PHYSICS HL Internal Assessment:

Electrolytic Capacitors' Temperature Dependence

Research Question:

How does the temperature of an electrolytic capacitor affect its capacitance?

Word count: 3000 words.

Index

Research:

Introduction:

Having a background in electronics, I am aware of the dangers of electric circuits at high temperatures, with capacitors being widely known for being subject of thermal tests. Personally, I have never used capacitors extensively, so my knowledge about them is limited.

Research Question:

Through this IA, I aim to expand my knowledge on capacitors through experimentation. The research question comes mainly from previous personal research on thermodynamics and CFD (Computational Fluid Dynamics), as one of its main uses is to study the efficiency of a device's cooling system. For what I have seen, capacitors, coils and transistors stand out because of their high temperatures. Hence, the selected research question is **"How does the temperature of an electrolytic capacitor affect its capacitance?"**.

Exploration:

Introduction to capacitors

Capacitors are electric components that store small amounts of energy in the form of an electric field. There are 3 main types of capacitors:

- Electrolytic capacitors
- Ceramic capacitors
- Double Layer capacitors

Capacitance is a quality of materials that represents their ability to store electric charges at a given voltage(s). This capacitance is directly proportional to the charge the capacitor holds:

$$C = \frac{Q}{V}$$

Equation 1: General equation for capacitance.

Where:

$\boldsymbol{Q} -$ Charge held.

$C-$ Capacitance.

$V-$ Potential difference across the electric field.

Capacitors store energy in an electric field by generating a potential difference between two conductive plates separated by an insulator:

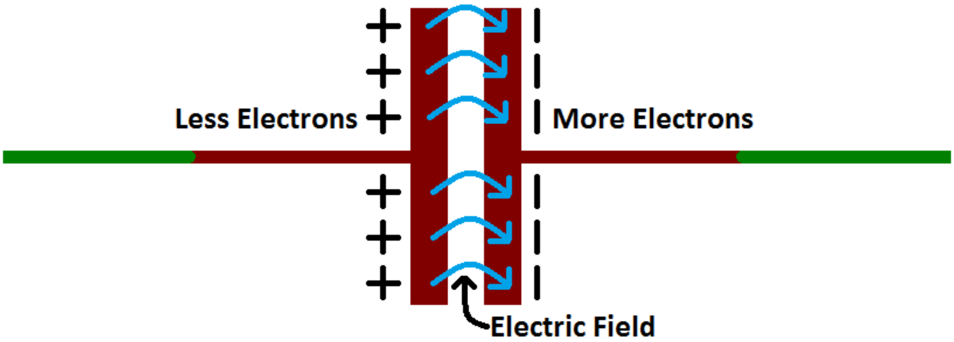


Figure 1 - Simplified diagram of the workings of a ceramic capacitor (SparkFun Electronics).

As seen in the diagram, the electrons located in the charged plate are attracted by the lack of electrons in the uncharged plate, locking them in place.

Electrolytic capacitors:

Electrolytic capacitors use an additional component that allows them to increase their capacitance: a dielectric material (see Figure 2). The “electrolytic spacer” or “electrolyte” present in Figure 2 is simply a conductor. Hence, it can be considered part of the cathode (negative plate) of the capacitor.

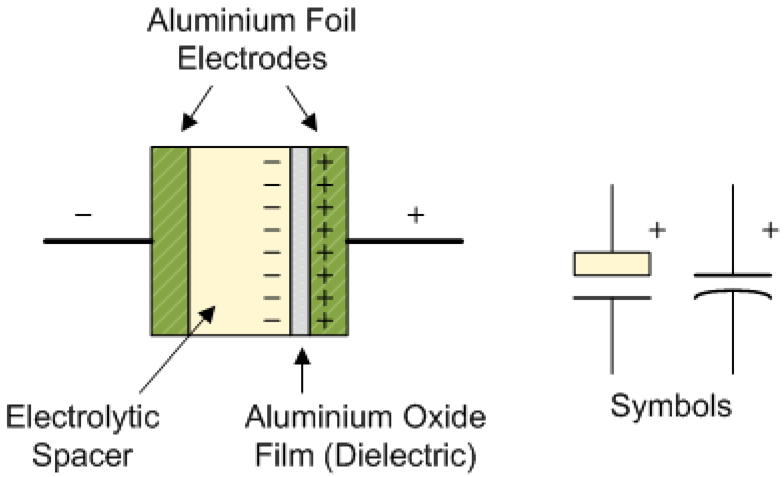


Figure 2 - Diagram featuring the workings of an electrolytic capacitor (ASPENCORE).

Dielectric materials do not conduct electricity (insulators), but, when under the effect of an electric field, their ions/electrons internally straying away from their usual position, polarizing (see Figure 3).

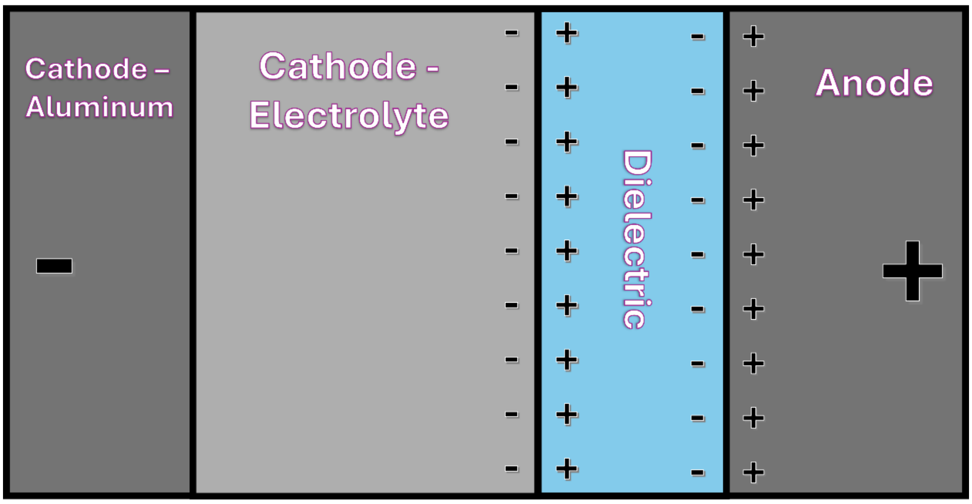


Figure 3 - Distribution of charges throughout the different components of an electrolytic capacitor (Author’s Own).

This polarization of the dielectric creates a small electric field that opposes the capacitor’s field, reducing its effects:

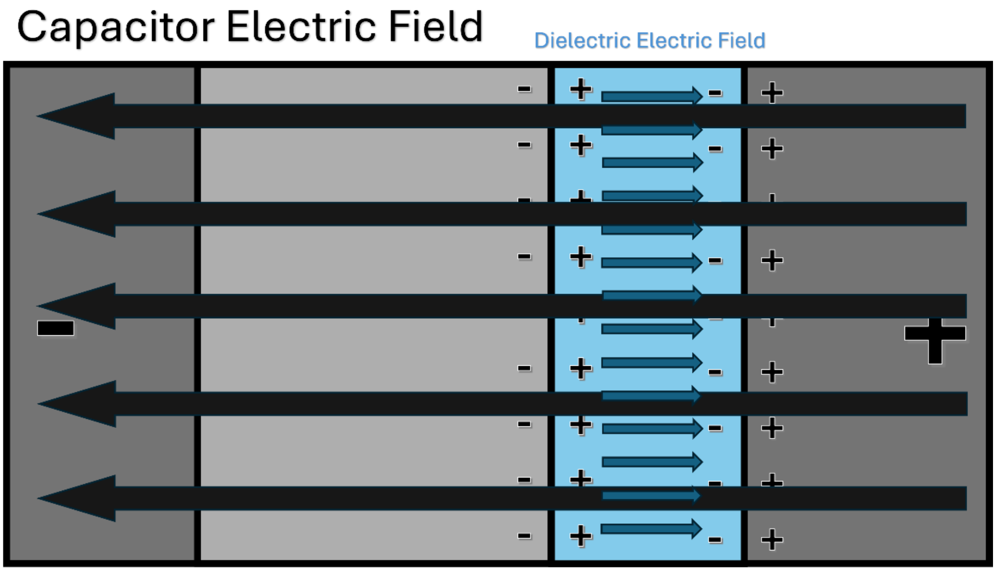


Figure 4: Representation of opposing electric field in dielectric (Author's Own).

