School of Technology and Experimental Sciences

Bachelor's Degree in Mechanical Engineering

Design, fabrication and analysis of an instrument to measure thermal conductivity of liquids and phase change materials using a thermoelectric device

Final degree thesis

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Abstract

The determination of the thermal properties of liquids is very important in many fields of engineering (energy industry, refrigeration, pharmaceuticals, etc).

The aim of this work is to develop a measurement system to determine thermal conductivity, thermal diffusivity, and specific heat of materials in liquid state. This instrument uses a thermoelectric device and impedance spectroscopy measurements. The apparatus aims to be able to determine that three thermal parameters in only one measurement without being too much expensive and not using very complex components.

It consists of an small container attached to the upper ceramic part of a thermoelectric device in which the liquid sample is placed. The lower part of the device is soldered to a heat sink.

The thermal properties of liquids (water, luzar antifreezer and diethylene glycol) were determined by impedance spectroscopic measurements. Total uncertainties of <8.6% for thermal conductivity, <6.3% for thermal diffusivity and <6.1% for specific heat capacity were obtained, which positions the new instrument as a good alternative to the currently used methods.

Subsequently it is extended to phase change materials. First, the behaviour of the material in liquid state is studied by obtaining its properties. Later it has been observed what happens to the material when it changes from a liquid to a solid state by using the same device.

Resumen

La determinación de las propiedades térmicas de los líquidos es muy importante en muchos campos de la ingeniería (industria energética, refrigeración, farmacéutica, etc.).

El objetivo de este trabajo es desarrollar un sistema de medida para determinar la conductividad térmica, la difusividad térmica y el calor específico de materiales en estado líquido. Este instrumento utiliza un dispositivo termoeléctrico y medidas de espectroscopia de impedancia. El aparato pretende ser capaz de determinar esos tres parámetros térmicos en una sola medición sin ser demasiado costoso y sin utilizar componentes muy complejos.

Consiste en un pequeño recipiente unido a la parte superior cerámica de un dispositivo termoeléctrico en el que se coloca la muestra líquida. La parte inferior del dispositivo está soldada a un disipador de calor.

Las propiedades térmicas de los líquidos cuyas propiedades son conocidas (agua, luzar anticongelante y dietilenglicol) se determinaron mediante mediciones espectroscópicas de impedancia. Se obtuvieron incertidumbres totales de <8,6% para la conductividad térmica, <6,3% para la difusividad térmica y <6,1% para la capacidad calorífica específica, lo que sitúa al nuevo instrumento como una buena alternativa a los métodos utilizados actualmente.

Posteriormente se amplía a los materiales de cambio de fase. Primero se estudia el comportamiento del material en estado líquido obteniendo sus propiedades. Posteriormente se ha observado lo que le ocurre al material cuando pasa de estado líquido a sólido utilizando el mismo instrumento.

Resum

La determinació de les propietats tèrmiques dels líquids és molt important a molts camps de l'enginyeria (indústria energètica, refrigeració, farmacèutica, etc.).

L'objectiu d'aquest treball és desenvolupar un sistema de mesura per determinar la conductivitat tèrmica, la difusivitat tèrmica i el calor especific de materials en estat líquid. Aquest instrument utilitza un dispositiu termoelèctric i mesures d’espectroscòpia d’impedància. L'aparell pretén ser capaç de determinar aquests tres paràmetres tèrmics en un sol mesurament sense ser massa costós i sense utilitzar components molt complexos.

Consisteix en un petit recipient unit a la part superior ceràmica d'un dispositiu termoelèctric on es col·loca la mostra líquida. La part inferior del dispositiu està soldada a un dissipador de calor.

Les propietats tèrmiques dels líquids (aigua, lluzar anticongelant i dietilenglicol) es van determinar mitjançant mesuraments d’espectroscòpia d'impedància. Es van obtenir unes incerteses totals de <8,6% per a la conductivitat tèrmica, <6,3% per a la difusivitat tèrmica i <6,1% per a la capacitat calorífica específica, cosa que situa el nou instrument com una bona alternativa als mètodes utilitzats actualment.

Posteriorment s'amplia als materials de canvi de fase. Primer s'estudia el comportament del material en estat líquid obtenint-ne les propietats. Posteriorment s'ha observat utilitzant el mateix dispositiu el que passa amb el material quan canvia d'estat líquid a sòlid.

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1. Introduction

1.1. Background

In our modern society, liquids of all kinds are required for a wide range of applications. Within engineering, working fluids with many types of properties are needed. Liquids to supply or remove heat, power generation systems, all kinds of heating and cooling systems, lubricants, etc.

Keep innovating and improving these fluids both to improve their performance and to protect their surroundings from corrosion or to reduce the carbon footprint of their production or operation is much needed. In processes where it is necessary to involve a liquid in any thermal process, it is necessary to know the behaviour and thermal properties of this working liquid.

Consequently, a crucial step involves thoroughly characterising these new fluids before implementation. Understanding their thermal properties, including thermal conductivity, thermal diffusivity, and specific heat, is particularly a vital prior to their application.

On the other hand, the phase change materials are of great importance in the industry. These materials can give or absorb energy during their phase change state and are widely used in various industries. It is also interesting to be able to characterize their properties.

There are current commercially available techniques to determine thermal properties of liquids (e.g. concentric cylinders, transient hot wire and laser flash among others). These techniques are considered to be versatile and robust, and after a careful minimization of any heat leakages, the uncertainties can be <3% for the measurement of the thermal conductivity.

Impedance spectroscopy measurements have been shown to be a good tool for measuring the thermal properties of a solid in contact with a thermoelectric (TE) module[1]. In a previous work carried out by the Thermal and Electrical Systems Laboratory of the Universitat Jaume I it was shown that impedance spectroscopy measurements on TE modules are sensitive to the thermal properties of a solid sample in contact with the module. This previous work points to the possibility of implement a similar system to measure the thermal properties of liquids.

1.2. Justification

The current methods for measuring thermal properties can be very costly and also can involves more difficult setups (such as the use of lasers). It is intended to develop a method that once put into operation can be more affordable and simpler.

On the other hand, the measurement methods currently available can be more complex. The aim of this work is to speed up the process and to obtain the three properties (specific heat, thermal conductivity and diffusivity) in a single measurement and with a simple assembly. By using a thermoelectric module, it is not expected to be an excessively expensive system.

To develop a system that involves a simpler setup , more affordable and able to obtain the three thermal parameters in a single measurement. This will be achieved by using a TE module attached to another elements not involving a very expensive

1.3. Location

Both the study and the development of this new apparatus was carried out at the Thermal and Electrical Systems Laboratory (TESLab) locatedin the Research Building 1 at the Universitat Jaume I in Castellón de la Plana, Spain.

2. Objectives and scope

The main objective is to design, build and validate a new instrument for measuring the thermal properties of liquids based on the use of a thermoelectric device and impedance spectroscopy measurements.

This device offers the advantage of being able to obtain in a single measurement for a small sample of the liquid to be studied three thermal parameters:

- Thermal conductivity.
- Thermal diffusivity.
- Specific heat.

The specific objectives of this work include:

I. Design of the device: Identify the necessary requirements and how to select and combine the components of the device to obtain accurate measurements.
II. Build the device: Select the elements to assemble the apparatus and the most optimal way to do it.
III. Validate the device using 3 liquids with different known thermal properties to test the effectiveness in different ranges.
IV. Determine the total uncertainty of the apparatus.
V. Study a phase change material.

3. Theoretical framework

3.1. Thermoelectric effects

Thermoelectricity fundamentally consists of generating electric current from a temperature differential. This process is primarily based on three phenomena. The Seebeck, the Peltier effect and the Thomson effect.

The following section elaborates on these three effects, which are interconnected through the Kelvin's relationships. The concept of the figure of merit zT is a parameter of great importance for the performance and efficiency of a TE material, will also be mentioned.

Seebeck effect

In the first half of the 19th century, in 1823, Thomas Seebeck first introduced this effect. This phenomenon refers to the existence of a potential difference between the ends of a conductive material when there is a temperature difference (see Figure 1).

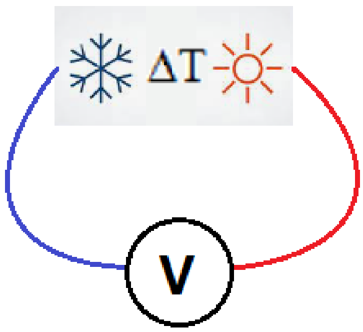

Figure 1. Schematic representation of the Seebeck effect.

The part with higher temperature hosts electrons with greater energy and therefore greater mobility, which promotes diffusion towards areas with lower temperature. This results in the accumulation of positive and negative charges on each side, generating a steady-state electric field in the opposite direction of thermal diffusion.

For materials with good TE properties like some semiconductors, the Seebeck coefficient can show values of 200 µV/K. On the other hand, in the case of metals, this value is below 50 µV/K [2].

The equation defining the Seebeck effect expresses the relationship between the potential difference and temperature difference as the latter approaches zero. Therefore, a higher coefficient implies a larger potential difference for the same temperature increment.

$$S = \lim_{\Delta T \to 0} \frac{\Delta V}{\Delta T} \quad (1)$$

When a TE device is generating electricity (converting thermal energy into electrical energy), it is said to be operating in generation mode or Seebeck mode.

Peltier effect

Twelve years later, Jean Peltier discovered a complementary phenomenon when he observed that a temperature variation occurs when an electric current flows through a TE material, which is the inverse case of the Seebeck effect.

The Peltier phenomenon refers to the transfer of thermal energy that occurs at the ends of a material. This results in a variation in temperatures along its length.

This effect is directly related to temperature and current intensity. The direction of the current determines which side experiences an increase or decrease in temperature. The heat power is related to the Peltier coefficient Π and the current I, such that,

$$Q_P = \Pi \cdot \mathrm{I} \quad (2)$$

In this case, a device is said to operate in Peltier mode when it is used to generate some form of thermal variation, whether heating or cooling [3][4].

Thompson effect

For low temperature gradients, this effect is practically insignificant, which is why its influence must be taken into account in situations with significant temperature changes. Unlike the other two effects, this one is irreversible. This effect involves a constant flow generated throughout the entire length of the TE material in the event of a temperature variation. The Thompson coefficient β is expressed based on absorbed heat:

$$Q_T = \beta \cdot I \cdot \Delta T \quad (3)$$

Figure of merit

To define if a TE material is good or not, is common to calculating his figure of merit. A higher figure of merit indicates that the TE device or material will have better performance and efficiency, converting thermal energy into electrical energy more efficiently.

Later, in the mid-20th century, Abram Ioffe defined the figure of merit parameter as:

$$z = \frac{S^2 \cdot \sigma}{\lambda} \qquad [4]$$

Today, it is common to use this dimensionless term as zT:

$$zT = \frac{S^2 \cdot \sigma}{\lambda} T \qquad [5]$$

In TEs, trying to find materials with a high zT has never been easy because changing one of the parameters directly affects the others (see Figure 2). This is why optimizing this parameter is challenging. For example, with a high Seebeck coefficient S, there is low electrical conductivity σ, and on the other hand, using materials with high electrical conductivity also results in high thermal conductivity λ, which decreases zT.

Given a TE material, the usual practice to determine this parameter is to determine each of these parameters individually [5].

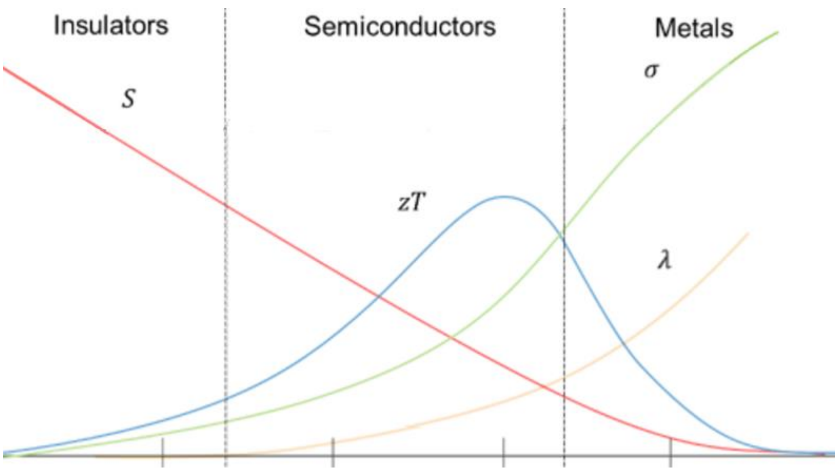

Figure 2. Influence of every parameter with the figure of merit [5].

