensors varied from 0.23°C to 0.26°C. The average systematic errors of each sensor respectively were 1.72°C, 0.86°C, 1.46°C, and 1.49°C compared to the true value. The average error value (%) before calibration was 4.9%.

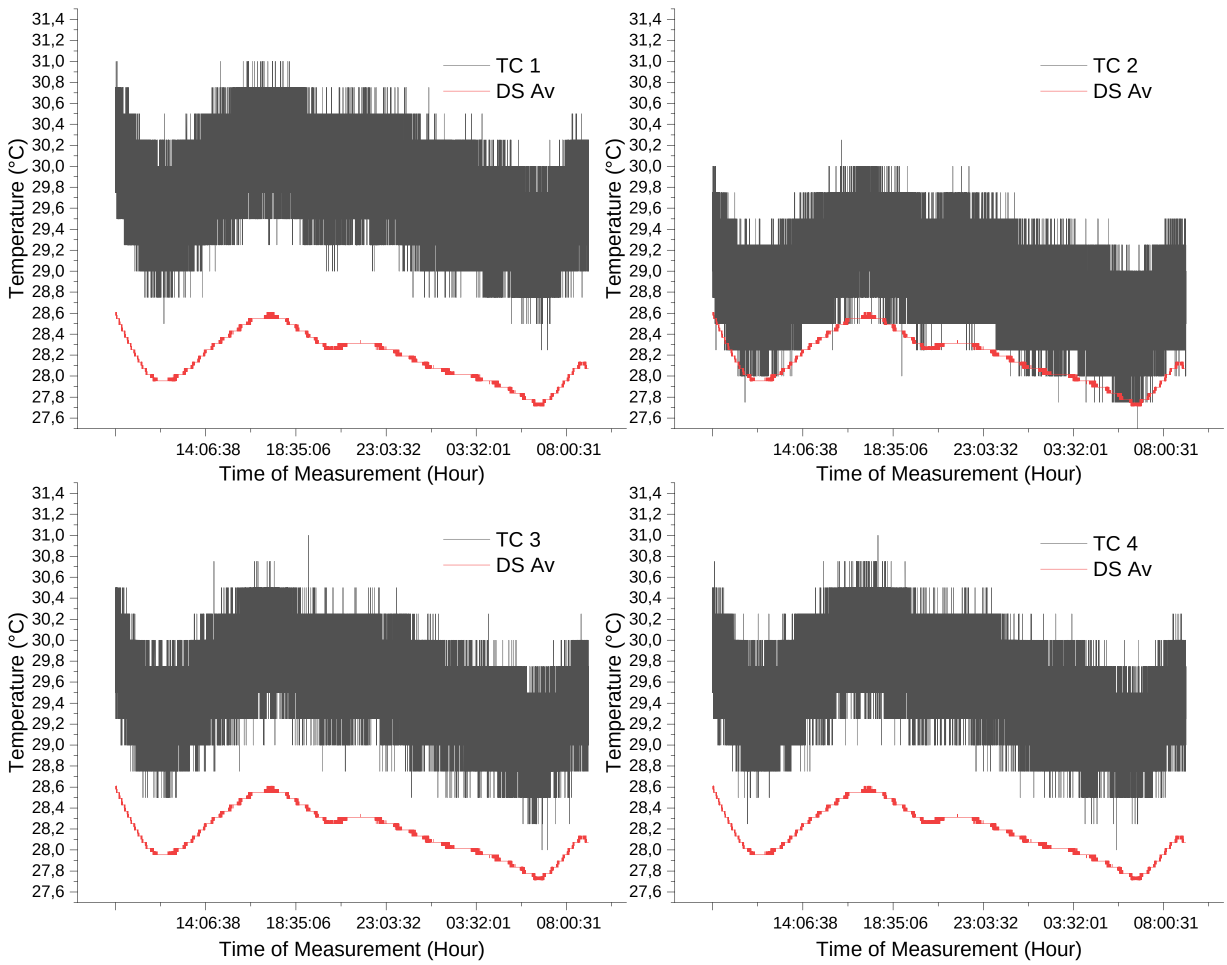

Fig. 2. The reading of K-type thermocouples (TC) in measuring ambient water temperature before calibration compared to the true value shown by the average of two DS18B20 sensors (DSAv)