The effect this has in the capacitance can be explained with the following equations:

The electric field in a capacitor is:

$$E_o = \frac{V}{d}$$

Equation 2: Electric Field Strength in a capacitor.

Where:

E_o – electric field strength.

V – Voltage across the plates.

d – distance between the plates.

The field strength is reduced by the dielectric, and, as the distance between the plates (d) remains unchanged, the voltage across the plates decreases.

From Equation 1:

$$C \propto \frac{1}{V}$$

Where:

C – Capacitance.

V – Voltage across the plates.

Hence, as voltage decreases, capacitance increases proportionally. This leads us to the following equation:

$$C = \varepsilon_o \cdot \varepsilon_r \cdot \frac{A}{d}$$

Equation 3: Capacitance of an electrolytic capacitor (TDK 2).

Where:

C – Capacitance.

$\boldsymbol{\varepsilon_o}$ – Absolute Permittivity (Permittivity in a vacuum).

$\boldsymbol{\varepsilon_r}$ – Relative Permittivity of the dielectric.

A – Area of one of the equal plates.

d – Distance between the plates.

Equation 3 includes the permittivity of the dielectric and the area of the plates, both directly proportional to the capacitance.

Dielectrics polarization:

There are multiple ways a dielectric can be polarized:

- **Electronic polarization**: The electrons in the material deviate from their original position around their respective atoms.
- **Ionic polarization**: When the dielectric is composed of ions, the positive and negative ions accumulate in opposite faces of the material's geometry.
- **Dipole (orientational) polarization**: The molecules forming the dielectric are dipoles, which reorient when subjected to an electric field.

Dielectrics and temperature:

Increasing a capacitor's temperature would make the dielectric's molecules vibrate, which would difficult their rotation/translation, hampering the activation of the opposing electric field of the dielectric. This would result in a decrease in the dielectric's relative permittivity.

As the opposition of the dielectric's electric field to the capacitor's electric field increases capacitance, the impedance generated by the temperature would make its capacitance decrease.

Consequently, a decrease in temperature would increase capacitance.

Thermal expansion:

As the capacitor's temperature increase, its plates expand:

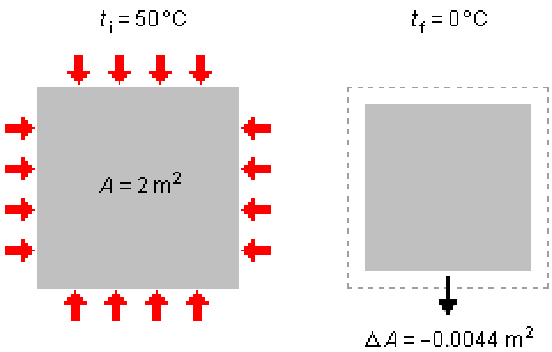


Figure 5: Area differential due to thermal expansion on a metal plate (fisicaexe.com).

As stated in Equation 3, capacitance is proportional to the area of the plates. Due to thermal expansion, the area of the plates increases along with the capacitance.

The effect of thermal expansion on the area of an object can be modelled through the following equation:

$$\Delta A = 2\alpha A_o \Delta T$$

Equation 4: Change in area of a material given its temperature (Ling, Moebs and Sanny 11).

Where:

$\boldsymbol{\Delta A}$ – Increment in area.

$\boldsymbol{A_o}$ – Initial area.

$\boldsymbol{\Delta T}$ – Increment in temperature.

$\boldsymbol{\alpha}$ – Coefficient of linear expansion.

Aluminium's coefficient of linear expansion is $25 \cdot 10^{-6}\ °C^{-1}$ (Ling, Moebs and Sanny 12)

Hypothesis:

According to the concepts explored in the background theory, temperature influences the capacitance through the thermal expansion of the plates and the dielectric constant.

Generally, as the temperature of a dielectric rises, its dielectric permittivity/constant decreases. As capacitance is proportional to the dielectric constant, the capacitance would decrease.

On the contrary, due to thermal expansion, the area of the plates increases with temperature. The area of the plates is also proportional to capacitance, so temperature will also increase capacitance.

Nonetheless, as electrolytic capacitors highly depend on the dielectric's performance, I expect the effect of the dielectric will be much greater than that of thermal expansion, effectively reducing capacitance as temperature increases.

Variables:

Independent:

Variable	Explanation	Range	Increment	Measuring device
Temperature of capacitor	Ensure the capacitor and its environment are at the experiment's designated temperature.	[26.0ºC, 90ºC]	+0.5ºC	**DS18B20** Temperature sensor. Average error: ±0.2ºC (Maxim Integrated Products 3).

Dependent:

Variable	Explanation	Measuring device
Capacitance of capacitor	Measure the capacitance once made sure the capacitor is at the required temperature.	**DM6013L** capacitance reader Error: $0.01\mu F$ (smallest division the measurement device can read)

Control:

Variable	Explanation	Control measures
Humidity of isolated environment	Ensure the humidity of the isolated enclosure remains constant throughout the entire experiment.	Seal the enclosure tightly.
Type of dielectric	Ensure the capacitor's dielectric is the same throughout the experiment.	Use the same capacitor every iteration.
Voltage applied to the capacitor	Ensure the voltage at which the capacitor is charged is always the same.	Fully discharge the capacitor before the experiments.
Reader	Ensure the capacitance meter is the same for all readings.	Use the same capacitance reader.
Heating methods	Ensure all capacitors are heated the same way (e.g. not heating a capacitor's top surface in one experiment, and the bottom surface in another).	Heating not the capacitor, but the enclosure, from every angle.
Capacitor's age	Ensure the capacitor's age (charge-discharge cycles) does not affect the experiment's results.	Discharging the capacitor only once and conducting all experiments with it.

Uncontrolled:

Variable	Explanation	Possible consequences
Resistance increase of the electric components	As the experiment heats up, all the electronic components' resistances will increase	This increase in resistance could affect the capacitance meter's readings.