3.2. Thermoelectric devices

The TE devices, also known as Peltier Devices, the standard architecture of these devices is formed by electrically connecting TE legs in series by alternating p-type and n-type semiconductor materials and thermally in parallel (see Figure 3).

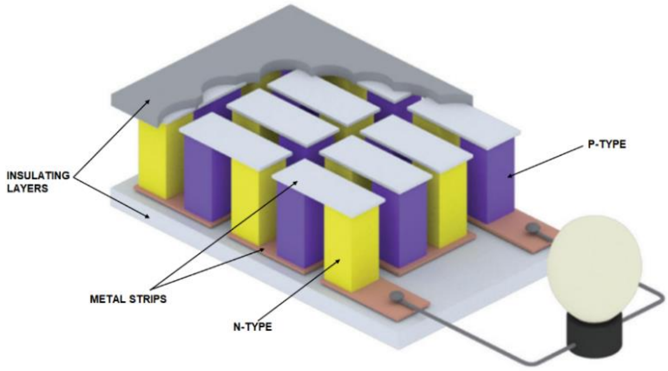

Figure 3. Conventional architecture of a Peltier module. In yellow the N-type legs and in purple de P-type legs. Connected in series by metallic strips [6].

These semiconductor legs are connected to each other with metalized layers that establish the electrical contact between them. These layers are attached to plates made of electrically insulating but thermally conductive material. Typically, these plates are made of alumina (Al_2O_3). Sintering techniques or powder processing methods are commonly used to produce these modules [6].

There are numerous variations within TE modules. The power output of this device will primarily vary based on the number of pairs of legs it has. It is common to find modules with 50 to 200 pairs of legs.

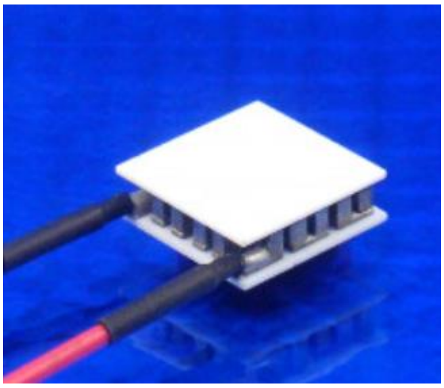

Figure 4. Peltier module model 01711-5L31-06CF from Custom TE.

3.3. Impedance spectroscopy on thermoelectrics

In this work the thermal conductivity and other thermal parameters of liquids are going to be determined by using a TE module. In order to measure the processes occurring in this module, the technique that yields the best results is impedance spectroscopy.

Impedance spectroscopy is a highly effective method widely employed in devices, such as Li-ion batteries, solar cells, and fuel cells. This technique involves applying a low-intensity sinusoidal current at a specific frequency to the system. This alternating current perturbation fluctuates around a constant current level referred to as the direct current, generating a sinusoidal variation in potential difference within the system at the same frequency and a specific phase shift. In this type of experiments, the system's impedance at the given frequency is calculated from the sinusoidal voltage and current waves (see Figure 5). The impedance value is plotted on the complex plane (Nyquist plot) as a point defined by a vector [7].

$$|Z| = \frac{V_{ac}}{I_{ac}} \tag{6}$$

The angle of this vector represents the phase shift angle (ϕ), while its magnitude indicates the ratio of voltage and current amplitudes (see Figure 5). The study is typically conducted over a frequency range from a few mHz to 1 MHz, with a total of 40-50 frequencies distributed logarithmically, generating a data point on the complex plane for each frequency and creating the final impedance spectrum [8], [9].

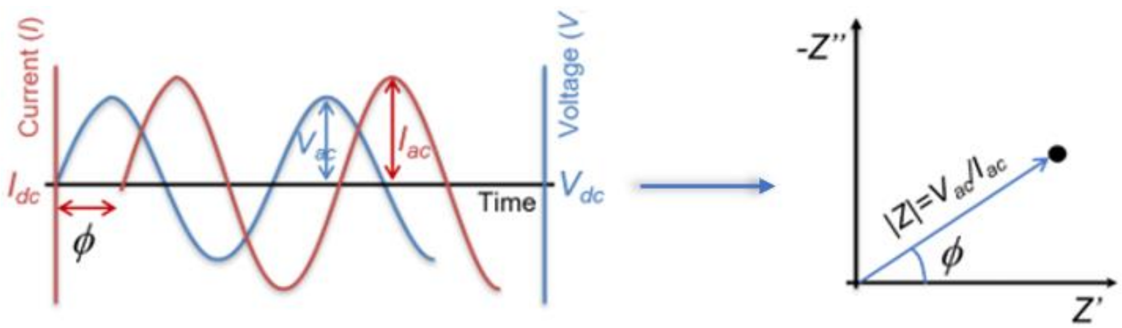

Figure 5. Perturbation, system response and complex plane (Nyquist) representation of a single frequency point of an impedance spectroscopy experiment [7].

The representation of this data is often displayed in Nyquist diagrams, as they provide a quick and clear view (see Figure 6).

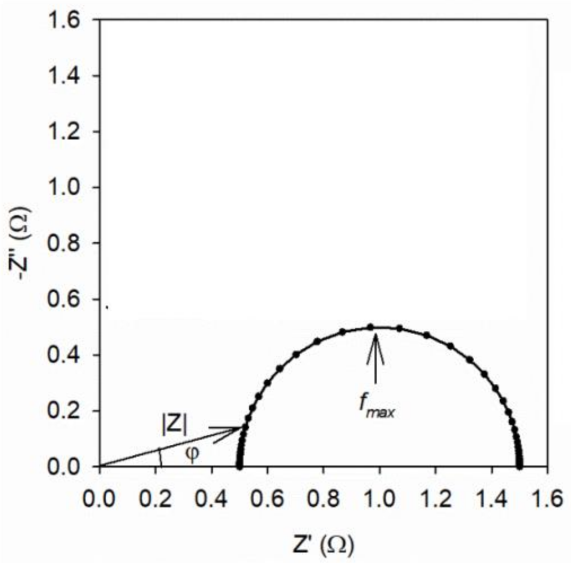

Figure 6. Nyquist diagram example. Shows an impedance spectrum simulation from 1mHz to 1MHz.[10]

Using impedance spectroscopy involves the need to employ equivalent circuits derived from the type of system (device physics) being analysed. These circuits often consist of combinations of resistors and capacitors in series and parallel as well as other elements. Properly determining the equivalent circuit of the system is crucial to obtaining consistent results in the study. This may not be easy because several physical phenomena are involved in this type of research.

3.3.1. Equivalent circuit for a suspended modulus

In this work we are going to use the equivalent circuit developed by Beltrán-Pitarch et al [7]. The impedance function Z of a TE module is given by:

$$Z = \frac{V(L) - V(0)}{I_0} = j\omega L_p + R_\Omega - 2N\frac{S[T(L) - T(0)]}{I_0} \tag{7}$$

where $j=(-1)^{0.5}$ is the complex number, $\omega=2\pi f$ the angular frequency and L_p the parasitic inductance. $V(0)$ and $V(L)$ are the voltages at x=0 and x=L, respectively, I_0 is the electrical current flowing through the device at x=0, and R_Ω is the total ohmic resistance, which includes the contribution of all the TE legs of the TE module, the metallic strips, the leads, and the electrical contact resistances. $T(0)$ and $T(L)$ are the temperatures at x=0 and x=L, respectively.

In this equivalent circuit it is assumed that the module consists of $2N$ where N is the number of legs. The most relevant contribution in this study is given by the third factor of equation (7). It is necessary to identify the temperature variation at with frecueny at de edges of the TE leg when sending a sinusoidal current signal.

To solve the impedance signal, it is necessary to solve the heat equation in the frequency domain considering all the effects of Figure *7*.

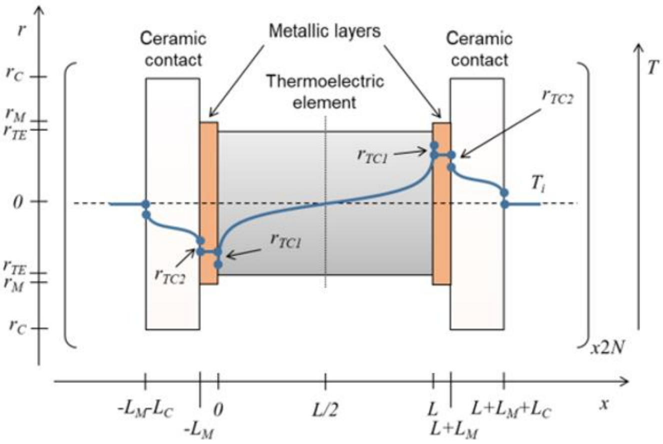

Figure 7. Schematic view of the theoretical model considered in this analysis [11].

Among other things, the developed model assumes the thermal resistance of contact between leg-metal strip and metal strip-ceramic layer.

Considering that the studies will be conducted under conditions where convection and radiation can be neglected (in a vacuum chamber), we have the equivalent circuit schema.

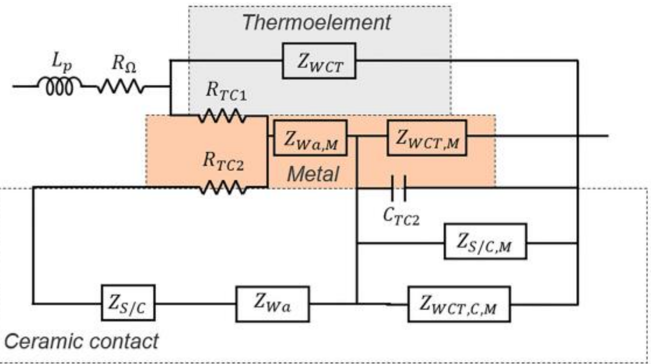

Figure 8. Simplified circuit in a vacuum conditions [12].

Dr. Beltrán-Pitarch developed a MATLAB code based on these circuits, from which, after a certain number of IS measurements, the parameters of the Peltier module can be obtained [11] This code could be used in our study as we will explain below.

3.3.2. Equivalent circuit for liquids

In the case of this thesis Dr. Beltrán-Pitarch developed a new MATLAB code (included in the annex) that considers the location of a liquid on one side of the TE module and a heat sink on the other side, this is explained in more detail in section 5.1. Figure 9 shows the model that will be used.

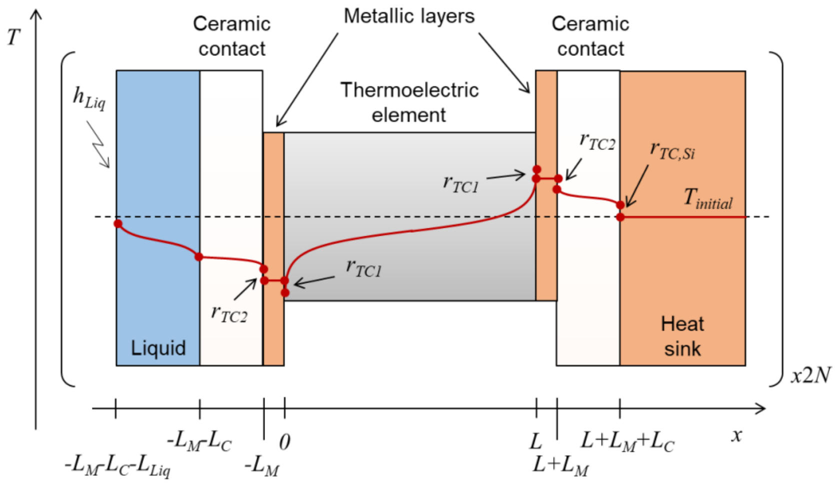

Figure 9. Schematic view of the model used. The dashed line represents the initial temperature before a current is applied, while the red line shows the temperature profile of a TE leg with positive Seebeck coefficient when a positive current is flowing through at a certain time [13].