Table 1
Uncertainties of the measurement before calibration

K-type Thermocouple mounted on MAX6675 (pair -)	Initial Characteristic Deviation (°C)	Initial Characteristic Systematic Error (%)
1st	0.26	6.1
2nd	0.25	3.0
3rd	0.23	5.2
4th	0.24	5.3

3.2 After Calibration

With a 100ms delay for data retrieval, only four readings are produced by Arduino in one second. This is most likely because Arduino needs time to convert and save the printed date, time, and measurement values into text in the SD Card. By averaging all data per every second of each measurement taken by the K-type thermocouple and MAX6675, the deviation becomes smaller, varying from 0.12°C to 0.14°C. Filtering the data by ±0.25°C can reduce the noise of measurement, as shown in Figure 3. The deviation after averaging and filtering the data varies from 0.11°C to 0.13°C as summarized in Table 2.

To ease the data-fitting of the four K-type thermocouple and MAX6675 sensors to DS18B20, the averaging of those four pairs was conducted using Eq. (3). The measurement values taken by either the four pairs of K-type thermocouple mounted on MAX6675 or the two DS18B20 sensors should have shown the same result because they were placed under the same conditions and relatively near to each other. However, as demonstrated in Figure 2, they showed different results in reading temperature value, so the averaging process was done to convert the four pairs shown to one value that represents the four of them. After calculating this average as shown in Figure 4, the delta between that one value and the true value, in this case the average of the DS18B20 sensors, was calculated. The delta of measurements between the sensors at ambient-steady conditions, from 8:00 PM to 11:00 PM, were then averaged to calculate one constant value or fitting value to fit the uncalibrated sensors to the true value. The fitting value for this experiment was 1.31°C.