Materials:

The materials used for the experiment are listed below:

1. Isolated chamber:
    a. Silicone sealer
    b. **1** Thermoplastic (polypropylene) chamber
2. Heating system:
    a. Boiling water
    b. **1** Heat-resistant beaker
    c. **1** Microcontroller
    d. **1** DS18B20 temperature sensor
    e. **1** 4.7KΩ resistor
    f. **1** Breadboard
3. Capacitance meter – DM6013L
4. Electrolytic capacitor – Panasonic EEAFC1E100
5. Computer with *Arduino IDE* installed
6. Lid and microcontroller-breadboard casing

Uncertainties:

Two measuring devices were used throughout the experiment:

- The DM6013L capacitance-meter, Scale: 0.01μF. **Uncertainty – 0.005μF**.
- The DS18B20 temperature sensor, Scale: 0.01ºC. **Uncertainty – 0.005ºC.**

Methodology:

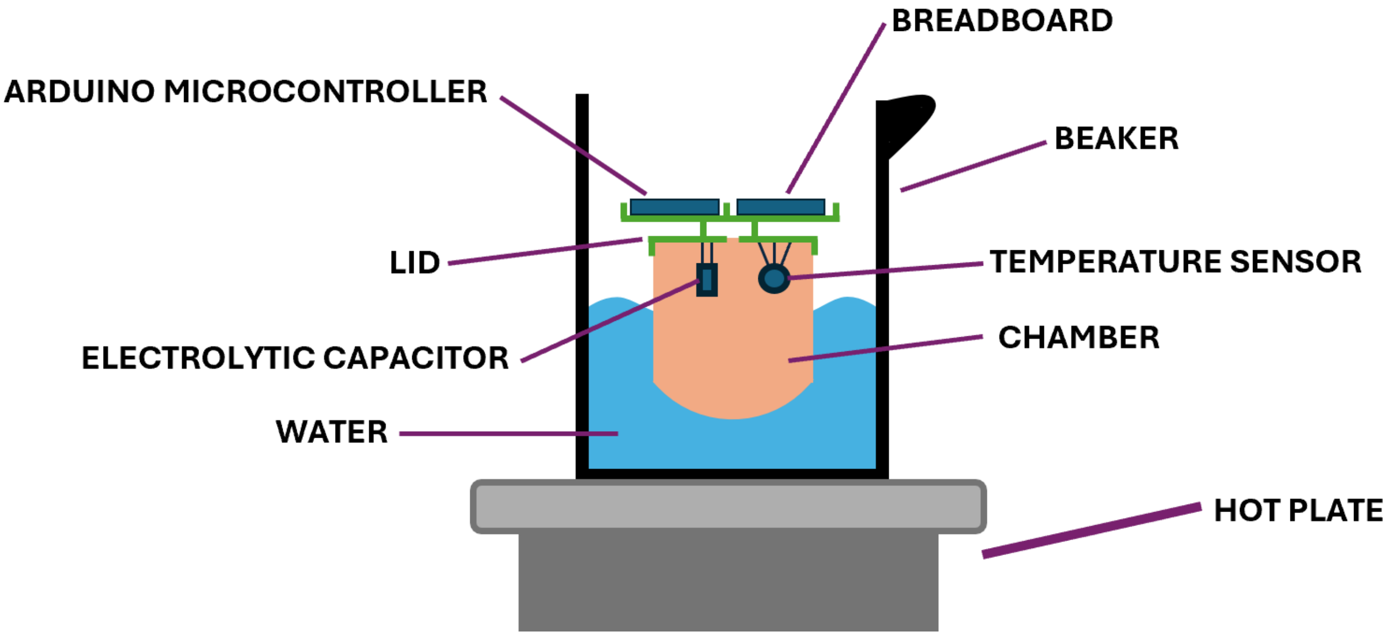


Figure 6: Diagram of the experiment (Author's Own).

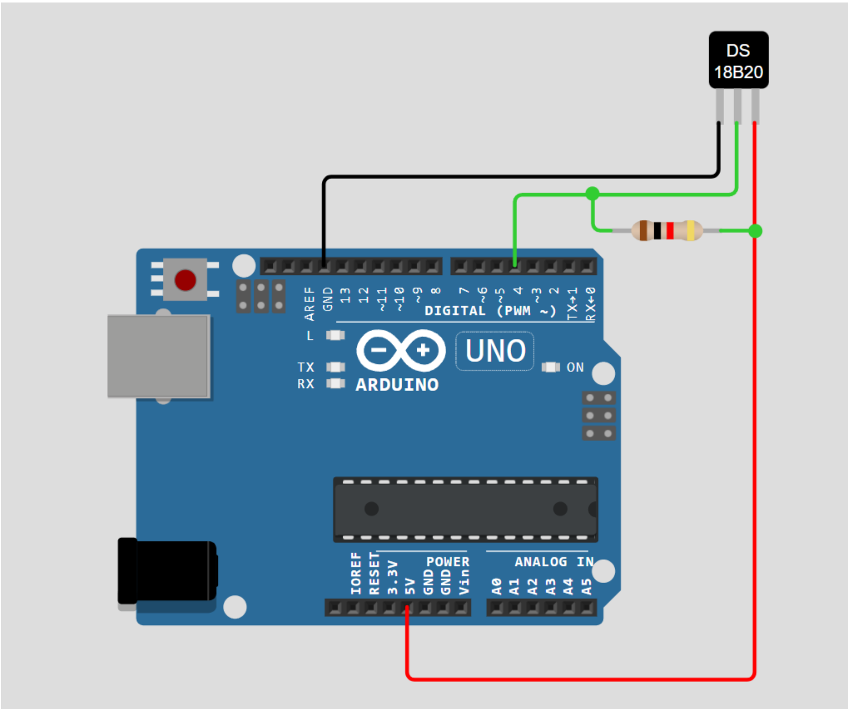


Figure 7: DS18B20 temperature sensor and Arduino simplified circuit diagram (Author's Own).

The **three iterations** of the experiment carried out as follows:

1. Set up the experiment as shown in Figure 7.
2. Wire the temperature circuit as shown in Figure 8.

3. Connect the positive and negative pins of the capacitor to their corresponding terminals of the capacitance-meter.
4. Cool the sealed enclosure until it reaches a temperature lower than 25ºC (place the enclosure in a fridge if needed).
5. Place the beaker on top of the heater and turn it on.
6. Heat the beaker with the water to almost 100ºC.
7. Place the enclosure inside the beaker.
8. Connect the Arduino microcontroller to a computer, and the capacitor to the capacitance-meter.
9. Check that no wires are touching the hot plate of the heater (prevents the wires' protective layers to melt or catch on fire).
10. Save the capacitance-meter's measurements every increase of 0.5ºC in temperature, starting from 26ºC.
11. Stop saving the readings when the temperature reaches 90ºC.
12. Turn the heater off.
13. Disconnect the Arduino and the capacitor to the computer and the capacitance-meter, respectively.
14. Take the enclosure out of the beaker
15. Repeat steps 3-12 twice (three iterations total).

Furthermore, prior to the first iteration of the experiment, the following security measures were taken:

1. Safely discharge the capacitor:
    a. Measure the voltage of the capacitor.
    b. Calculate the resistance needed to discharge the voltage at a current of 30mA.
    c. Connect both pins of the capacitor together through the resistor.
    d. Leave it discharging until the capacitor's voltage reaches zero.
2. Check that the wirings of the capacitor and the sensor are correct (short-circuit prevention).
    a. With a resistance-meter, check the continuity between critical points, such as the breadboard's wires, the microcontroller's pins and resistors.

Risk assessment:

Safety:

HAZARD	RISK	CONTROL
Capacitors could cause electric shocks	High	**Safely discharging it at 25mA max.** (50mA being the current needed to cause respiratory arrest (Occupational Safety and Health Administration, U.S. Department of Labor 6)) Using protective gloves.
Water could boil and escape the beaker, damaging electric components.	Medium	Ensure the heater is set to <100ºC. Mix salt with the water to increase boiling point.
Capacitor might explode, releasing dangerous fumes.	Medium	Not charging the capacitor

Environmental:

HAZARD	RISK	CONTROL
Excessive water used	Low	**Doing all three experiments with the same wate**r, refilling only the water lost due to vaporization.
3D printed parts (see Figure below) might cause environmental impact after use.	Low	Design the 3D printed parts to be reusable for other projects. Those that are not, recycle them.