The dashed line through the diagram represents the initial temperature, before applying any current, and the red line represents the temperature when a positive current flows for a certain time. Using impedance analysis, the parameters shown in the figure will be obtained, such as the contact resistances and the other characteristic variables of the module and the liquid under study [13].

4. Methods to measure thermal properties of liquids

4.1. Definitions

4.1.1.Thermal properties

In terms of the thermophysical properties of materials, one of the most studied is thermal conductivity λ, which is closely related to heat flow. This parameter expresses the capacity of a material to transfer heat due to a temperature gradient.

$$[\lambda] = \frac{W}{m\,\mathrm{K}} \tag{9}$$

Where W is the power in watts, m is the metres and K is the temperature in Kelvin. The thermal conductivity is defined by Fourier's law, such that,

$$Q = -\lambda A \frac{dT}{dx} \tag{10}$$

where q is the heat transfer rate, A is the cross-sectional area, and $\frac{dT}{dx}$ is the temperature gradient. This parameter is directly related to the thermal diffusivity α, a property that relates the transport of heat and the capacity to absorb that heat.

$$\alpha = \frac{\lambda}{\rho \cdot c_P} \tag{11}$$

Where c_P is the specific heat capacity, a thermal property that refers to the heat that a certain material can store per unit mass when its temperature changes, and ρ is the density.

Knowing these parameters is interesting both at a scientific level and for all their applications in engineering [14].

4.1.2. Phase change materials

One of the materials to be analysed in this work is a phase change material. These materials are primarily used in energy storage applications. They can change their physical state at a specific temperature and pressure, giving off or absorbing energy when transitioning from one phase to another repeatedly without degradation (they can withstand 10^5 working cycles). While the material is in phase change it does not change its temperature and releases a lot of energy.

These materials have a multitude of applications; for instance, they can absorb heat and are used in fire protection systems. They can be employed for cooling purposes also, as they can maintain cold temperatures for longer periods. In heating and cooling systems, they provide a certain increase in efficiency as they can reduce the load on these systems.

There are various types of PCMs, and they can be classified according to the following graph:

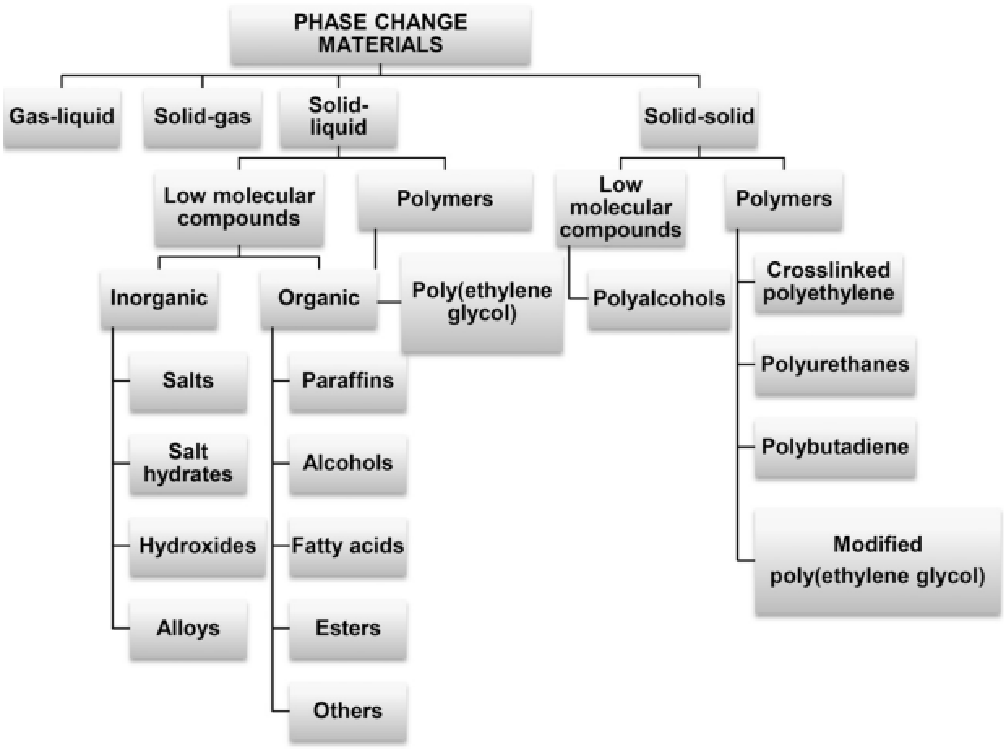

Figure 10. Diagram of the types of PCMs.[15]

Due to its high potential in various fields, studying and optimizing these materials is crucial. That is why in this study, we will attempt to measure thermal conductivity and the other parameters when the material is in a liquid state [15],[16].

4.2. Current methods

In this section, some of the techniques currently in use will be presented.

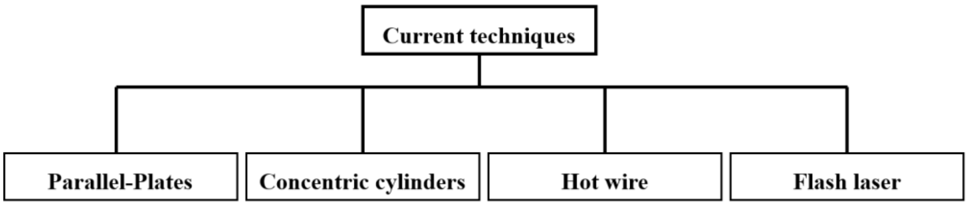

Figure 11. Outline of currently used methods.

4.2.1. Parallel-Plates

This method attempts to accurately represent the behavioural idea of Fourirer's law. It is based on the fact that the total heat flow is caused by pure conduction, without any other effect apart from this. This makes it often very unreliable, especially in the study of fluids. Because of this, constant calibration of the measuring equipment is necessary to avoid possible erroneous measurements.

This method is based on applying a heat increase to a liquid previously at room temperature. By studying this perturbation, the parameters conductivity and thermal diffusivity can be determined. Measurement uncertainties of less than 3% are obtained as long as possible heat leakage is minimised.

$$Q_{cond} = \frac{A}{s}\lambda(T_{hot} - T_{cold}) \tag{12}$$

Where Q_{cond} is the amount of heat transferred by conduction. The heat flux is a function of the cross-sectional area A and the thickness of the sample s [17].

4.2.2. Concentric cylinders

This method is a modification of the previous one developed due to the complexity and difficulty in avoiding thermal losses.

It consists of a hollow cylinder with another solid cylinder inside it. Between these two cylinders, there is a thin layer where the liquid is introduced, making this configuration more optimal in terms of heat loss.

The inner cylinder of these devices is heated slightly; usually, it is not necessary to exceed a $\Delta T = 1°C$. Assuming that there are no heat losses at the upper and lower ends of the cylinder, the temperature is recorded on the outer cylinder.

With the following expression, thermal conductivity can be obtained:

$$\lambda = \frac{Q_{cond}}{2\pi\Delta T}\ln(\frac{r_2}{r_1}) \quad (13)$$

Being r_1 and r_2 the radius of each cylinder.

The main drawback of this method is again the potential presence of thermal effects caused by thermal convection.

Varying the thickness of the studied liquid with the aim of mitigating heat losses effects is very interesting, especially at high temperatures. This alternative is called the "variable space method" [17]

4.2.3. Hot wire

This method is one of the most widely used today due to its precision and simplicity. The measurement apparatus that used this technology typically consist of a wire immersed in the liquid under study. This wire is heated through a voltage change, creating a certain temperature gradient. The thermal conductivity of the sample, along with other parameters, can be obtained from the temporal evolution of the temperature experienced by the wire during the heating interval. These devices perform measurements very quickly; in certain cases, the temperature can be raised by 30 ºC in just over 50 milliseconds.

The main problem with this technique appears when studying liquids with high electrical conductivity, where the margin of error can increase considerably. However, among the commercial thermal measurement and characterization devices used today, this technology is one of the most employed [17], [18].

Figure 12. Hot wire instrument [19].

4.2.4. Laser flash technique

This method for the determination of thermal diffusivity (from which thermal conductivity is subsequently obtained). Starting with the consideration of adiabatic conditions the diffusivity is assessed based on the recorded temperature. Since the main problem that can arise is the presence of convection and radiation, very small samples of the material are used.

The measurement is quite fast and is carried out by applying a laser flash that heats the sample. Studying the evolution of temperature in the liquid over time provides the desired data. If the equipment is properly calibrated and the measurement is carefully conducted, good results can be obtained [19].

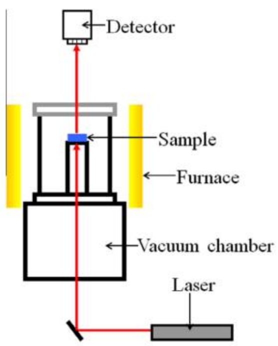

Figure 13. Laser flash schema [20].

5. Instrument design and fabrication

The key element of our instrument is a TE module. These devices can sense all thermal processes taking place in their surroundings. The general idea is to attach a liquid to one side of a TE device and try to minimize the temperature change at the other side. This will be achieved by placing a heat sink at the bottom. In this way, we expect to have a significant influence from the liquid which is in contact to the device.

5.1. Design requirements

Considering the operation of the TE devices, the following items were considered before starting the design.

Container Design

A container to locate the liquid is needed. This container must have minimal contact with the module; otherwise, it could interfere with the measurements. It is crucial that the liquid completely covers the surface of the TE module. If there are any empty spaces, the ambient air could meet the module, leading to inaccurate results. Large sample quantities are not needed to determine the thermal properties of the liquid. That is why the TE module doesn't have to be excessively large, it is considered that using samples of about 1 mL will be optimal. In addition, it is necessary that the container is made of a chemically stable material in case corrosive liquids are analysed.

Adiabatic Study

Ideally, the study should be conducted adiabatically. However, achieving true adiabatic conditions would require studying the sample in vacuum, which is impossible because liquids would evaporate. Therefore, efforts will be made to prevent external effects due to convection. The container of the liquid will be covered to prevent the mentioned issues.

Thermal Stability

As mentioned earlier, one side of the TE module cools down while the other heats up, which happens constantly on one side and on the other side when the current polarity changes, and the heat sink is there to minimize the thermal variation on that side. This will be achieved by using a heat sink.

In the Figure 14, the conceptual design that was established is shown.

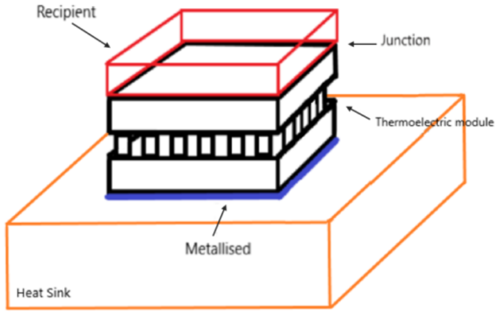

Figure 14. First conceptual design of the setup.

5.2. Prototype fabrication

5.2.1. Prototype parts

TE module

The main part of the experimental setup is a TE module from *Custom Thermoelectrics* (ref. 07111-5L31-03CJ-T1). This module has *N=70* TE couples, where each TE leg has a length L=1.58 mm and a cross-sectional area *A=1.05 mm* × *1.05 mm*. The legs are connected by metallic strips of thickness $L_M = 0.3$ mm and held together by ceramic plates of $L_C = 0.7$ mm thickness and 23 mm × 23 mm area. A sample of 1 mL is intended to be used, so a is selected a module where a container of that capacity can fit.

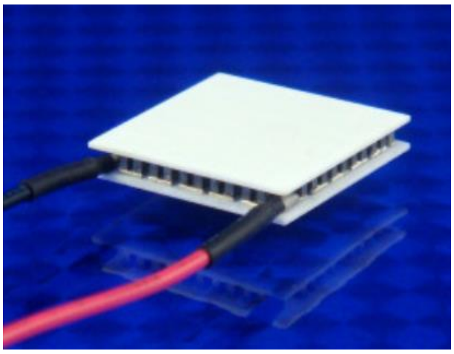

Figure 15. Used Peltier module [20].

