COMPARISONS OF THERMAL RESPONSES OF DIFFERENT TEMPERATURE SENSORS

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Abstract: Three temperature sensors; thermocouple, thermistor and BME280 environmental sensor were developed and their thermal responses were assessed to find out which among the three has a quicker thermal response. When thermocouple and thermistor were touched and then released, the thermocouple had a quicker thermal response than the thermistor, taking 400 ms and 1600 ms respectively. When hot air was blown to the thermocouple and thermistor they both showed same low response spending 1600 ms. When hot air from the hair dryer was blown to both the thermistor and the BME280 environmental sensor, the thermistor took 0.12 computer clock cycles to respond to the thermal energy increase while the BME280 responded instantly after the introduction of the thermal energy change. According to the results obtained in this experiment, the BME280 environmental sensor had a quicker thermal response than the thermistor and the thermocouple when determining thermal energy changes in the air. On the other hand, the thermocouple had a quicker thermal response than the thermistor when used to investigate thermal energy change in solids.

Keywords: Temperature, Sensors, Thermocouple, Thermistor, BME280 sensor

1.0 Introduction

When air gains thermal energy it is transformed into kinetic energy of its molecules and moves with a higher speed which results to temperature rise of the air molecules. The molecules with high temperature mean having high speed and since air can move to fill the whole space, it becomes difficult to detect a small temperature change unless all the air molecules come to a thermal equilibrium (1, 2). Therefore, knowing the temperature of the surrounding is one of the important aspects in dealing with day to day activities and challenges. Quick temperature sensors which can produce a rapid change in output corresponding to temperature change are thus needed (3, 4).

Measuring temperature needs to be a rapid process but it faces some challenges. Before a sensor can record a particular temperature it has first to attain a thermal equilibrium with the object whose temperature is to be measured (1). This process of attaining thermal equilibrium actually takes some time, short or a little longer, depending on the nature of the material making the sensor and thermal contact between the sensor and the object. The time taken for the sensor to reach thermal equilibrium with the object is called time lag of the pair which varies depending on the type of sensor used. (5, 6). Different sensors made with different materials do have different time lag. A sensor with short time lag will be quicker to respond to temperature change than that with a longer time lag. Thus, it is difficult to measure an abrupt change in temperature unless a very quickly responding thermometer is used because thermometers need a small time lapse to be in thermal equilibrium with the object whose temperature is to be measured before it can measure it (7, 8).

Another challenge is the amount of thermal energy absorbed by the sensor before it can actually measure the temperature. If the sensor has a large heat capacity, it will tend to draw thermal energy from the object when brought into contact. When this happens, the resulting value of temperature recorded by the sensor will thus be lower than its actual value. Water, for example, has large heat capacity (4.179 $Jg^{-1}°C^{-1}$) and that is why it is not preferred to be used as thermometric liquid as compared to mercury (0.140 $Jg^{-1}°C^{-1}$). For comparison purpose, specific heat capacity of aluminium is 0.902 $Jg^{-1}°C^{-1}$ and that of copper is 0.385 $Jg^{-1}°C^{-1}$. A good temperature sensor should have small heat capacity to ensure it does not absorb thermal energy from the object whose temperature is to be measured (9, 10).

In this study, detailed comparisons of thermal responses of three temperature sensors which are thermocouple, thermistor and BME280 environmental sensor were developed to assess their thermal responses and find out which among the three has a quicker thermal response. A good temperature sensor (thermometer) is supposed to have a quick thermal response to ensure notable temperature recording even for small changes in thermal energy. This is a kind of temperature sensor in which the study is aimed at, and especially one that can be able to record the temperature of air.

2.0 Materials and methods

To accurately measure air temperature, we need a very sensitive thermometer with a fast thermal response. In this experiment three temperature sensors were designed and their thermal responses were compared. The thermocouple used was type K (Chromel/ Alumel) thermocouple whose voltage increases with an increase in temperature while thermistor used was NTC thermistor whose resistance decrease with an increase in temperature and the BME280 environmental sensor.