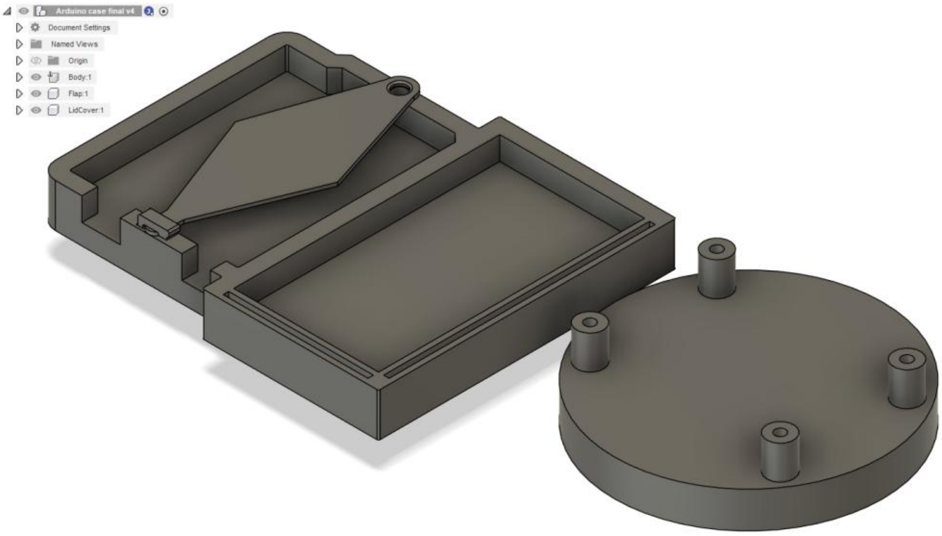


Figure 8: Lid and microcontroller-breadboard holder (Author's Own).

Analysis:

Results:

All iterations averaged:

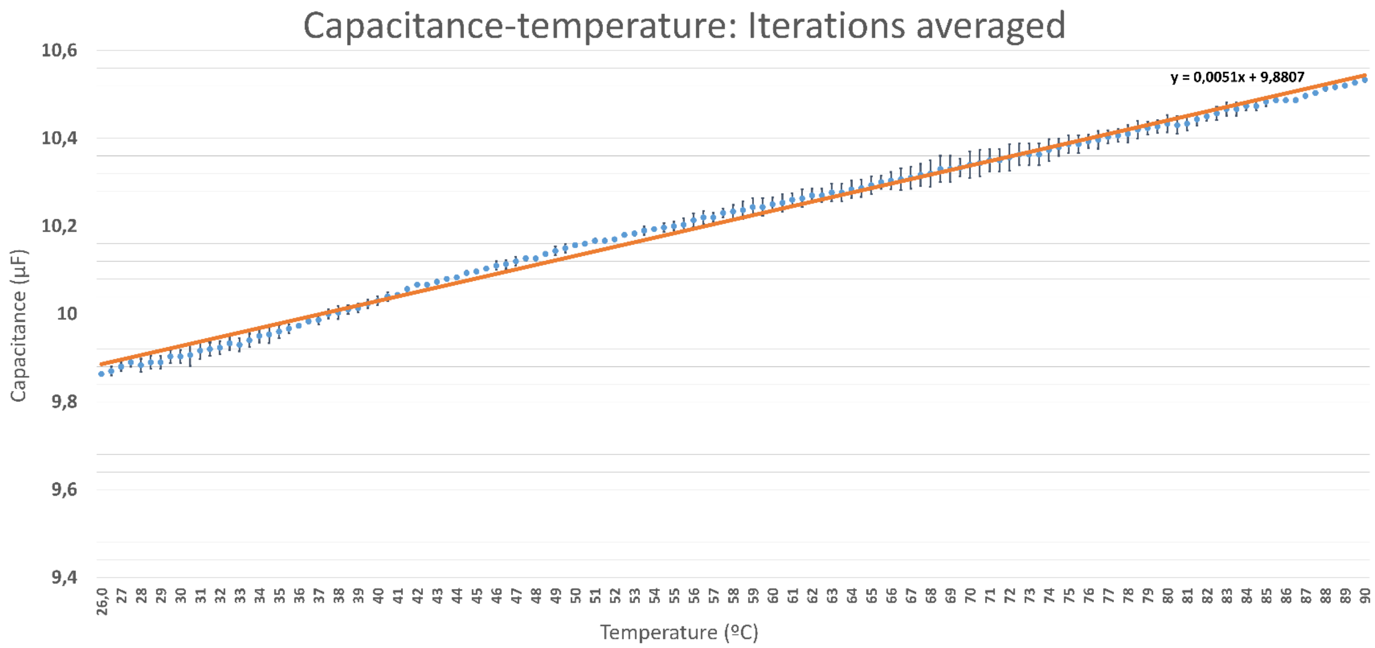
Temperature (± 0.01℃)	**Capacitance ($\pm 0.001\mu F$)**	**Error in the mean value**
26,00 ºC	9,86 μF	0,005 μF
26,5 ºC	9,87 μF	0,01 μF
27 ºC	9,88 μF	0,01 μF
27,5 ºC	9,89 μF	0,01 μF
28 ºC	9,88 μF	0,015 μF
28,5 ºC	9,89 μF	0,015 μF
29 ºC	9,89 μF	0,015 μF
29,5 ºC	9,90 μF	0,015 μF
30 ºC	9,90 μF	0,015 μF
30,5 ºC	9,91 μF	0,025 μF
31 ºC	9,92 μF	0,02 μF
31,5 ºC	9,92 μF	0,015 μF
32 ºC	9,92 μF	0,015 μF
32,5 ºC	9,93 μF	0,015 μF

33 ºC	9,93 µF	0,015 µF
[…]		
87 ºC	10,5 µF	0,005 µF
87,5 ºC	10,5 µF	0,005 µF
88 ºC	10,5 µF	0,005 µF
88,5 ºC	10,5 µF	0,005 µF
89 ºC	10,5 µF	0 µF
89,5 ºC	10,5 µF	0,005 µF
90 ºC	10,5 µF	0,005 µF

Table 1 (Author's Own)

Data Processing:

All iterations averaged:



Graph 1 (Author's Own)

Results:

As it can be observed in graph 4, the relationship between the temperature of an electrolytic capacitor and its capacitance is linear, showing a **strong positive correlation**. This is, the higher the temperature of a capacitor, the higher its capacitance.

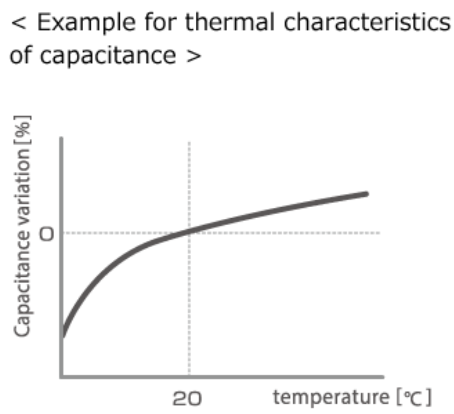
For this capacitor in particular, an equation for its capacitance against its temperature can be found using linear regression (see Graph 4):

$$y = 0.0051x + 9.8807$$

The results show that for every increase of +1ºC the capacitance increases by +0.0051μF, with a capacitance of 9.8807μF at 0ºC.