As mentioned above, the module must be connected to a heat sink. That is why the bottom side of the TE module was tinned by the supplier with an In alloy so that it can be soldered to the copper block.

In order to know the exact geometry of each part of the TE module, pictures were taken with a microscope, in order to see the module clearer.

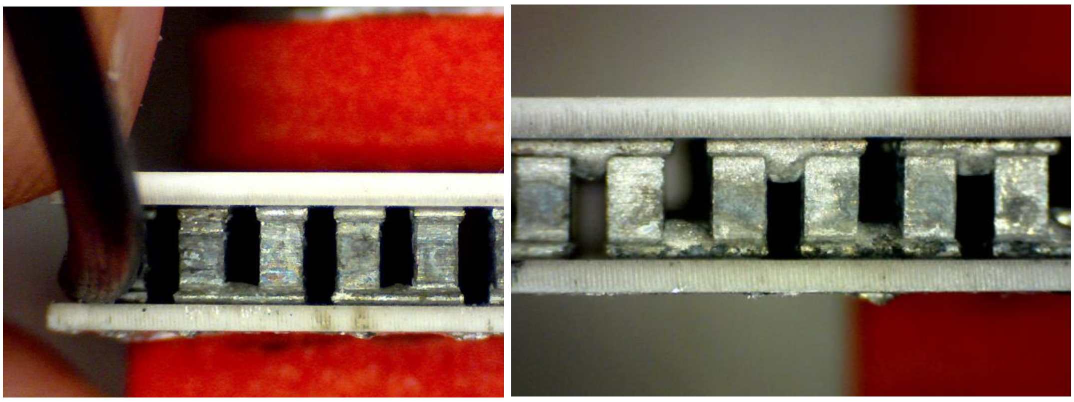

Figure 16. Microscope images of the TE module. A) Front. B) Side.

In the Figure 16 the geometry of the module and the In alloy layer at the bottom can be seen.

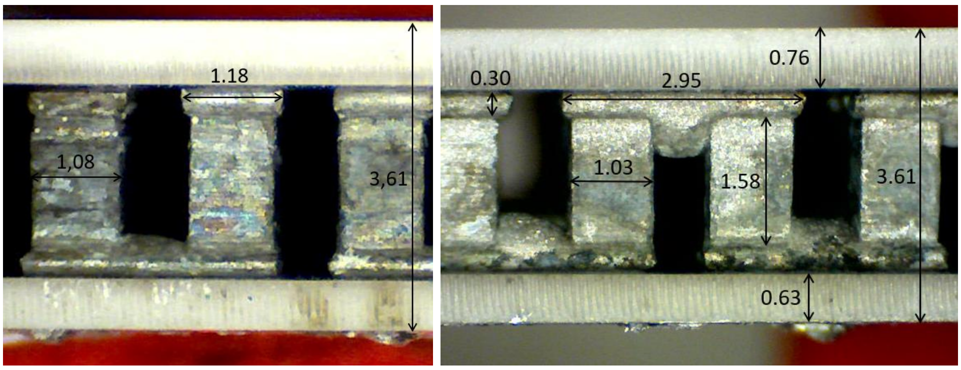

Figure 17. Detail images front and side with the relevant measures (in mm).

By obtaining the module measurements, ratios can be calculated which will later be used for modules characterisation and other experiments (see Figure 17).

Ratio between legs and metallic strips

$$\eta_M = \frac{2A_{TE}N}{A_M N} = 0.56 \quad (14)$$

With $A_{TE} = 1\,mm^2,\ A_M = 3.6\,mm^2$ and $N = 70$.

Filling factor. Ratio between the total area of the TE legs and the area of the ceramic layer

$$\eta = \frac{2A_{TE}N}{A_C} = 0.26 \qquad (15)$$

With $A_{TE} = 1\ mm^2$, $A_C = 529\ mm^2$ and $N = 70$.

To sum up, the ratio between the total area of the TE legs and the metallic strips is $\eta_M = 0.56$, and the filling factor (ratio between the total area of the TE legs and the area of the ceramic layer) is $\eta = 0.26$.

Heat sink

The heat sink must have sufficient thermal conductivity to ensure a constant temperature on the side where it contacts the module and a high volume of material. The copper has a thermal conductivity of about 400 W/m·K compared to 230 W/m·K for aluminium, for example. It is therefore decided that the material from which the heat sink must be made will be copper. As for the shape and size of the heat sink, two options are initially considered:

-Solid copper block.

-Copper heat sink with internal water circulation.

Both options could be appropriate in this case. To simplify the process and avoid the need for water circulation, the first option was selected.

This block has dimensions of 10 cm x 10 cm x 5 cm and weights 4.5 kg. It is large enough in relation to the TE module but not too large, which would make it difficult to handle in the laboratory.

Figure 18. A) Solid copper block. B)Smaller block with water circulation.

Container

The 1 mL sample must fit inside the container and it must ensure tight sealing with minimal contact with the Peltier module, as mentioned earlier.

The material used must be chemically stable, as it could react with certain liquids.

Two material options were considered:

-Thin stainless steel plate.

-Some type of resin manufactured through 3D printing.

Initially, the first option was chosen because with the second option, the integrity of the container could be compromised with such a thin structure when handling the device.

The TE module has dimensions of 23x23 mm, and the container must fit tightly to the edges but leave enough space for applying an adhesive, this is very imporant. The container was manufactured by the company *Demetal S.L* and has the dimensions shown in the Figure 19:

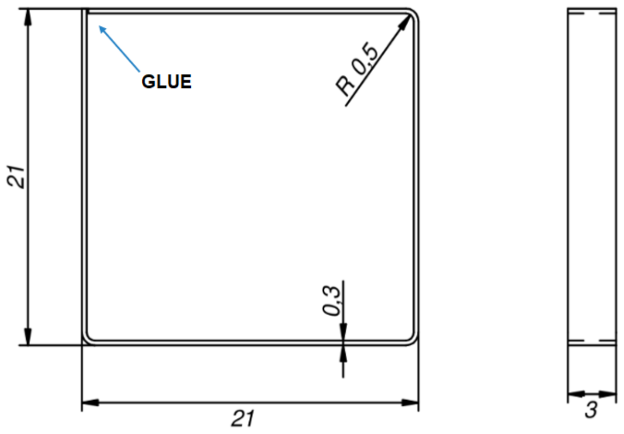

Figure 19. Container dimensions in mm.

As it is a very small container, it is manufactured by bending a strip of AISI 304 steel. Subsequently, adhesive will have to be applied to the remaining free corner. The glue to be used is cyanoacrylate (*Loctite SuperGlue 3*), which is ideal for this type of operation.

With these dimensions (21x21x3 mm), it can perfectly accommodate 1 ml of the sample, and it is anticipated that the arrangement of the container on top of the TE module will not influence the impedance measurements.

5.2.2. Fabrication

Soldering

With all the parts of the device ready the assembly proceeds.

First, the TE module was soldered to the copper block. To ensure that the process is carried out correctly, the block was thoroughly cleaned using acetone.

To solder the module to the block, a hot plate from the brand *IKA*, model *C-MAG HS-7*, was used.

Figure 20. Heating plate used for the welding process. [21]

The temperature on the upper surface will be measured using a thermocouple. This is crucial because exceeding the temperature limit can compromise the physical integrity of the TE module (TE legs and junctions can be unsoldered). The appropriate temperature for the In alloy layer to bond with the copper block is around 115ºC. This information was provided by the manufacturer of the TE module.

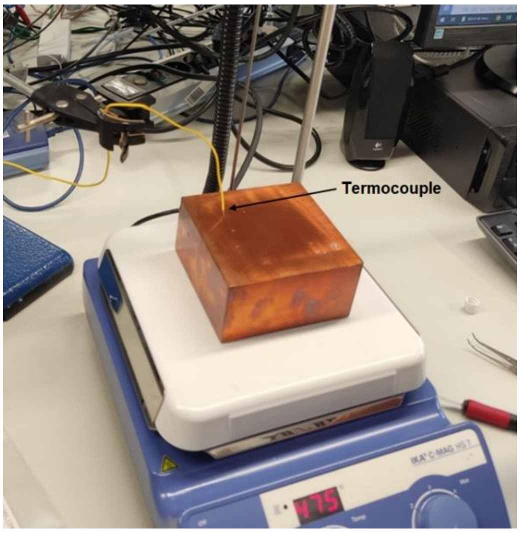

Figure 21. Welding process. The block can be seen on the heating plate and a thermocouple on its surface monitoring the temperature.

To ensure that the temperature is sufficient for soldering, the manufacturer was asked to provide a sample of the welding material.

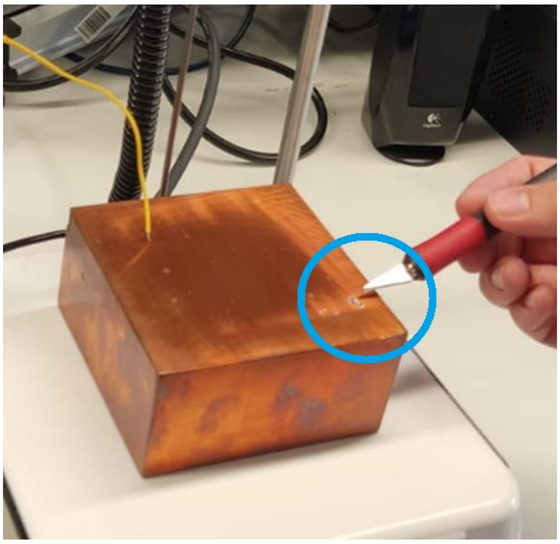

Figure 22. A small amount of welding material is placed on top of the block before starting the welding process to ensure that the temperature is correct and that the block is sufficiently hot.

Once the test piece of the solder starts melting and reaches the desired temperature, the TE module is carefully placed onto the copper block, applying slight pressure to facilitate the welding process.

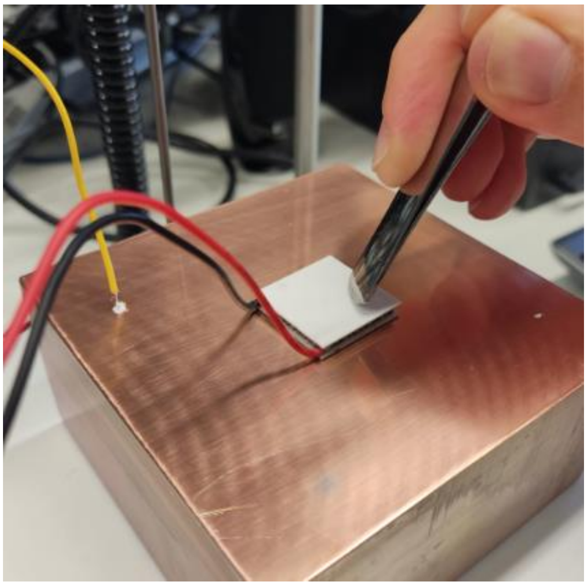

Figure 23. TE module being welded onto the block. Some pressure is applied to ensure that it is securely attached.

After maintaining pressure on the plate for a seconds, the heating plate is turned off. The assembly will be allowed to cool down to room temperature for a few hours.

Gluing of the container

Once everything has returned to room temperature, the assembly process can continue.

As mentioned in previous sections, the container is made from a bent metal strip. Therefore, the two ends need to be glued together to close the container. This should be done at least 24 hours before mounting it on the TE module to ensure that the adhesive has cured properly.

With the container ready for assembly, it is placed in its final position, applying pressure on top to prevent any movement during assembly. An improvised system using two copper pieces and a clamp was used, as seen in Figure 24.