2.1 Experiments using Thermocouple

Initially, thermocouple was used together with a sensitive galvanometer and a hair dryer. The thermocouple was connected with the sensitive galvanometer and on touching it a deflection was noted on the galvanometer showing that there was a thermocouple voltage produced of about 1.1 mV. Later on, the hair dryer was blown onto the thermocouple and a greater deflection was obtained on the galvanometer showing that the thermocouple voltage was dependent of the temperature; this was similar to how the theory proposed. The problem here was that the thermocouple voltage obtained, around 2.0 mV, was way too small and so it needed amplification to obtain a notable voltage. Then the thermocouple voltage was amplified using non-inverting operational amplifier. Thermocouple, non-inverting operational amplifier and a digital multimeter were used to obtain the amplification and measure the amount of thermocouple voltage obtained **(figure 1)**.

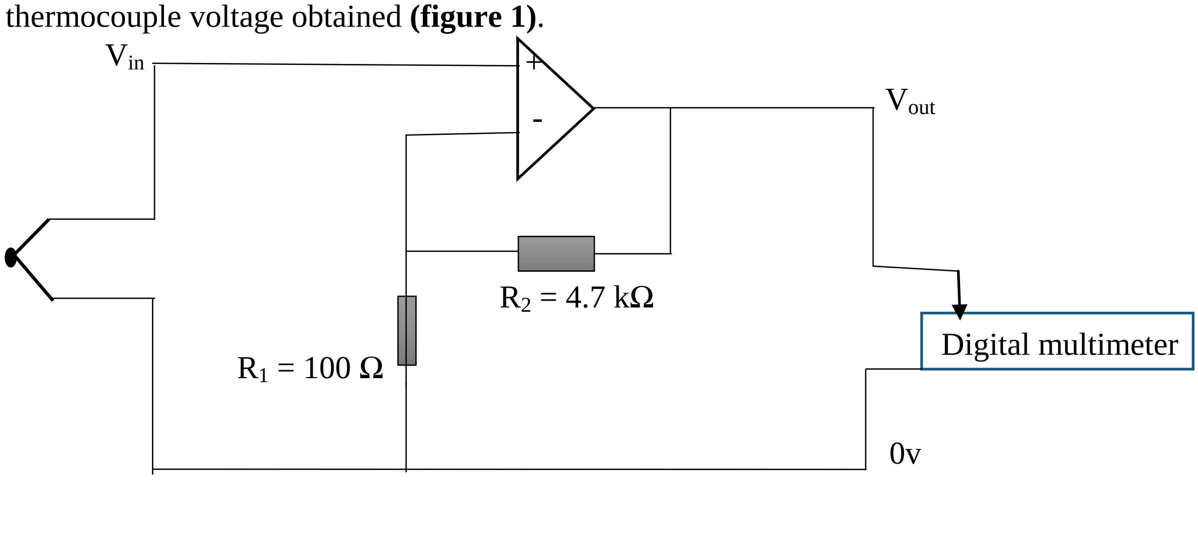
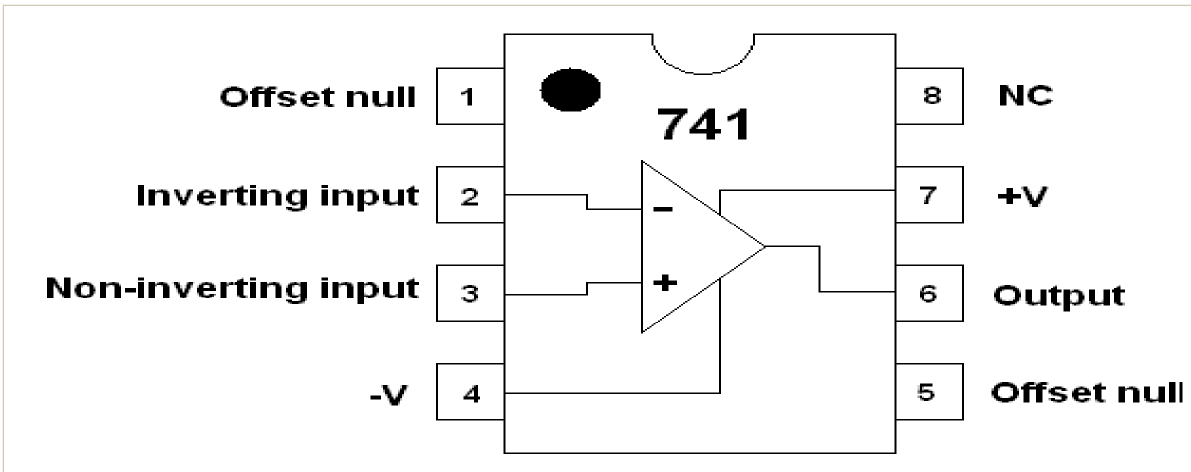