Conclusion:

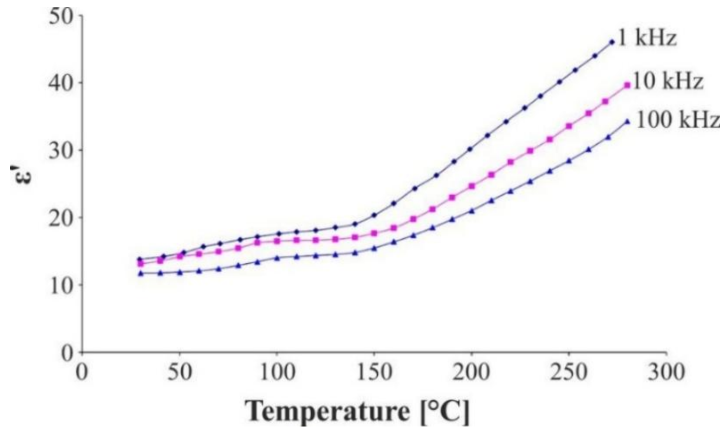
Contrary to what has hypothesised, the temperature of the capacitor and its capacitance show a positive correlation. These same results can be observed in other research on similar electrolytic capacitors:



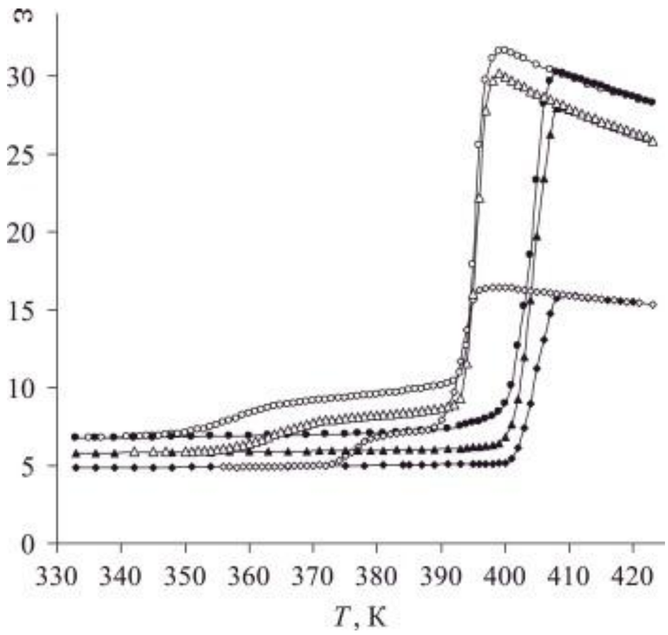
Graph 2: Capacitance vs temperature for an electrolytic capacitor (TDK).

While the results of this experiment show a constant linear correlation between temperature and capacitance, Graph 6, shows the same positive correlation, but in a non-linear shape when temperature is smaller than 20ºC. The results of this paper do not show the capacitance related with temperatures lower than 20ºC, so a comparison is only possible after those temperatures. When compared, the results are similar in both experiments.

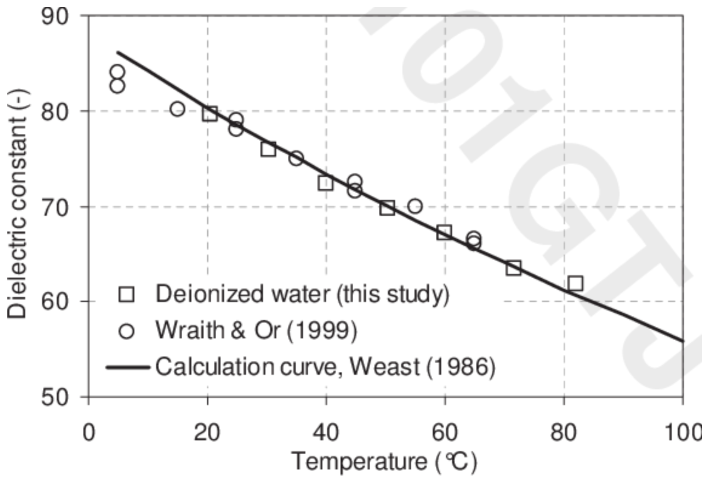
However, while it was hypothesised that the capacitance was going to experience a decrement, the opposite was proven. Research on different capacitors suggests that the internal structure (chemical bonds) of the dielectrics heavily influence the capacitor's behaviour towards temperature:



*Graph 3: Variation of the dielectric constant of a dielectric that undergoes **electronic polarization** (Milinskiy, Dielectric properties of a potassium nitrate–ammonium nitrate system).*



*Graph 4: Variation of the dielectric constant of a dielectric that undergoes **ionic polarization** (Penugonda, Naga Raju and Prasad).*



*Graph 5: Variation of the dielectric constant of a dielectric that undergoes **dipole polarization** (Schanz, Nguyen Tuan and Baille).*

The three graphs above show the variation of the relative permittivity (dielectric constant) of a dielectric with temperature for three compounds of distinct structures. The structure of the compound represented in Graph 3 makes it undergo electronic polarization (see "Background Information"), while the compounds in Graphs 4 and 5 undergo ionic and dipole polarization when subjected to an external electric field.

The capacitor used in this experiment uses an Aluminium Oxide (Al_2O_3) dielectric (NIPPON CHEMI-CON CORPORATION). Being ionically bonded, this dielectric behaves similarly to the one shown in Graph 4, as between 330K (57ºC) and 367K (90ºC) the variation in the dielectric constant is minimal but positive and approximately linear, as found in this experiment's results too.

Capacitors that use dielectrics of different chemical formulation tend to behave differently with temperature, as is the case with some ceramic capacitors. Depending on the type of dielectric used, the capacitance increases or decreases differently:

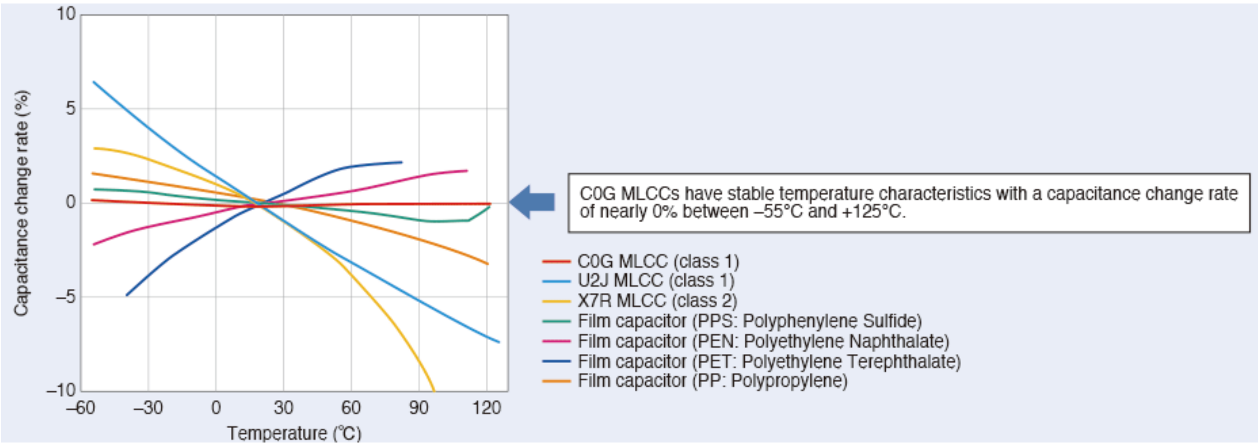


Figure 9: Capacitance change rate of different ceramic and film capacitors (doEEEt Media Group).