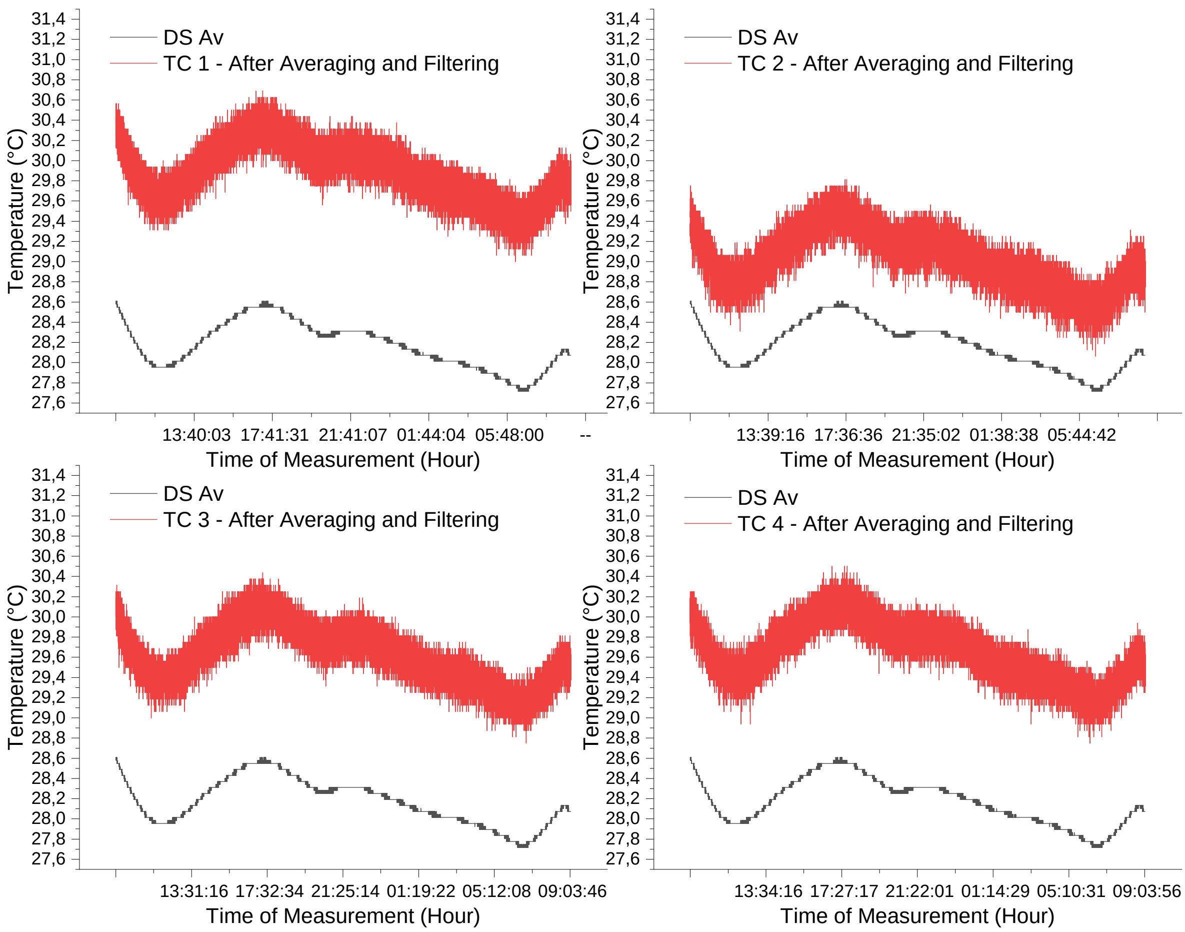

Fig. 3. Results after filtering and averaging four data measured by each K-type thermocouple mounted on MAX6675

Table 2
Uncertainties of the measurement after calibration

K-type Thermocouple mounted on MAX6675 (pair -)	Averaging		Filtering		Fitting – Water		Fitting - Air	
	Deviation (°C)	Systematic Error (%)	Deviation (°C)	Systematic Error (%)	Deviation (°C)	Systematic Error (%)	Deviation (°C)	Systematic Error (%)
1st	0.13	6.1	0.12	6.1	0.087	0.42	0.112	0.61
2nd	0.14	3.0	0.13	3.0	0.087	0.42	0.112	0.61
3rd	0.12	5.2	0.11	5.2	0.087	0.42	0.112	0.61
4th	0.13	5.3	0.12	5.3	0.087	0.42	0.112	0.61