Fig. 1: Amplification circuit using non-inverting amplifier

The above amplification circuit produced amplification up to about 2.4 mV when the thermocouple was touched but still further amplification was needed. Great thermocouple voltage amplification was later achieved by using a 741 operational amplifier chip making use of its non-inverting operation. The UA741 operational amplifier has some pins which enhance its function as they are shown below.



The UA741 op-amp was mounted on a breadboard and the amplification circuit was built with the input connected to the non-inverting pin/leg of the amplifier while the inverting pin/leg was grounded.

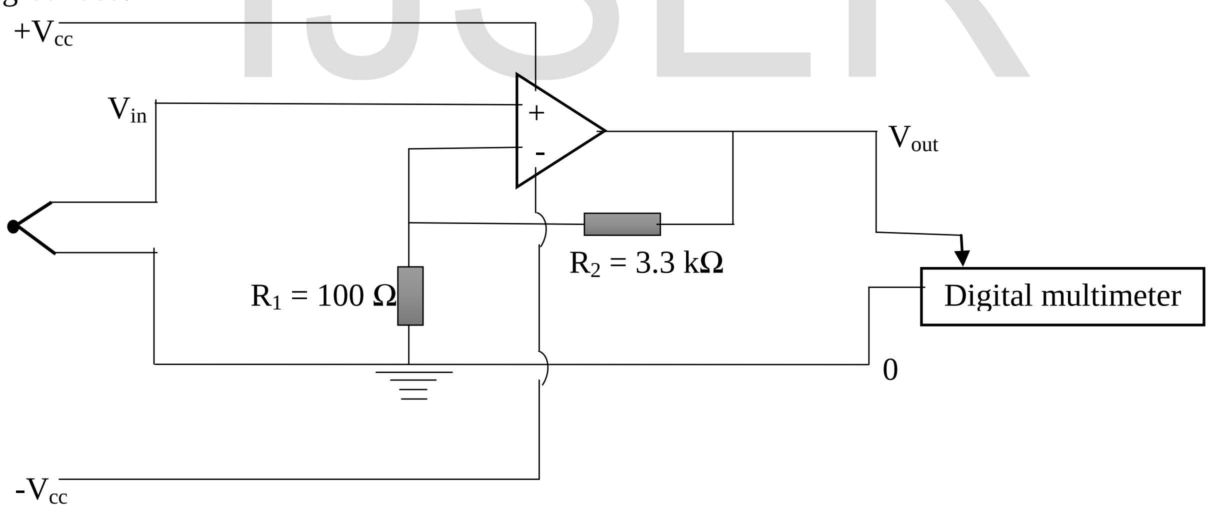


Fig. 2: Amplification circuit using UA741 op-amp

This amplification circuit produced a large amplification. The thermocouple voltage of about 106 mV was produced without touching the thermocouple and when the thermocouple was touched a thermocouple voltage of up to 117 mV was produced. The thermal response was observed to be good as there was a direct change in thermocouple voltage when the thermocouple was subjected to temperature changes. This result was enough to be fed to a computer via a voltage sensor for further analysis.

2.2 Experiments using Thermistor

Thermistor was used with a digital multimeter across it to observe the variation of thermistor resistance with changes in temperature when it was touched or hot air blown to it from a hair dryer. It was observed that the thermistor had a very high resistance of around 87 kΩ when cold; the resistance was reduced to around 60 kΩ when touched and down to around 8 kΩ when hot air from the hair dryer was blown to it for a time interval. These observations show that the thermistor resistance varied inversely with temperature, which is similar to the theory of thermistor which have negative temperature coefficient (NTC). The thermistor resistance was later changed to voltage using a potential divider to ensure sensors, thermistor and thermocouple are analysed basing on the same physical units.