Additionally, a compound's structure can organize differently depending on its temperature. For instance, Barium Titanate can undergo dipole polarization at some temperatures, while at others not:

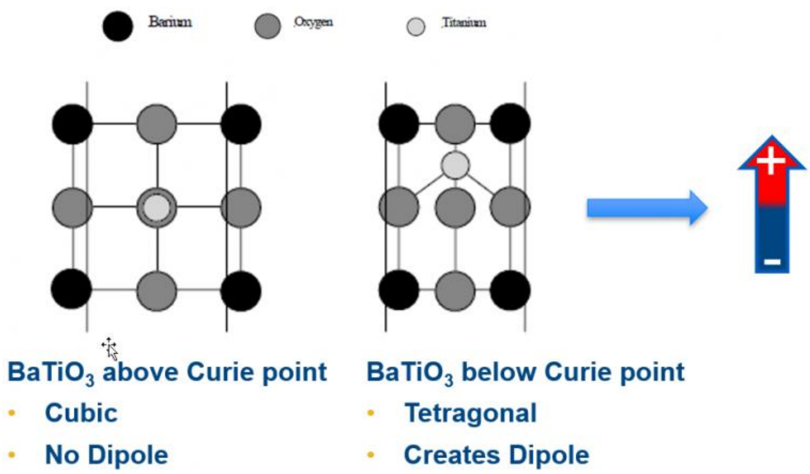


Figure 10: Barium Titanate dipole formation (KEMET Corporation).

Furthermore, there are other factors that were not considered in the hypothesis, such as the viscosity of the dielectric and the electrolyte, especially the latter. In aluminium electrolytic capacitors like the one used, the electrolyte is in liquid form. An increased temperature would decrease the viscosity of the material, allowing it to make a better contact with the anode and cathode, increasing the capacitance.

These factors influenced the change in the dielectric constant, the main contributor to the increase in capacitance.

Through the equation for thermal expansion discussed in the background knowledge, an estimation for the change in area of the capacitor's plates can be calculated:

$$A_f - A_o = 2\alpha A_o \Delta T$$

$$A_f = A_o + 2\alpha A_o \Delta T$$

$$A_f = A_o(1 + 2\alpha \Delta T)$$

$$A_f = A_o(1 + (2 \cdot 25 \cdot 10^{-6}{}^{\circ}\mathrm{C}^{-1}) \cdot (90{}^{\circ}\mathrm{C} - 26{}^{\circ}\mathrm{C}))$$

$$\frac{A_f}{A_o} = (1 + (2 \cdot 25 \cdot 10^{-6}{}^{\circ}\mathrm{C}^{-1}) \cdot (90{}^{\circ}\mathrm{C} - 26{}^{\circ}\mathrm{C}))$$

$$\frac{A_f}{A_o} = 1.0037$$

Hence, the area has increased by 0.37%. As area is directly proportional to the capacitance in a capacitor, the capacitance saw an increment of 0.37% due to the thermal expansion of the plates.

The total capacitance increase observed in the experiment was of:

$$\frac{C_f}{C_o} = \frac{10.53}{9.863} = 1.0679 \rightarrow [6.793\%]$$

Therefore, factors such as the variation in the dielectric constant or the viscosity of the material caused an increase in capacitance of:

$$1.0037 \cdot \mathrm{k} = 1.0679$$

$$k = 1.0640 \rightarrow \mathbf{6.4}\%$$

A contributor for that 6.4% increase in capacitance is the dielectric constant. For aluminium oxide, the variation in relative permittivity between 26ºC and 90ºC can be estimated from the following graph (assuming the increase is linear between 0ºC and 200ºC):

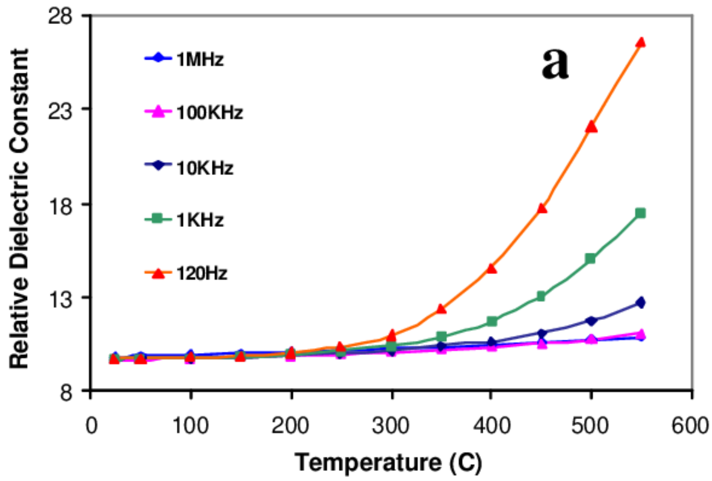


Figure 11: Aluminium Oxide's dielectric constant against temperature, measured at different frequencies (Liang-Yu and W. Hunter).

The change in Aluminium Oxide’s dielectric constant with temperature can be modelled from Figure 11:

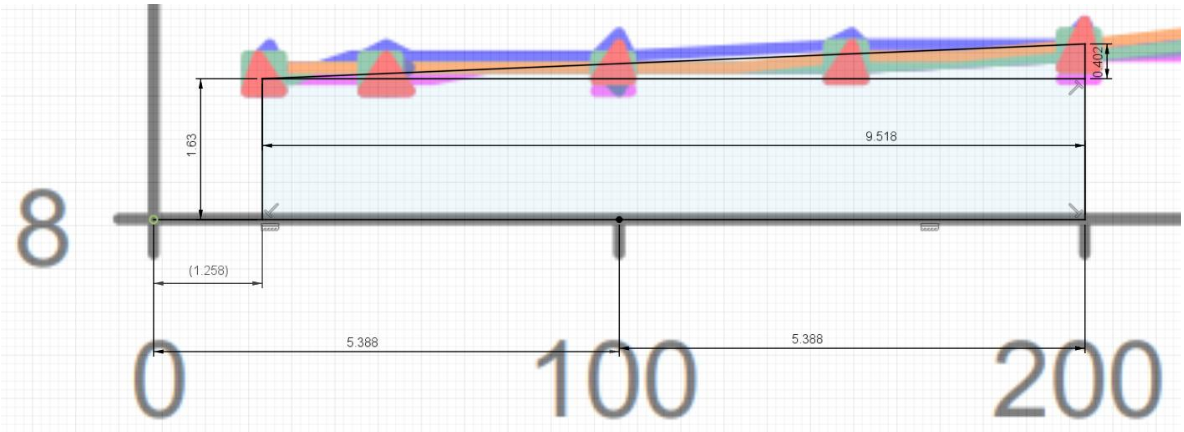


Figure 12: Proportions (Author's Own).

Hence, the dielectric constant for temperatures between 0ºC and 200ºC can be modelled as:

$$\boldsymbol{\varepsilon = 9.63 + 0.00228T}$$

Where:

$\boldsymbol{\varepsilon}$ – Dielectric constant.

T – Temperature in ºC.

Hence, the increase in the dielectric constant in the experiment was of:

$$\varepsilon_o = 9.63 + 0.00228 * 26 = 9.689$$

$$\varepsilon_f = 9.63 + 0.00228 * 90 = 9.835$$

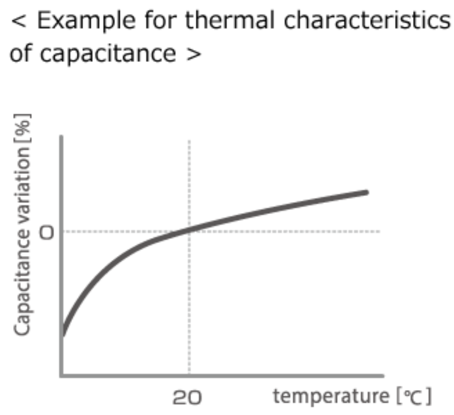
$$\frac{\varepsilon_f}{\varepsilon_o} = 1.0151 \rightarrow \mathbf{1.51}\%$$

Therefore, it is the reduction in the electrolyte's viscosity and other factors that make up for the remaining increase in capacitance:

$$1.0151 \cdot 1.0037 \cdot k = 1.0679$$

$$k = 1.048 \rightarrow 4.8\%$$

In conclusion, and answering the research question "How does the temperature of an electrolytic capacitor affect its capacitance?", the results of this experiment, supported by other research on electrolytic capacitors, have shown that it depends on many different factors, such as the atomic structure of the dielectric material, the viscosity of the electrolytic or the thermal expansion on the capacitor's plates. This relationship can be linear, exponential or take undefined forms, while being positive or negative. Aluminium electrolytic capacitors in particular undergo an exponential increase in capacitance, similar to the one shown in the following figure:



Graph 6: Capacitance vs temperature for an electrolytic capacitor (TDK).