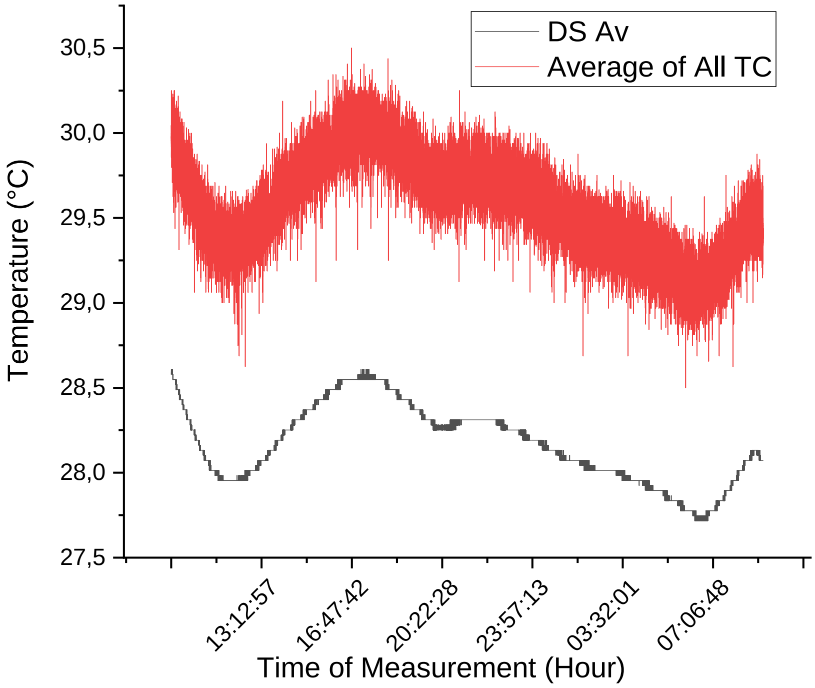

Fig. 4. The average of All K-type thermocouple and MAX6675 sensors to ease the fitting process

As shown in Figure 5, the measurement taken after inserting the fitting value based on Eq. (4) in the Arduino's coding has proven that K-type thermocouple and MAX6675 already measure the same temperature as DS18B20 sensors in water-ambient medium but with bigger fluctuation due to the resolution of the sensors. The deviation and error (%) after calibration in ambient water respectively are 0.087°C and 0.42%.

The same coding was used to measure air ambient conditions for 24 hours so both hot junction and cold junction thermocouple were in ambient air. Based on Figure 6, the proposed methods with a fitting value of 1.31°C can still be used even though the fitting value was a result of hot junction thermocouple in the water medium. The deviation and error (%) after calibration in ambient air as summarized in Table 2 were 0.112°C and 0.61%, respectively.

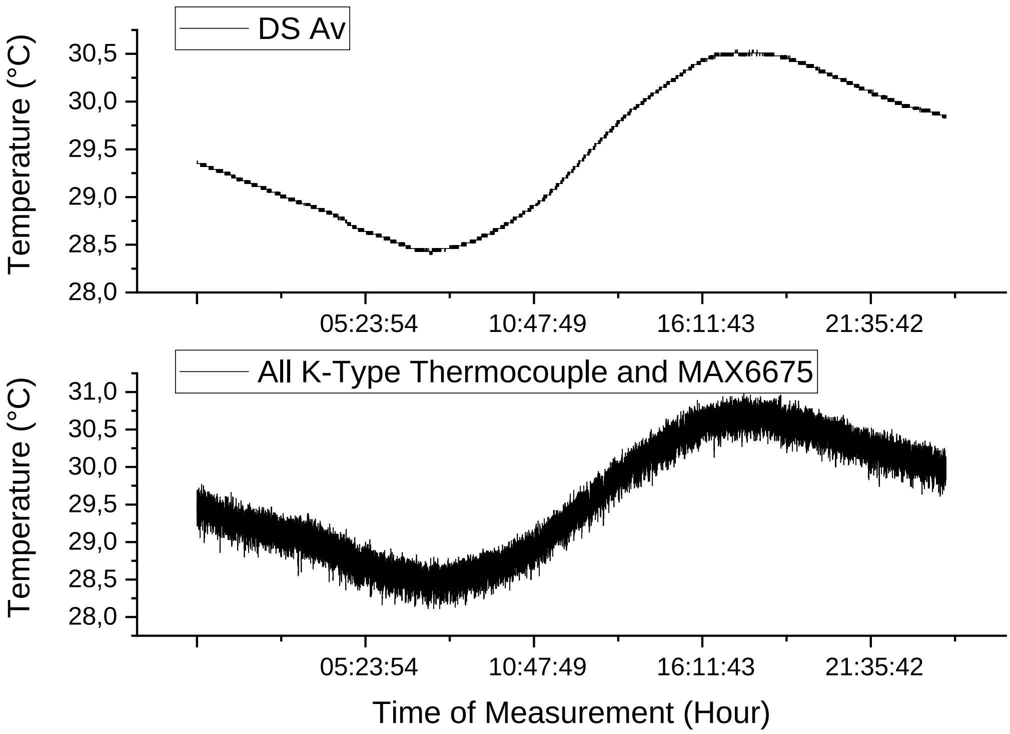

Fig. 5. K-type thermocouple and MAX6675 in reading water ambient temperature values after calibration