The potential divider was built using a resistor in series with the thermistor connected to a direct current power source set at 12 V. The resulting thermistor voltage was initially fluctuating and not stable until a similar large resistor (of 91 kΩ) was connected in series with the thermistor where the thermistor voltage was seen to be stable and changing as the temperature was changed. It was observed that, the resulted thermistor voltage was about 6.20 V when it was cold (at room temperature), fell down to around 5.36 V when touched and again down to around 1.42 V when hot air was blown for a short time interval from the hair dryer. After both thermocouple and thermistor have given their results in voltage then these voltages were fed into a computer using voltage sensor so that the thermal responses of the thermocouple and thermistor can be analysed from the computer.

2.3 Experiments using BME280 environmental sensor.

The thermistor in a potential divider with a suitable resistor was embedded in the BME280 environmental sensor circuit and a General Purpose Input/ Output (GPIO) sending a signal to the Raspberry Pi to trigger it high (1) when the thermistor is hot and low (0) when it is cold. The two inputs from the BME280 environmental sensor and the thermistor were then processed by the Raspberry Pi to see which one responded quickly.

Interfacing the Raspberry Pi and Logging Data

In order to read data from the Raspberry Pi, the following processes and procedures were adopted. Firstly, after the I2C port was enabled in Raspbian, a hardware check-up was done to see if the chip (BME280 sensor) was communicating or being detected by the Raspberry Pi running under I2C protocol. To do so, the LXTerminal was opened and at the command prompt typed in "**i2c detect -y 1**" to run a check-up for a device connected to I2C1 port. The first chip used was not detected by the Raspberry Pi so it was replaced with another one. The second chip was detected as a signal when it was displayed at the same address (0x76 in hexadecimal) as that of the BME280 sensor chip.

After the device being detected, the programming of the Raspberry Pi module in python was done. This was done to tell it what to read from the connected chip, in which way and how to print/ display the obtained results. In the LXTerminal a program was developed to set a continuous reading of data (register address 0xF4 in hexadecimal for normal mode), the number of readings to be done per a single run was set as 200 times. The register address for least significant byte for temperature was imported as 0xFB and that for most significant byte as 0xFA. The two signals were later added together [$am = lsb + (254 \times msb)$] and printed as output. The program was saved and when run it gave results for temperature related values read by the BME280 sensor which increased with an increase in thermal energy and vice versa.

To read the data from the BME280 environmental sensor in the LXTerminal, the program was run and then the output values were printed in a window such that it was possible to analyse them and copy them to a Mathematica. Later on, the thermistor input was added as a GPIO input and to print its results along with those of the BME280 sensor, the program was modified such that it was able to print the two results next to each other. For easier analysis of the results obtained, another field of time was added in the program in such a way that all the temperature, thermistor digital input and the time were printed per every data reading cycle. The final results were then imported into the Mathematica and the file saved as a text document which can be opened with excel or spreadsheet for further analysis and comparison.

3.0 Results and discussion

The Pico Scope (oscilloscope) was used together with its data logging software to feed the results from the sensor to the computer for analysis. Thermocouple voltage and thermistor resistance recorded by sensor were assessed on how they vary with temperature change. It was simplified by software which collected values of thermocouple voltage and thermistor resistance over a time interval. The analysis was done in two cases, when thermocouple and thermistor were touched simultaneously and when hot air from hair dryer was blown to them.

3.1 When Thermocouple and Thermistor were touched simultaneously.

In this case, both thermocouple and thermistor were touched simultaneously and the values of thermocouple voltage and thermistor resistance were recorded with the aid of data logging. The data was then extracted from the Pico Scope data logging software and then plotted on the same graph against time in excel. Below is the graph of potential difference/ resistance against time.