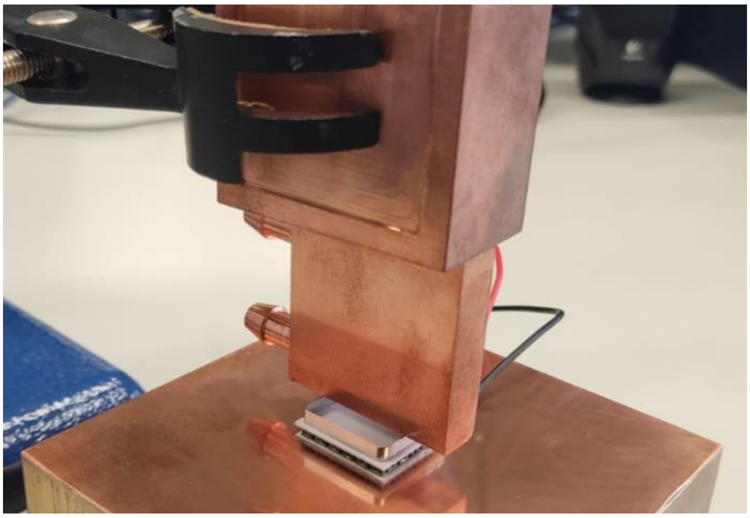

Figure 24. To ensure that the container does not move, weight is applied using two copper blocks held in place with a claw.

Once the entire system is secured, cyanoacrylate glue is applied using a syringe needle. It's important to note that applying more than necessary could influence impedance measurements. However, applying less than necessary could cause the liquid inside to leak out. Therefore, it's crucial to strike a balance and apply just the right amount of glue for optimal results.

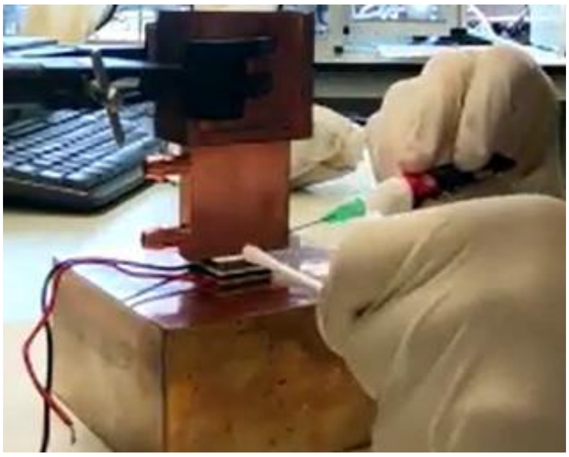

Figure 25. Glue being applied with a needle. The excess is removed with a cotton swab.

In the previous image, the moment when the adhesive was applied with a needle and a cotton swab to remove any excess can be seen. After applying the adhesive, it is advisable to wait at least one day for it to dry completely. Water was added to check that it is well sealed.

In the following image, you can see the finished setup with all its components attached. There is a K-type thermocouple on top of the copper block with thermal grease and another one inside the TE module, which will provide us with the temperature of the liquid.

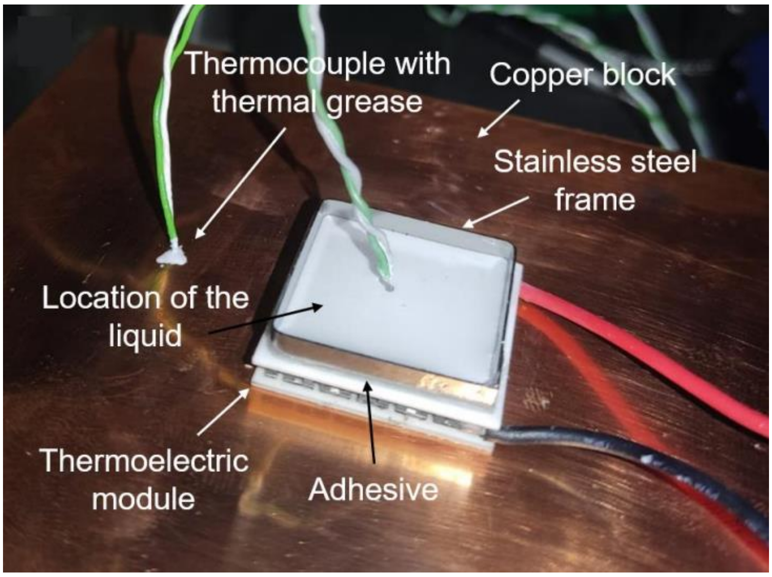

Figure 26. Final setup with all its parts.

6. Thermal properties determination

Once the device was assembled, we tested if the thermal properties of different liquids can be obtained.

6.1. Validation and optimisation

In order to obtain the desired parameters, the Seebeck coefficient and the different thermal resistance of the instrument must first be obtained. So, in order to define the system correctly, both the module and the complete system have to be characterised. The process can be schematized as follows (see Figure 27).

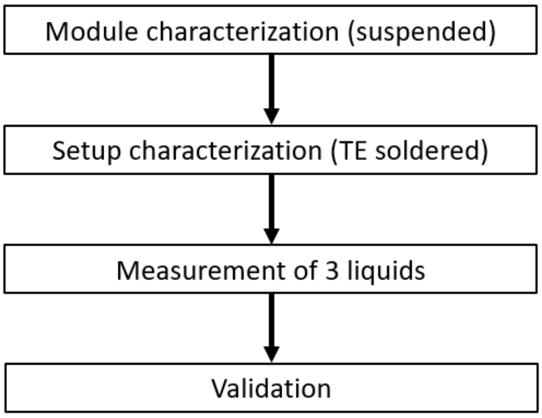

Figure 27. Experimental part schema.

6.1.1. Determination of the system properties

In this section, three liquids with known thermal conductivity will be analyzed. Before proceeding with the samples, all parameters of the TE module, the copper block, and the container assembly need to be characterized. This is essential for conducting subsequent analyses with the liquid samples. The code implemented in MATLAB requires as many fixed variables as possible to provide more precise results for the variables left free. As mentioned in section 3.3.1, there are numerous physical parameters involved in a TE module, such as thermal contact resistances, parasitic impedance, etc. Even with more than one variable left free, other parameters can be obtained since they do not always appear together at the same frequency. For example, at low frequencies, L_p is negligible, which means one less variable needs to be considered at those frequency points.

From now on, all measurements will be conducted inside a vacuum chamber, which also acts as a Faraday cage.

Figure 28. At the top the vacuum chamber. On the floor the pumping station to generate de vacuum.

First, before soldering and assembling the container, an impedance analysis of the TE module was be conducted. This analysis will be carried out with the module suspended in a vacuum (pressure below 10^{-4} mbar).

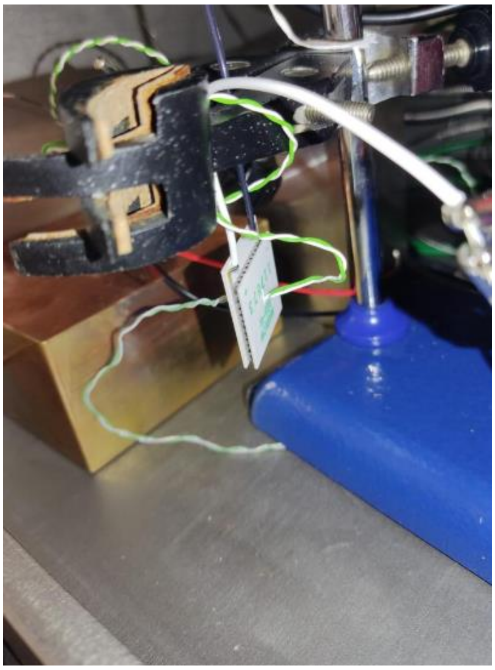

Figure 29. Module suspended with thermocouples attached..

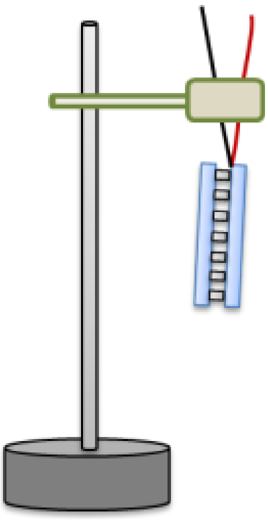

Figure 30. Schematic view of the suspended module.

To perform these measurements, both surfaces need to be cleaned, and then the module should be positioned as shown in the previous figures.

In this part of the process and throughout the experiment, to apply electrical signals, a Metrohm Autolab PGSTAT302N potentiostat equipped with an FRA32M impedance module and controlled using Nova 1.11.2 software was used. In all the experiments, 50 points logarithmically separated was taken between 1 mHz and 100 kHz with a current amplitude of 20 mA.

For temperature measurements, the PicoLog TC204 system will be used. Two K-type thermocouples SE030 with thermal grease should be placed on both faces of the module to measure temperature differences. It is important to use thermal grease to thermalize the whole thermocouple tip.

To obtain the Seebeck coefficient, the voltage and temperature difference on both sides of the module are measured when different current intensities are applied through it, as expressed in Eq. 1.

To perform the Seebeck measurement, a constant current is first applied and a steady state is reached. The current is then stopped, and the change in open circuit voltage that has occurred is measured. Five current intensities are applied, yielding the following results.

Current (mA)	Vf (mV)	Vi (mV)	ΔV (mV)	Th (ºC)	Tc (ºC)	ΔT (ºC)
20	-0,17	35,02	35,19	25,21	23,98	1,23
40	-0,13	70,31	70,44	25,83	23,40	2,43
60	-0,14	105,71	105,85	26,65	23,05	3,60
80	-0,21	141,39	141,60	27,67	22,82	4,85
100	-0,36	177,55	177,91	28,93	22,90	6,03

Table 1. Applied currents from 20 to 100mA with respective voltage variations and temperature increments.

The 5 points represented in Figure 31 are obtained. From these data, the Seebeck coeficient of the module is obtained, which corresponds to the slope of the straight line obtained:

$$S_{module} = 29.664 \frac{mV}{K}$$

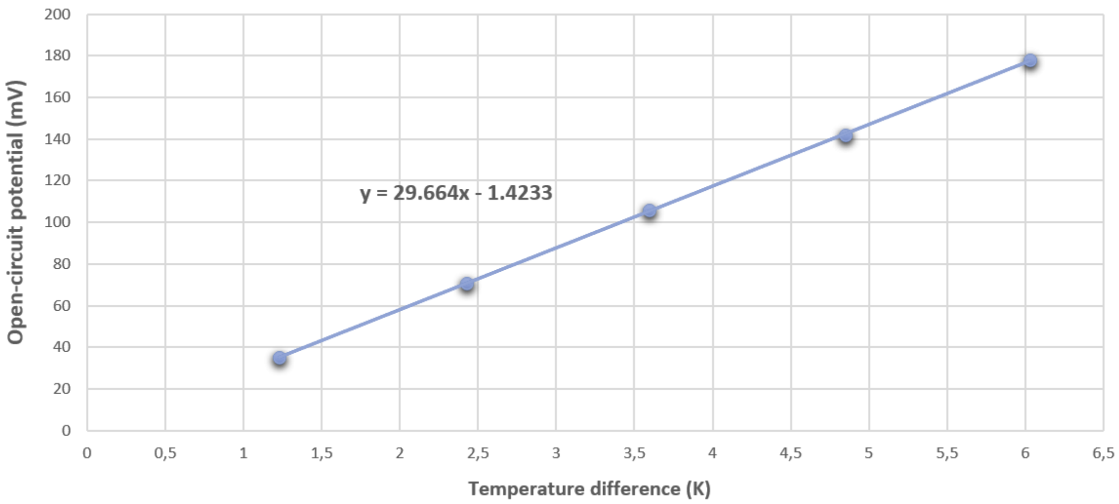

Figure 31. Open circuit potential $\Delta V(mV)$ vs the temperature rise $\Delta T(°K)$. Five points corresponding to the 5 applied currents.

After obtaining the voltage of the complete module, it has to be divided by the total number of legs, as they are arranged in series, it is obtained by means of the Eq. 16:

$$S = \frac{1000 \cdot S_{module}}{2 \cdot N} \qquad [16]$$

The Seebeck coefficient of each leg is $S = 211.9\,\frac{\mu V}{K}$.

After obtaining the Seebeck coefficient, a vacuum impedance measurement was carried out, the result is fitted with MATLAB code. In the Figure 32, you can see the impedance spectrum obtained experimentally and the fitting obtained through the MATLAB code. This code can be found in reference [12].