Specifically, through contrasting the results of the experiment with research on the dielectric of the capacitor used, and physical principles such as thermal expansion, the following factors were found to influence the final capacitance at 90ºC of the Panasonic EEAFC1E100 electrolytic capacitor:

- Thermal expansion increased capacitance by a factor of 1.0037.
- The increase in the dielectric constant accounted for an increment in capacitance by a factor of 1.0151
- Other factors such as the potential decrease in viscosity of the electrolytic increased capacitance by a factor of 1.048.

Evaluation:

Several issues came up during the testing part of the experiment, most of them related to the behaviour of the 3D printed parts with temperatures over 55ºC. Initially, the Arduino case and lid were printed in PLA plastic, but due to its low Heat Deflection Temperature (temperature at which it starts to easily deform) of 56ºC, it melted before the experiment was over. Therefore, I switched to a more resistant plastic: PETG. With a Heat Deflection Temperature of 69ºC, it proved to work perfectly, as, even though the enclosure was subjected to temperatures up to 90ºC, the printed parts were not in direct contact with it and were constantly being cooled down.

The hot glue's temperature resistance proved to be too low too. During the first experiment, the hot glue melted and left the enclosure partially unsealed for a second, which required to prepare the experiment again to ensure constant humidity. To ensure this would not happen again, I covered the hot glue with duct tape to protect it from the heat.

As for the results of the investigation, the hypothesis was not correct due to an initial lack of research. It was hypothesized that the capacitance would decrease with temperature, but as explained in the conclusion, the capacitance for these types of electrolytic capacitors decreases with temperature.

Moreover, contrasting the numerical results of this experiment with others proved challenging due to the narrow temperature range, chosen to make the experiment easier to produce. On the other hand, choosing a minimum temperature of 26ºC brought the advantage of not having to cool the enclosure. Similarly, a temperature of 90ºC was designated as the maximum temperature as it allowed for water to be used as a heating medium between the beaker and the enclosure's walls without boiling.

As discussed in the conclusion, unlike this experiment, others showed non-linear graphs for the capacitance of aluminium electrolytic capacitors. The main improvement for future development of the investigation would involve increasing the temperature range at which the experiment is carried out, as it will allow for a better comparison of results

To achieve a wider temperature range, both the enclosure and the 3D printed parts would need to be replaced with other more heat-resistant ones. Some material options include UV Resin, Epoxy or Aluminium. These will withstand more extreme temperatures without melting or showing cracks. Additionally, depending on the new temperature range, a different temperature sensor might be required, as the current one detects temperatures from -55ºC to 125ºC. The temperature sensor PT-111 would be more appropriate for the new, wider range, withstanding temperatures between -262ºC and 400ºC (Lake Shore).

Concerning the temperature sensor, the investigation would benefit from a more accurate sensor, as, with temperature increases of 0.5ºC between measurements and an uncertainty of 0.2ºC in each of them, the individual results are not reliable on their own. Otherwise, the experiment could be carried out in bigger increments.

Similarly to the temperature sensor, the capacitance-meter, which currently holds an uncertainty of 0.005μF, limits the calculations of the experiment, especially considering the electrolytic capacitor used throughout the experiment is rated at 10μF of capacitance. As the values dealt with in the calculations (such as the dielectric constant or the increase in area due to thermal expansion) are significantly small, reducing the uncertainty will increase total accuracy.

Appendix:

Data Acquisition:

Iteration 1:

Temperature (± 0.001ºC)	**Capacitance ($\pm 0.001\mu F$)**
26,0 ºC	9,87 µF
26,5 ºC	9,88 µF
27 ºC	9,89 µF
27,5	9,9 µF
28 ºC	9,9 µF
28,5 ºC	9,91 µF
29 ºC	9,91 µF
29,5 ºC	9,92 µF
30 ºC	9,92 µF
30,5 ºC	9,93 µF
31 ºC	9,94 µF
31,5 ºC	9,94 µF
32 ºC	9,94 µF
32,5 ºC	9,95 µF
33 ºC	9,95 µF
[…]	
87 ºC	10,5 µF
87,5 ºC	10,5 µF
88 ºC	10,51 µF
88,5	10,52 µF
89 ºC	10,52 µF
89,5 ºC	10,53 µF

90 ºC	10,53 µF

Table 2

Iteration 2:

Temperature (± 0.001ºC)	**Capacitance ($\pm 0.001 \mu F$)**
26,0 ºC	9,86 µF
26,5 ºC	9,87 µF
27 ºC	9,88 µF
27,5 ºC	9,89 µF
28 ºC	9,87 µF
28,5 ºC	9,88 µF
29 ºC	9,88 µF
29,5 ºC	9,89 µF
30 ºC	9,9 µF
30,5 ºC	9,91 µF
31 ºC	9,91 µF
31,5 ºC	9,91 µF
32 ºC	9,92 µF
32,5 ºC	9,93 µF
33 ºC	9,92 µF
[…]	
87 ºC	10,50 µF
87,5 ºC	10,51 µF
88 ºC	10,52 µF
88,5 ºC	10,52 µF
89 ºC	10,52 µF
89,5 ºC	10,53 µF
90 ºC	10,54 µF

Table 3

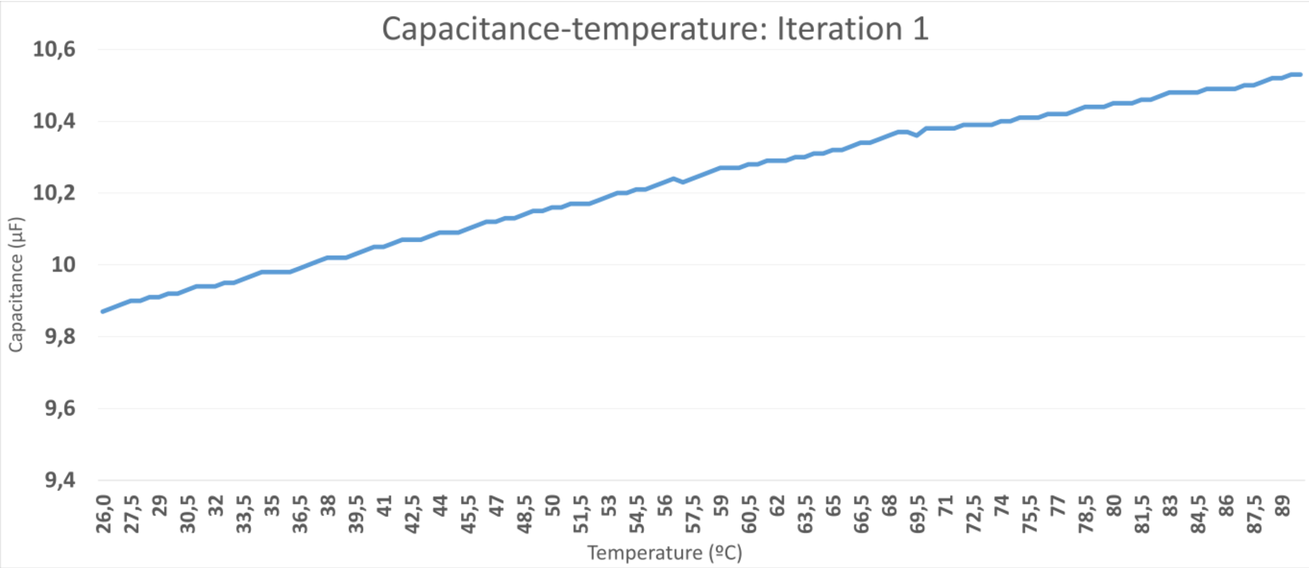
Iteration 3:

Temperature (± 0.001°C)	**Capacitance** ($\pm 0.001\mu F$)
26,0 ºC	9,86 μF
26,5 ºC	9,86 μF
27 ºC	9,87 μF
27,5 ºC	9,88 μF
28 ºC	9,88 μF
28,5 ºC	9,88 μF
29 ºC	9,88 μF
29,5 ºC	9,9 μF
30 ºC	9,89 μF
30,5 ºC	9,88 μF
31 ºC	9,9 μF
31,5 ºC	9,91 μF
32 ºC	9,91 μF
32,5 ºC	9,92 μF
33 ºC	9,92 μF
[…]	
87 ºC	10,49 μF
87,5 ºC	10,50 μF
88 ºC	10,51 μF
88,5 ºC	10,51 μF
89 ºC	10,52 μF
89,5 ºC	10,52 μF
90 ºC	10,54 μF

Table 4

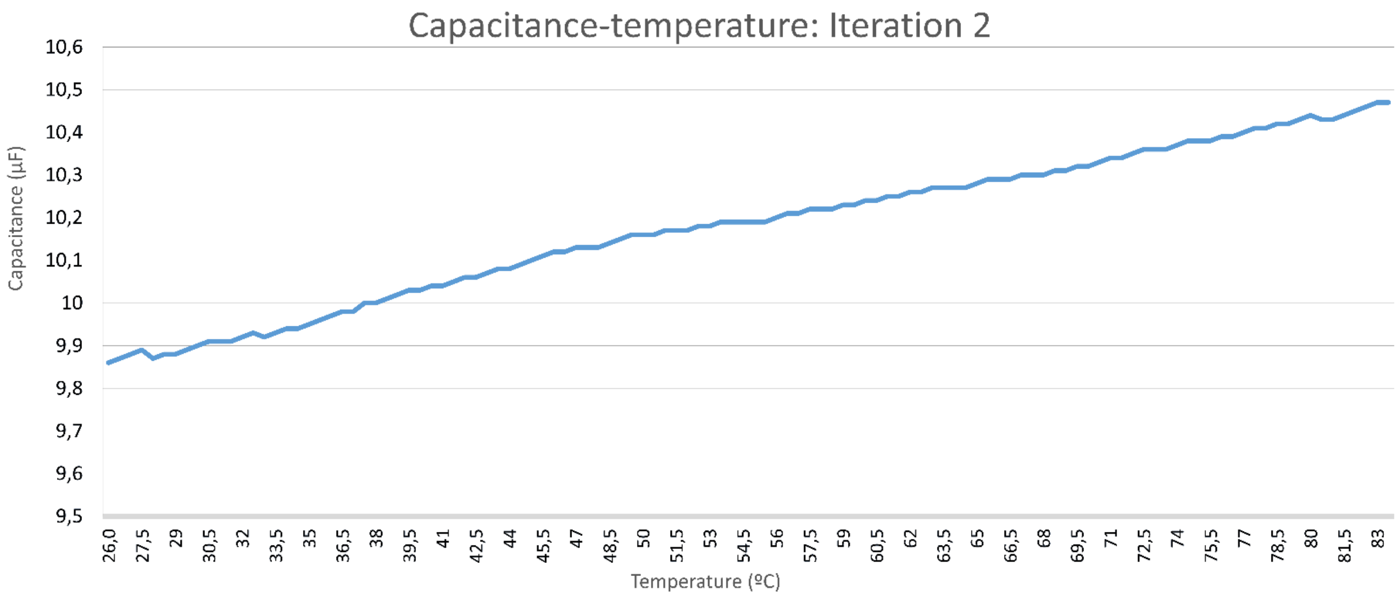
Graphs:

Iteration 1:



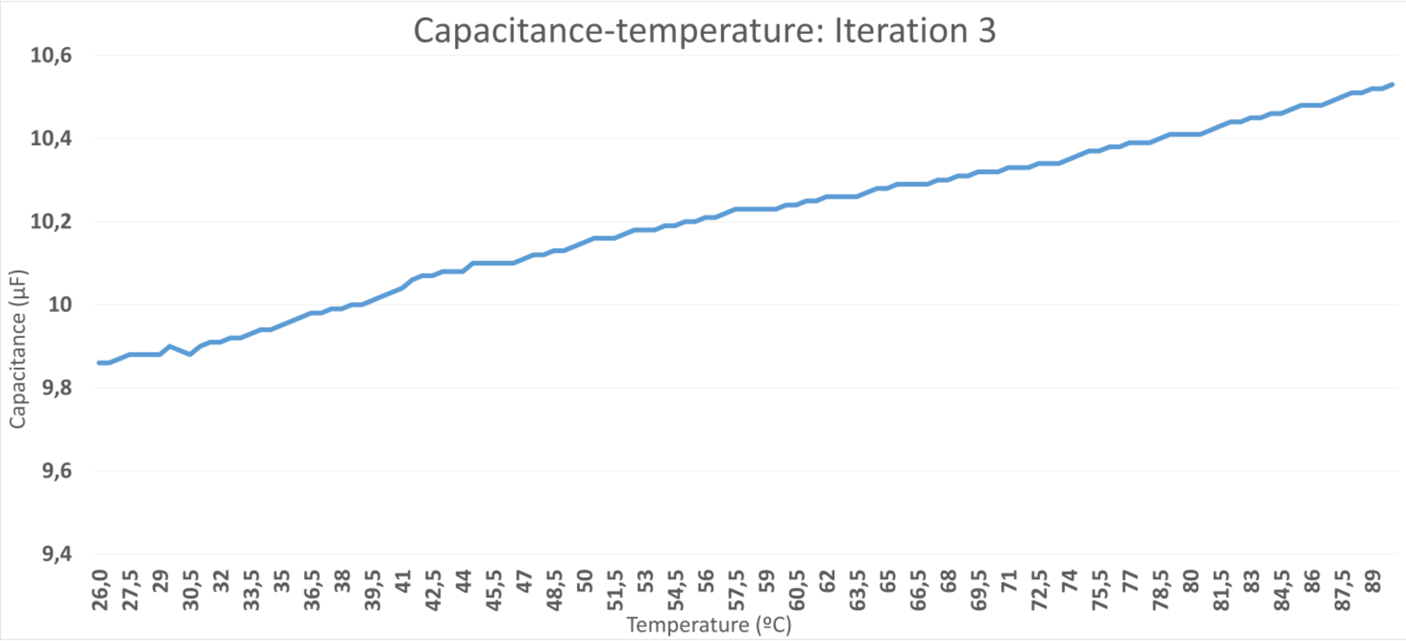
Graph 7

Iteration 2:



Graph 8

Iteration 3:



Graph 9

Code:

ArduinoCodeTemperatureDS18

```
#include <OneWire.h>
#include <DallasTemperature.h>


#define ONE_WIRE_BUS 4


OneWire oneWire(ONE_WIRE_BUS);
DallasTemperature sensors(&oneWire);

|
void setup(void)
{
  Serial.begin(9600);
  sensors.begin();
}

void loop(void)
{

  sensors.requestTemperatures();

  Serial.print("Celsius temperature: ");
  Serial.println(sensors.getTempCByIndex(0));
  delay(50);
}
```

Figure 13: Data acquisition script, written in C++.

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