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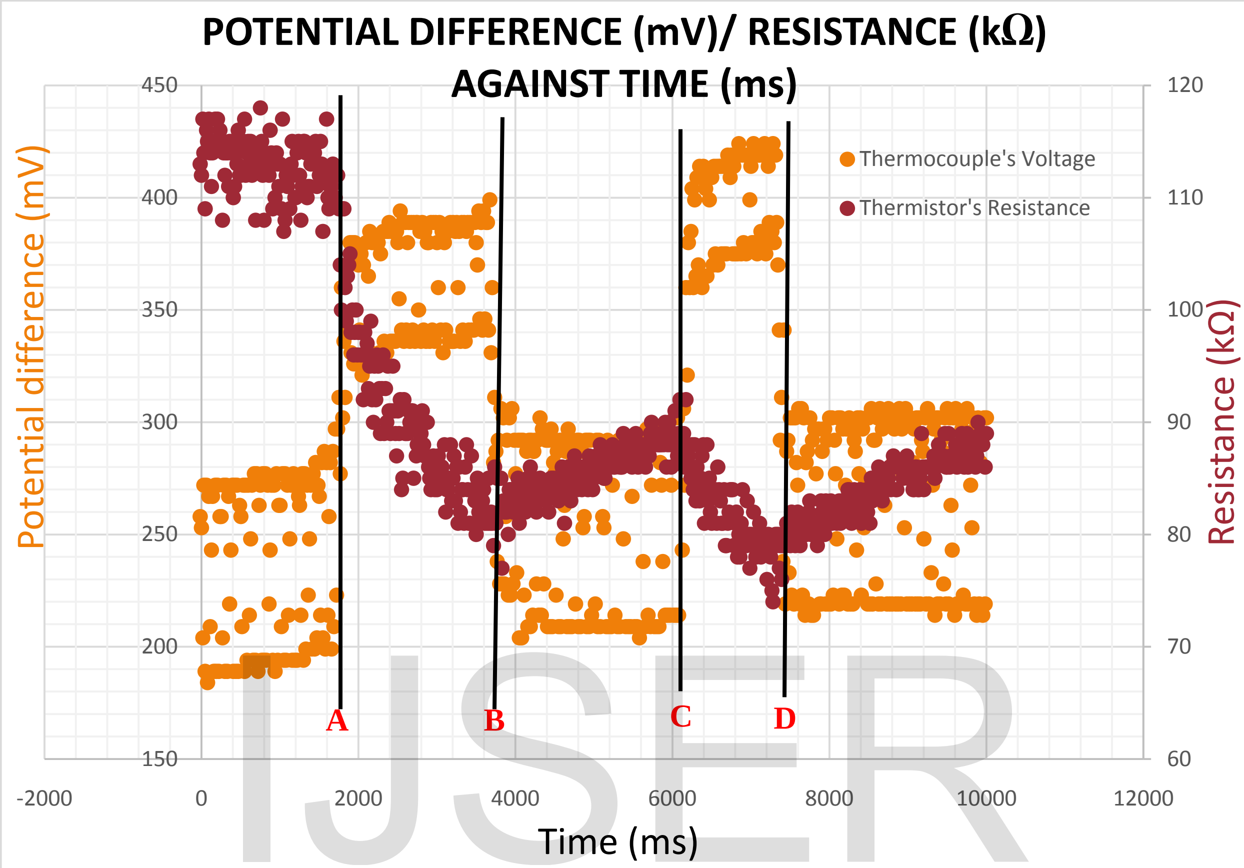
Graph 3.1.1: Graph of potential difference/ resistance against time when thermocouple and thermistor were touched.



When touched at A; thermocouple and thermistor were heated from room temperature for a time interval A to B. The thermocouple required about 400 ms (about 1 minor time-scale interval) for its voltage to rise from the minimum value (about 230 mV) to its maximum value (about 360 mV) which was maintained up to time at B while it was still touched. On the other hand, the thermistor took about 1600 ms (almost 4 minor time-scale intervals) for its resistance to fall from around 112 kΩ to about 80 kΩ.

When released at B; thermocouple and thermistor were left to cool to room temperature. The thermocouple spent about 400 ms for its voltage to fall from around 360 mV to about 250 mV which is very close to the initial voltage of 230 mV as it is seen from graph 3.1.1 above. The thermistor required about 2400 ms (about 6 minor time-scale intervals) for its resistance to rise from around 80 kΩ to about 90 kΩ in which as it was seen from the graph there is nowhere near the initial thermistor resistance of about 112 kΩ at room temperature.