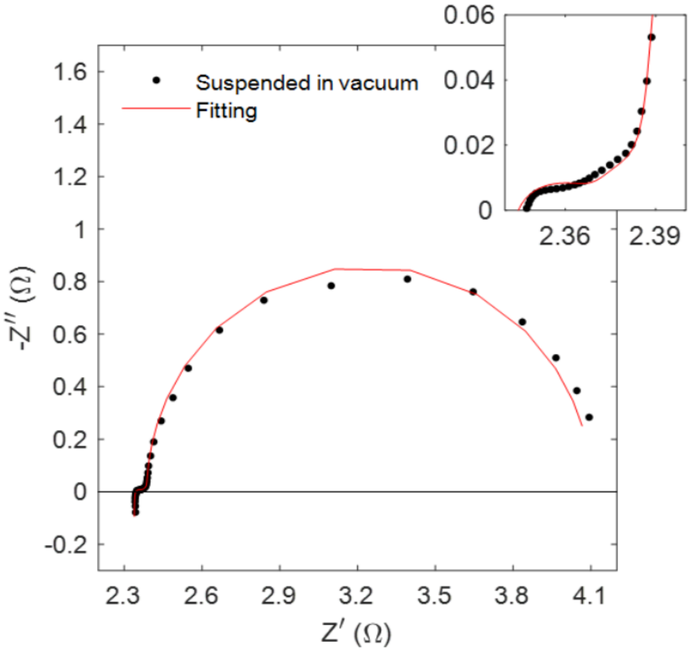

Figure 32. Nyquist diagram of measured impedance spectra (dots) obtained for the TE module suspended in vacuum. The fitting was performed using the MATLAB code.

For this initial fitting, the following parameters have been fixed, as they are specific to the materials of which the TE module is made: thermal conductivities and diffusivities of the metal junctions, the ceramic and the legs of the TE module: $\alpha_{TE} = 1.2\frac{mm^2}{s}$, $\lambda_M = 400\frac{W}{m{\cdot}K}$, $\alpha_M = 110\frac{mm^2}{s}$, $\alpha_C = 10\frac{mm^2}{s}$, $S = 211.9\frac{\mu V}{ºK}$.

r_{TC1}, λ_{TE}, λ_C are determined from the impedance spectrum and the previously fixed parameters.

Condition	L_p (H)	R_Ω (Ω)	r_{TC1} (m^2KW^{-1})	λ_{TE} ($Wm^{-1}K^{-1}$)	λ_C ($Wm^{-1}K^{-1}$)
Suspended in vacuum	1.53×10^{-7} (11.7%)	2.34 (0.04%)	1.21×10^{-5} (4.94%)	1.53 (0.74%)	24.4 (1.12%)

Table 2. Thermal contact resistance between legs and metallic layers, thermal conductivity of the leg and thermal conductivity of the ceramic obtained values, apart from resistance and inductance.

Due to good thermal contact between the metallic strips and ceramics $r_{TC2}=0$. Note that L_P y R_Ω will be left as free variables in all fittings since they only undergo minor variations. This process is described in detail in Reference [11].

Once the suspended module has been analysed and the assembly described in section 5.2.2. has been carried out, the module soldered to the copper block will be analysed. This analysis is conducted to determine the thermal contact resistance between the module and the new copper block/bottom ceramic interface: $r_{Tc,Si}$. In this case, the analysis is carried out in air and not in vacuum since the rest of the measurements with the liquids will be conducted in the air. In the Figure 33 is the impedance spectrum from the module soldered to the copper block.

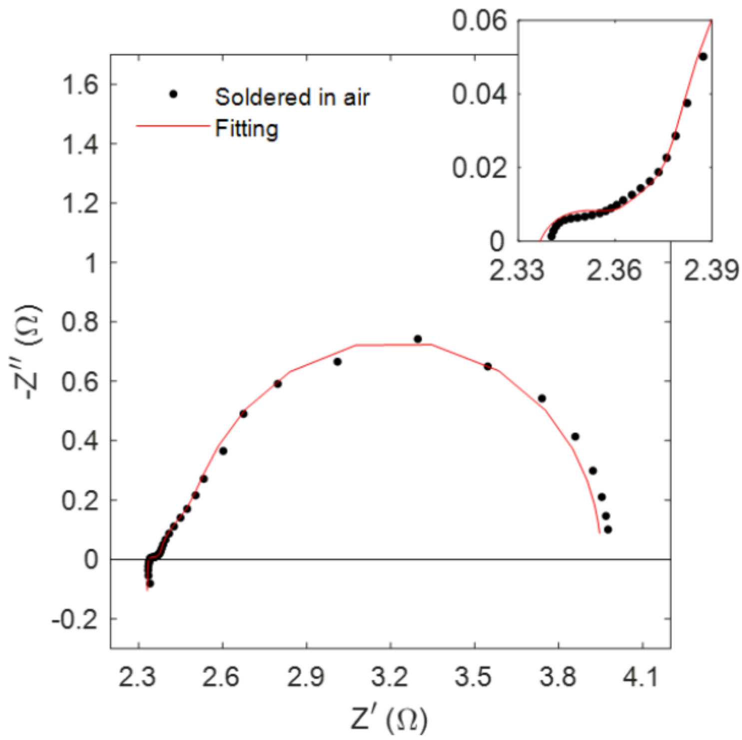

Figure 33. Measured impedance spectra (dots) obtained after soldering to the copper block, the fitting (line) in was performed using the MATLAB code.

The thermal contact resistance is obtained, as mentioned, using the MATLAB code (see code in Annex 1), being: $r_{TC,Si} = 2{,}05 \cdot 10^{-4} \frac{m^2 \cdot K}{W}$.

These parameters are kept fixed in the following measurements where the thermal conductivity of the liquids placed in the container will be obtained.

6.1.2. Thermal conductivity of liquids determination

To test the prototype and validate the technique, 3 liquids of known thermal conductivity will be tested. For all measurements, a quantity of 1000 μL will be placed in the container using a micropipette. The selected liquids have different thermal conductivities to test the effectiveness in various ranges.

-Distilled water [22]: $\lambda_{water} = 0.595\ {}^{W}/_{m\ K}$

-Antifreezer Luzar Orgánico (*Carpemar Technology*) [23]: $\lambda_{luzar} = 0.404\ {}^{W}/_{m\ K}$

-Diethylene glycol (*MEGlobal*) [24]: $\lambda_{glycol} = 0.242\ {}^{W}/_{m\ K}$

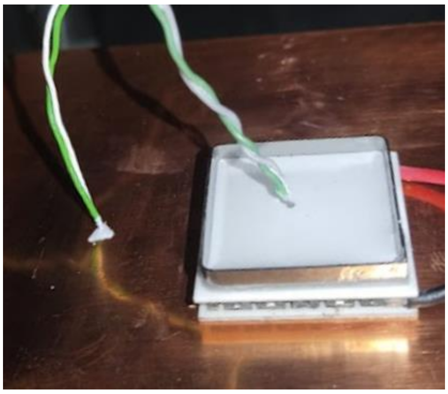

Figure 34. Setup with water into the container and two thermocouples, one on the surface and the other on the liquid.

When measurements with liquids began, it was observed that although convection within the air inside the vacuum chamber was minimal, it still had some impact. It was decided to place a cover on top of the container with the liquid.

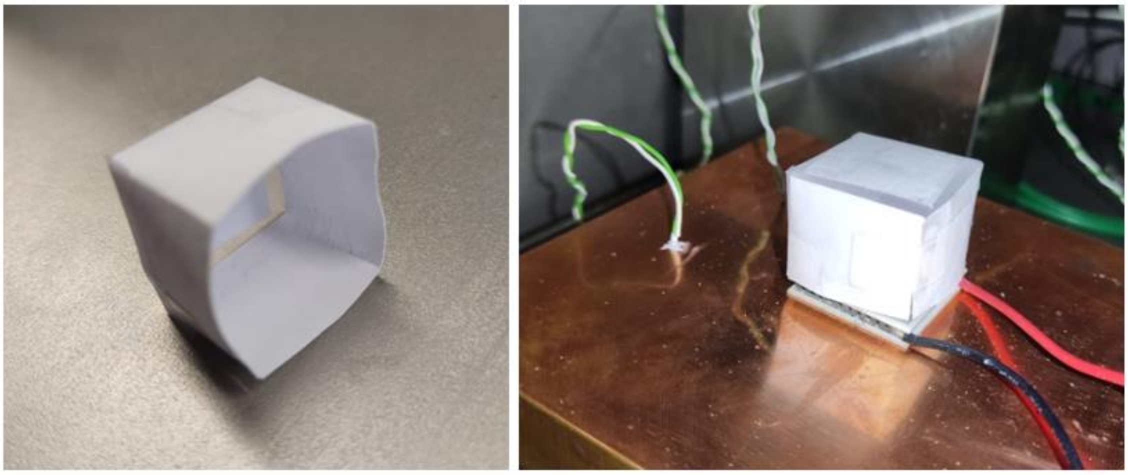

Figure 35. Small paper box that fits perfectly on the TE module.

As seen in the images of Figure 35, it is a simple paper cube with dimensions matching the TE module. It has minimal contact with the surface but it serves its purpose perfectly well. With this cover, heat transfer by convection with the air is reduced.

Once this issue was resolved, three measurements were conducted for each liquid.

Both the ambient and liquid temperatures should always be similar and constant. This was achieved by adjusting the laboratory thermostat every day to the same temperature: $24.5 \pm 0.5ºC$. This is important because most thermal parameters are highly influenced by temperature and can vary significantly.

Each time a measurement is taken, the liquid must be changed as it could be contaminated. Additionally, the container needs to be cleaned after each measurement, which was done using cotton swabs.

Figure 36. Fresh and used samples. A) Luzar. B) Diethylene-Glycol.

Once these aspects are clear, the impedance spectroscopy of the system is carried out with each liquid. Three effective measurements will be taken with each liquid. Please note that each impedance spectroscopy takes around one hour to be completed.

Below, the diagrams of the three liquids are presented.