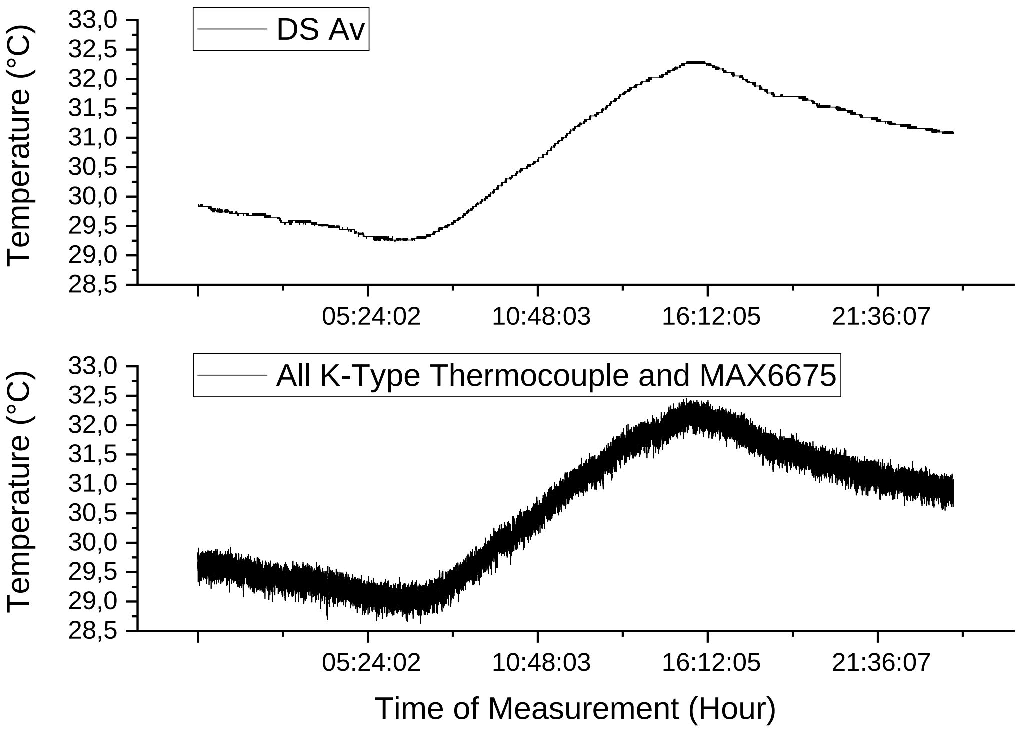

Fig. 6. K-type thermocouple and MAX6675 in reading air ambient temperature values after calibration

4. Conclusions

The stabilization and calibration of MAX6675 and K-type thermocouple sensors in reading ambient temperatures are needed because of the working principle of thermocouple. In ambient conditions, the thermocouple junctions almost have no temperature difference, so the values measured should be stabilized as the basis of zero offset. Ambient conditions that are close to the natural-steady state can be used as the basis to calibrate the K-type thermocouple mounted on MAX6675 sensors because in this condition, the temperature varies only very slightly which is beneficial for calibration.

The calibration process utilizing simple mathematical methods such as averaging, filtering, and fitting can be used to stabilize and calibrate the sensors. The averaging and filtering process increased the precision of the measured values, while the fitting process reduced the systematic error. Using the proposed methods, $TC^* = TC - 1.31$, and the natural steady-state condition to calibrate the sensors increased the accuracy of the sensors from 4.9% to 0.42% in reading ambient water temperature and to 0.61% in reading ambient air temperature, with an average deviation of 0.12°C. In sum, the the proposed method utilizing Arduino microprocessor can be used to increase the precision and the accuracy of K-type thermocouple and MAX6675 sensors in reading temperature values.

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