When touched again at C; the thermocouple and thermistor were once again heated for a time interval C to D. From the graph it was observed that, the thermocouple spent about 400 ms (about 1 minor time-scale interval) for its voltage to reach the peak value of about 390 mV from 250 mV and this value was maintained for the whole time when it was touched. On the case of the thermistor it took about 1200 ms (about 3 minor time-scale intervals) for its resistance to fall from around 90 kΩ to about 75 kΩ.

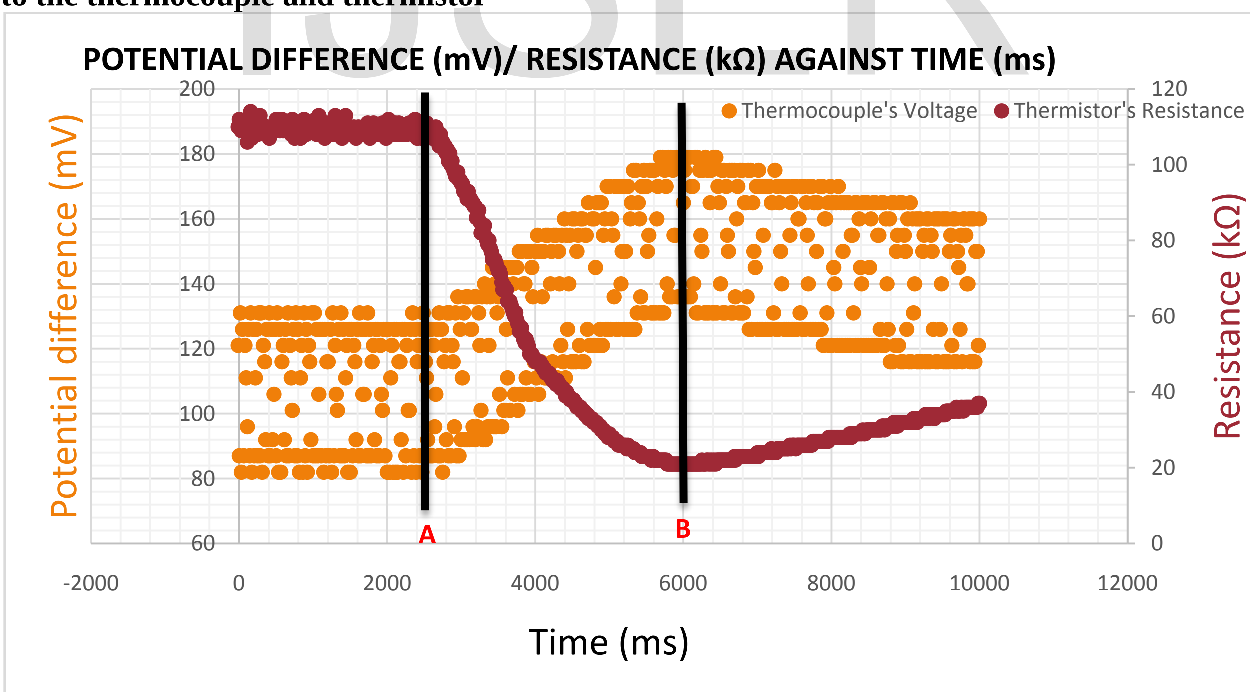
When released at D; both thermocouple and thermistor were allowed to cool to match the room temperature. The thermocouple took about 400 ms (about 1 minor time-scale interval) for its voltage to fall from 390 mV to around 260 mV which was close to the initial thermocouple voltage recorded at room temperature of about 230 mV as it was seen on the graph. On the other hand, the thermistor spent at least 2400 ms (at least 6 minor time-scale intervals) for its resistance to rise to 90 kΩ from around 75 kΩ. As it was seen from the graph, this room temperature thermistor resistance registered was very small compared to the initial room temperature thermistor resistance of about 112 kΩ.

From the above descriptions it was observed that, the thermocouple had a quicker thermal response and a shorter time lag than the thermistor when the thermal change was associated with making contact between the sensor and the body to be measured. The thermocouple produced an abrupt change in voltage whenever the thermal energy was changed and it registered almost a constant voltage corresponding to unchanged thermal energy but this was not the case for the thermistor which had a slow thermal response with a longer time lag.