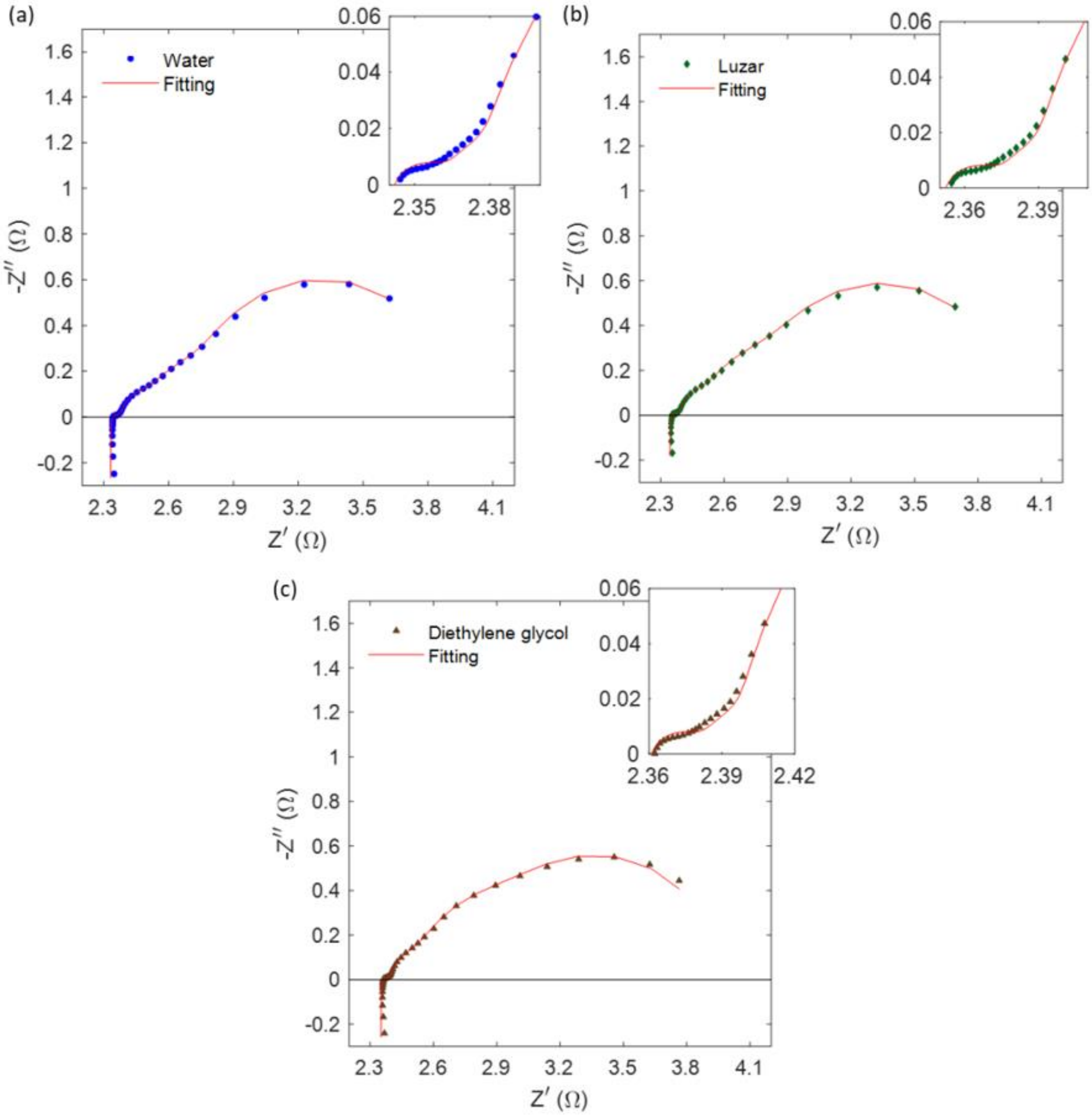

Figure 37 The symbols in (a), (b), and (c) show experimental data of water, Luzar, and diethylene glycol, respectively, while the lines show the fittings using the MATLAB code.

On the Nyquist diagrams the three measurements appear quite similar at first glance. To visualize the differences between the analysis of each liquid more accurately, the three will be superimposed. In this diagram, the point where $Z'' = 0$ corresponds to R_Ω. To overlap the three analyses, this parameter is removed. This ensures that all liquids start at the same point in the graphic

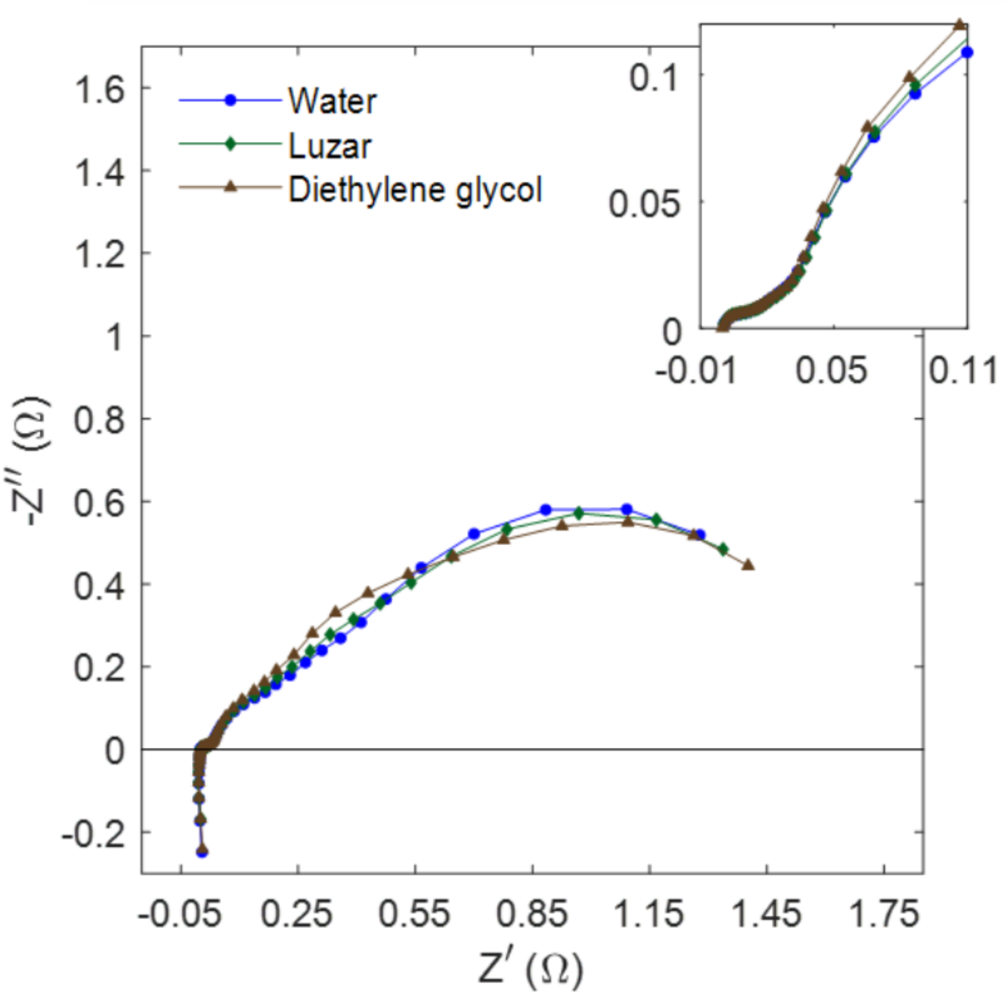

Figure 38. All three liquids comparison. The symbols show experimental while the lines show the fittings using the MATLAB code. Top right a detail at high frequencies.

In the images, differences are observed directly related to the thermal properties of the analysed liquids. In Figure 38, it can be seen that diethylene glycol rises with a steeper slope due to its lower thermal conductivity. This happens because more heat is absorbed during diffusion. As shown, the other two liquids have a shallower slope.

On the other hand, in the right part of figure 40.a, at low frequencies, water ends earlier than the other liquids, because is being able to absorb less heat.

With the MATLAB fittings, it will be possible to obtain the parameters L_p, R_Ω, λ_{Liq}, α_{Liq} and h_{Liq} (convection coefficient at the top of the liquid) for each of the three cases. Look at the following table along with the respective fitting uncertainties from the fittings.

Liquid	Measurement	L_p (H)	R_Ω (Ω)	λ_{Liq} ($Wm^{-1}K^{-1}$)	α_{Liq} (m^2s^{-1})	h_{Liq} ($Wm^{-2}K^{-1}$)
Water	a	4.24×10^{-7} (1.63%)	2.33 (0.02%)	0.566 (2.07%)	1.43×10^{-7} (1.98%)	33.1 (20.3%)
	b	4.26×10^{-7} (1.64%)	2.33 (0.02%)	0.538 (1.05%)	1.31×10^{-7} (1.29%)	28.5 (20.2%)
	c	4.26×10^{-7} (1.63%)	2.34 (0.02%)	0.531 (1.17%)	1.30×10^{-7} (1.48%)	28.9 (20.6%)
Luzar	a	2.92×10^{-7} (3.50%)	2.34 (0.02%)	0.414 (1.13%)	1.22×10^{-7} (1.56%)	31.3 (17.5%)
	b	3.07×10^{-7} (2.20%)	2.34 (0.02%)	0.375 (0.94%)	1.05×10^{-7} (1.49%)	34.6 (16.9%)
	c	3.08×10^{-7} (2.28%)	2.33 (0.02%)	0.417 (0.97%)	1.21×10^{-7} (1.53%)	30.9 (16.9%)
Diethylene glycol	a	4.14×10^{-7} (1.97%)	2.35 (0.02%)	0.253 (1.20%)	9.31×10^{-8} (2.50%)	35.7 (19.7%)
	b	4.07×10^{-7} (1.82%)	2.35 (0.02%)	0.249 (1.30%)	9.41×10^{-8} (2.50%)	33.2 (19.9%)
	c	4.02×10^{-7} (2.05%)	2.34 (0.02%)	0.262 (1.26%)	9.60×10^{-8} (2.84%)	39.9 (19.1%)

Table 3. Measurement a, b and c of each liquid. From left to right: parasitic inductance, ohmic resistance, thermal conductivity, thermal diffusivity and convection coefficient values and their respective uncertainties.

It can be observed that in most cases, the thermal conductivity has an uncertainty below 2%, and in the case of thermal diffusivity, it is below 3%, which is a good result at first glance.

On the other hand, the uncertainties for the convection coefficient are higher. Since it has to pass through both the module and the liquid, determining this parameter is difficult. Perhaps with a thiner module, lower uncertainties could be obtained. However, as seen, it does not initially affect the determination of the desired thermal parameters.

Specific heat ratio calculation

Knowing the experimental values of thermal conductivity and thermal diffusivity, the specific heat of the liquid can be determined. These values are related to each other through Eq. 11, mentioned earlier in section 3.4.1.

The density of the liquid can be easily obtained using a balance. Since a volume of 1 mL has always been used, it is only necessary to obtain the mass of an identical sample to calculate the material's density.

$$\rho = {}^{weight}/_{volume} \quad (17)$$

Table 4 shows the specific heat values obtained from the averages.

Liquid	Thermal conductivity mean ($\frac{W}{m\cdot K}$)	Thermal diffusivity mean ($\frac{m^2}{s}$)	Density ($\frac{kg}{m^3}$)	Specific heat ratio ($\frac{kJ}{kg\cdot K}$)
Water	0.545	$1.35\cdot10^{-7}$	997	4.06
Luzar	0.402	$1.16\cdot10^{-7}$	1075	3.23
Diethylene glycol	0.255	$9.44\cdot10^{-8}$	1118	2.42

Table 4. Specific heat calculation using expression (11) and the mean of the obtained values.

6.2. Uncertainty evaluation

In the previous section, the data obtained from the fitting and the corresponding uncertainties are provided. To perform an uncertainty evaluation of an experimental process like this, where the sample size is small (3 measurements per liquid), several factors must be considered [25] [26]

The final uncertainty of each obtained parameter will be determined by:

$$u_t = \sqrt{u_c{}^2 + u_s{}^2} \quad (18)$$

Where u_c is a combination of the uncertainty caused by the deviation and u_s is due to error propagation.

For thermal conductivity and thermal diffusivity, the following should be considered:

Uncertainty due to deviation:

In samples with low populations, the standard deviation can be calculated by observing the deviation between the measured values in the following manner:

$$u_d = \frac{[k_{max} - k_{min}]}{2\sqrt{3}} \quad (19)$$

This has to be obtained for each parameter λ and α of every liquid studied.

Uncertainty due to error propagation

When combining a certain number of values with their respective uncertainties in an equation, there is an accumulation of uncertainty as a result. It can be expressed as:

$$u_p = \sqrt{(\frac{u_{k1}}{3})^2 + (\frac{u_{k2}}{3})^2 + (\frac{u_{k3}}{3})^2} \quad (20)$$

To obtain the uncertainty of λ and α taking into account the influence of these factors, the following expression needs to be is used:

$$u_{c\_KLiq} = \sqrt{u_d^2 + u_p^2} \quad (21)$$

Where k represents the uncertainty of thermal conductivity and thermal diffusivity in each case.

On the other hand, for the uncertainty of the specific heat, it is necessary to consider that it is a function of both conductivity and diffusivity, and both parameters with his uncertainties. The contribution of the material density is considered negligible as it is expected to be much smaller than the other two.

For this type of calculations, where uncertainty is a function of other parameters, the following relation is used:

$$u_{c\_CpLiq} = \sqrt{(\frac{\partial C_{p,Liq}(\lambda_{Liq})}{\partial \lambda_{Liq}} u_{\lambda Liq})^2 + (\frac{\partial C_{p,Liq}(\alpha_{Liq})}{\partial \alpha_{Liq}} u_{\alpha Liq})^2} \quad (22)$$

Finally, the deviation from the reference value.

$$u_s = 1 - \frac{k_{measured}}{k_{reference}} \quad (23)$$

Finally, the total uncertainty is obtained through the expression (18). The following table shows all the data obtained.