3.2 When hot air from the hair dryer was blown to the Thermocouple and Thermistor.

In this case, hot air from a hair dryer was blown to both thermocouple and thermistor placed close to each other for the same time interval. The values of thermocouple voltage and thermistor resistance were recorded with the aid of data logging then extracted from the Pico Scope data logging software and then plotted on the same graph against time in excel. Below is the graph of potential difference/ resistance against time.

Graph 3.2.1: Graph of potential difference/ resistance against time when hot air was blown to the thermocouple and thermistor



When hot air was blown from the hair dryer to the thermocouple and thermistor for a time interval A to B, both spent the same time to respond to the increase in thermal energy change.

From graph 3.2.1 above it was observed that, when thermal energy was added starting at time A the thermocouple voltage started to increase to its maximum value at time B when the hair dryer was switched OFF. Likewise, for the thermistor its resistance started to fall from time A until it reached its minimum value at time B when the hair dryer was switched OFF.

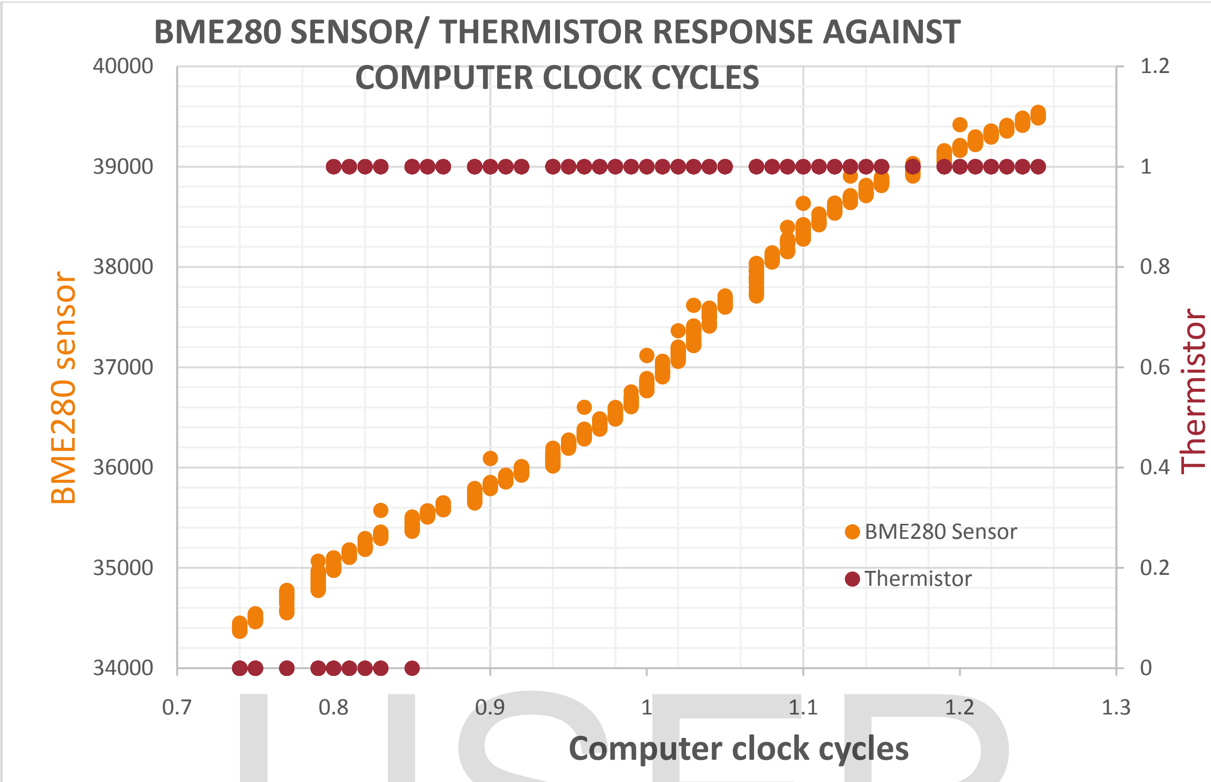
Again, when the hair dryer was switched OFF at time B, the thermocouple voltage started to fall while the thermistor resistance started to rise. From the graph it was seen that even after two major time-scale intervals (4000 ms) neither the thermocouple nor the thermistor registered the initial values corresponding to the room temperature. Therefore, it was observed that despite both thermocouple and thermistor giving a change in their voltage and resistance values respectively when there is a change in thermal energy, they did not have a quick response as it was suggested in their delay to record values corresponding to the room temperature after the hair dryer was switched OFF.

Also the fact that the change in recorded values for thermocouple were smaller when hot air was blown (from 104 mV to 156 mV in graph 3.2.1) compared to when it was touched (from 230 mV to 360 mV in case A of Graph 3.1.1) suggests that, thermocouple was not a good sensor when the thermal energy change was not associated with touching it. On the other hand, the thermistor had a larger change in recorded values when hot air was blown (from 110 kΩ to 20 kΩ in graph 3.2.1) compared to when it was touched (from 112 kΩ to 80 kΩ in case A of graph 3.1.1), this suggests that the thermistor had a better thermal response than thermocouple when the thermal energy change was not associated with touching it.

3.3 When hot air from the hair dryer was blown to the Thermistor and BME280 sensor.

It was found that, thermistor has a good thermal response than the thermocouple when hot air was blown to them; for that reason, thermistor was then compared with the BME280 environmental sensor to see their responses. When hot air was blown from the hair dryer to BME280 sensor and thermistor simultaneously their responses was noted from the data processed by the Raspberry Pi. The two output signals from the BME280 sensor and thermistor were all fed to the Raspberry Pi which processed them to produce two values at a time, one corresponding to the temperature on the BME280 sensor and another being a binary signal with low (0) or high (1) value when the thermistor was cold and hot respectively, registered next to each other such that their variations were used to indicate their thermal energy responses. The obtained data was then extracted and imported to excel where a graph was drawn to compare the thermal response between the BME280 sensor and the thermistor as shown in graph 3.3.1 below.

Graph 3.3.1: Graph of BME280 sensor/ Thermistor response against computer clock cycles



From graph 3.3.1 above, when hot air was blown from the hair dryer to both the BME280 sensor and thermistor, the BME280 sensor was the quickest to respond. The BME280 sensor registered values corresponding to temperature instantly after the air temperature started to increase. For the case of thermistor, it took almost 0.12 clock cycles (about 3 minor scale intervals) to trigger from low (0) to high (1) since it needed a temperature change to be recognised by the thermistor for it to trigger. The above observation suggests that the thermistor needed a longer time compared to the BME280 sensor in responding to the change in thermal energy.

It was noted that, the BME280 environmental sensor had a shorter time lag compared to the thermistor making it a suitable temperature sensor to quickly detect and when calibrated. It measure the amount of temperature change in the air due to a given thermal energy change. Point to note here is that, for convenience, the comparison between thermistor and the BME280 environmental sensor was done by neglecting the idea that the thermistor needed to hit a certain value for it to give a signal. This does not give full assurance that the thermistor was not detecting the thermal energy change until it triggered but rather being a digital input it had to reach a certain value for it to change from low (0) to high (1) signal. When that is neglected, as in the above analysis, it is easy to assert that the BME280 environmental sensor was quicker to respond to thermal energy change than the thermistor but yet this might not be the case.

Conclusion and recommendations

The findings of this study were seen to be useful in a daily life when detecting and measuring thermal energy change occurring on solids and particularly on air. To measure the temperature of solids where the sensor has to touch the object, the thermal energy transfer from object to the sensor is mainly by conduction. The thermocouple was seen to have a quicker response than the thermistor and hence the researcher recommends thermocouple to be used in detecting thermal energy change in solids. The measuring junction of the thermocouple is bare, not covered by insulators, while the thermistor has its end covered with ceramic materials.

To measure temperature of air where there is no one point of contact between the sensor and the air, the thermal energy from the air (surrounding) reaches the sensor by convection. The results obtained from this study showed that neither the thermocouple nor the thermistor was useful but the BME280 environmental sensor. This observation was reached by neglecting the idea that the thermistor, being a digital input, had to reach a certain temperature for it to give a signal. The BME280 environmental sensor gave values corresponding to the temperature of the air but it did not give the actual temperature value in the temperature scale. Improvements need to be done to manage and convert the given values into the temperature scale for it (BME280 environmental sensor) to be used to measure an exact value of temperature of the air in a proper temperature scale.

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