Liquid	Property	Reference	Measured (u_c)	Deviation, u_s	Total uncertainty, u_t
Water	d_{Liq} (kg m^{-3})	997	---	---	---
	λ_{Liq} (W m^{-1}K^{-1})	0.595	0.545 (2.04%)	-8.39%	8.63%
	α_{Liq} (m^{2}s^{-1})	1.43×10^{-7}	1.35×10^{-7} (2.95%)	-5.61%	6.33%
	$C_{p,Liq}$ (kJ kg^{-1}K^{-1})	4.18	4.06 (3.58%)	-2.90%	4.61%
Luzar	d_{Liq} (kg m^{-3})	1075	---	---	---
	λ_{Liq} (W m^{-1}K^{-1})	0.404	0.402 (3.00%)	-0.46%	3.04%
	α_{Liq} (m^{2}s^{-1})	1.13×10^{-7}	1.16×10^{-7} (4.33%)	2.56%	5.03%
	$C_{p,Liq}$ (kJ kg^{-1}K^{-1})	3.33	3.23 (5.27%)	-3.07%	6.10%
Diethylene glycol	d_{Liq} (k gm^{-3})	1118	---	---	---
	λ_{Liq} (W m^{-1}K^{-1})	0.242	0.255 (1.68%)	5.32%	5.58%
	α_{Liq} (m^{2}s^{-1})	9.40×10^{-8}	9.44×10^{-8} (1.75%)	0.42%	1.80%
	$C_{p,Liq}$ (kJ kg^{-1}K^{-1})	2.30	2.42 (2.42%)	4.87%	5.44%

Table 5. Mean value from each parameter, with their respective u_c, then the deviation with the reference value u_s and finally the total uncertainty u_t.

Overall, the total uncertainty was <8.6% for the thermal conductivity, <6.3% for the thermal diffusivity, and <6.1% for the specific heat capacity, which are reasonably low values. Interestingly, no clear correlation between the systematic deviations and the studied property values was observed.

6.3. Evaluation of a phase change material

In this part of the project, a phase change material has been analysed using the same setup used for liquids. As explained in section 3.5, these materials release a lot of energy at the moment of phase change.

In this project, the effectiveness of the developed device will be studied qualitatively by analysing a PCMat.

6.3.1. Thermal conductivity analysis

The material to be studied was *PlusICE Hydrated Salt S30* obtained from the company *PCM Products* and is used for storage of high or low temperature energy for later use. This material is in a solid state below 30ºC.

First, the effectiveness of the method for analysing the thermal properties of liquids used in previous sections was tested. But in this case, the material must be taken to temperatures above 30 degrees in order to treat it as a liquid, since at room temperature this material is completely solid. It is decided to use 40ºC as temperature so that it is above its melting temperature.

To carry out this process, the Seebeck of the module at this higher temperature must first be obtained. Repeating the same process as in section 5.1.1. but in this case at this temperature. This process and the following ones are all carried out in an oven.

A slightly higher Seebeck is obtained in this case:

$$S = 222{,}6 \frac{\mu V}{ºK}$$

Once this parameter has been obtained, the conductivity and other parameters of the material are measured. As mentioned above, the material must be brought to a liquid state. To do this, it is placed inside the oven at 40ºC and left for a few hours for it to change to a completely liquid state. The material is supplied by the manufacturer in capsules of about 20 cm long. Once in a liquid state, a sample of the material is taken and placed in small jars as with the other liquids studied.

Figure 39. Encapsulated PCM.

Now, 1mL of the sample is placed in the container and by repeating the above process the thermal conductivity of the material is obtained.

The obtained conductivity is: $\lambda_{PCM} = 0{,}535\ {}^{W}/_{mK}, u = 1{,}18\%$.

This is a result which again verifies the accuracy of the method, as according to the manufacturer the material has a conductivity of 0.510 W/(m·K).

6.3.2. Phase change material analysis

In this section, the phase change material was analysed at different temperatures in order to qualitatively analyse the impedance response obtained. Again, this analysis was carried out inside the oven.

To do this, the material will be initially placed in a liquid state at 30.6ºC. After a first measurement, the oven temperature is reduced to 26.5ºC and a second measurement was carried out. This process is repeated 4 times, reducing the temperature for each analysis, with a maximum difference of one hour between each analysis. See table below for the temperature of each analysis.

Analysis number	Temperature of the analysis (°C)
1	30,6
2	26,5
3	25,3
4	24,6 (oven off)
5	24,5 (oven off)

Table 6. The five measurements carried out and the temperature in each of them.

Note that in the first measurmeent the PCMat is completely liquid and after lowering the temperature and then turning off the oven, leaving it at room temperature, the material will be in its phase change state and will start to solidify. At that moment the material does not change its temperature but absorbs energy from the environment.

The Figure 40 shows the impedance graphs of the 5 analyses carried out.

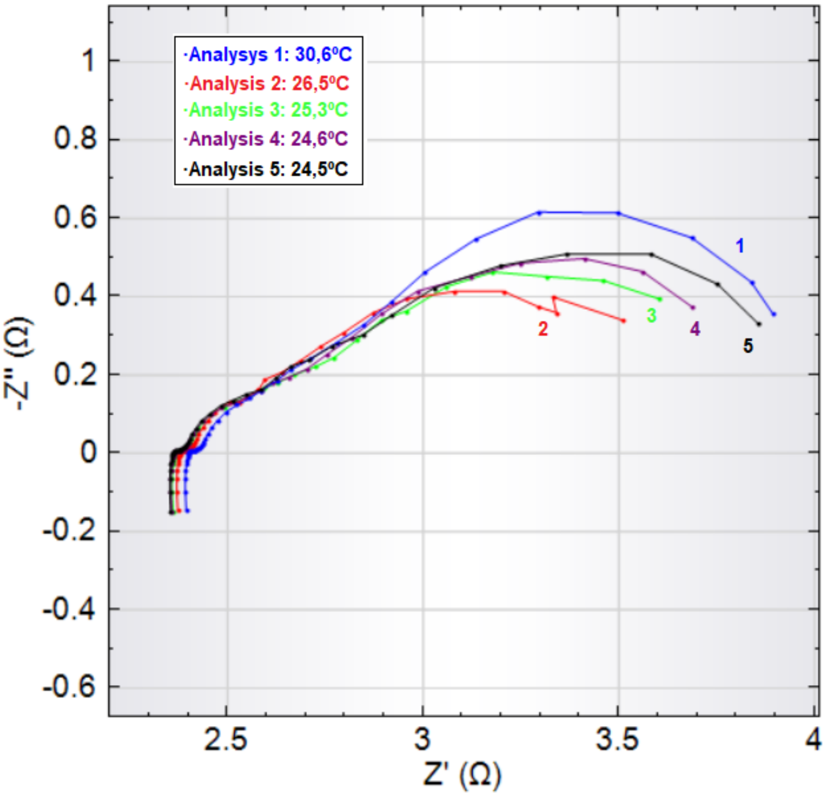

Figure 40. Nyquist plot of the five analysis with the PCMat superposed. see graph chart to identify each measurement.

In the figure, where the analyses are overlapped, the phase change is clearly visible. Analysis 1 has a normal behaviour, where it is completely in a liquid state. In analysis 2 is when it is in a state of phase change, which is why the impedance is shorter in the graph, as all the heat it receives is absorbed without any variation in temperature. This can be seen in Eq. 7, since there is no temperature difference (third term of the equation) and the impedance signal is lower. In the following analyses, the material recovers and the phase change finishes to solid state, at room temperature, which is why the response is more and more similar to the initial one.

6.4. Budget summary

The project costs can be divided into several sections, the detailed breakdown of each part of the project cost can be found in detail in document *V Budget*. The total cost amounts to **8,320.55 €** including VAT.

7. Conclusions

In this work, an instrument to measure the thermal properties of liquids was developed. This instrument relies on the use of a thermoelectric module with a heat sink soldered at the bottom (large copper block) and a thin stainless-steel container, where the sample is placed, at the top.

Impedance measurements conducted before and after the soldering were utilized to examine the module's characteristics and determine the thermal contact resistance between the module and the copper block. After fabrication, three liquids with known thermal properties were tested using an equivalent circuit that includes all thermal effects occurring in the system. This approach allowed for the determination of thermal conductivity and thermal diffusivity. Additionally, specific heat could be obtained from these measurements. The liquids analysed were water, Luzar (antifreeze), and diethylene glycol.

The proof of concept was demonstrated, yielding satisfactory results. The total uncertainty was <8.6% for thermal conductivity, <6.3% for thermal diffusivity, and <6.1% for specific heat capacity.

This new method, whose effectiveness has been demonstrated, can obtain three of the most relevant thermal parameters of a liquid from a single measurement conducted in a single apparatus. This simplifies and reduces the cost of characterizing liquids.

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II Annexes

Table of contents

1. Annex 1: MATLAB Code

```
clear all; clc

% To introduce the data follow the next steps:

% 1.- Create a .txt file with name DataFit.txt introducing the
experimental
% data. It has to contain 3 tab-delimited columns, the first column must
be
% the frequency, the second must be the real part of the impedance, and
the
% third must be the imaginary part. As an example:

% 1000000   2.6727      2.0503
% 686650    2.3348      1.4682
% 471490    2.1673      1.03
% 323750    2.0844      0.71864
% 222300    2.0411      0.50019
% 152640    2.0267      0.34747
% 104810    2.014 0.24009
% 71969     2.0088      0.1621
% 49417     2.0061      0.11015
% 33932     2.0059      0.074041
% 23300     2.0068      0.049143
% 15999     2.0084      0.032076
% 10985     2.0101      0.020498
% 7543.1    2.0098      0.012562
% 5179.5    2.0111      0.0071148
% 3556.5    2.012 0.0031936
% 2442.1    2.0128      0.00030262
% 1676.8    2.0135      -0.0018978
% 1151.4    2.0144      -0.00367
% 790.6     2.0156      -0.0049584
```

```
% 542.87    2.0173      -0.0060208
% 372.76    2.0193      -0.0067979
% 255.95    2.0217      -0.0073832
% 175.75    2.0244      -0.0079354
% 120.68    2.0273      -0.0085252
% 82.864    2.0298      -0.0091093
% 56.899    2.032 -0.0094687
% 39.069    2.0339      -0.010035
% 26.827    2.036 -0.010634
% 18.421    2.0385      -0.011879
% 12.649    2.0413      -0.013157
% 8.6851    2.0437      -0.014701
% 5.9636    2.0466      -0.016474
% 4.0949    2.0487      -0.019178
% 2.8118    2.0504      -0.023687
% 1.9307    2.0521      -0.030576
% 1.3257    2.053 -0.041131
% 0.9103    2.0562      -0.058153
% 0.62506   2.0583      -0.079167
% 0.42919   2.0619      -0.117
% 0.29471   2.0758      -0.17252
% 0.20236   2.096 -0.24521
% 0.13895   2.1507      -0.34264
% 0.09541   2.2208      -0.44386
% 0.065513  2.3892      -0.58876
% 0.044984  2.5605      -0.70337
% 0.030888  2.8073      -0.71554
% 0.02121   3.0799      -0.6587
% 0.014563  3.2924      -0.55202
% 0.01      3.4232      -0.42626

% 2.- Save this file (ManuscriptCode_v1.m) and the created .txt file
% (DataFit.txt) in the same directory.
```

```
% 3.- Run this code.

name_file='DataFit.txt';

% ------------------- NO NEED TO MODIFY ANYTHING ELSE ----------------
-----

struct1=load(name_file);
dd=  {'L  (H)','Rohm  (Ohm)','rTC1  (m^2K/W)','rTC2  (m^2K/W)','rTCSo
(m^2K/W)','rTCSi (m^2K/W)',...
    'hSO     (W/m^2K)','S     (V/K)','lambdaTE     (W/(mK))','alphaTE
(m^2/s)','lambdaM (W/(mK))',...
    'alphaM  (m^2/s)','lambdaC  (W/(mK))','alphaC  (m^2/s)','lambdaSo
(W/(mK))',...
    'alphaSo     (m^2/s)','Err_L     (%)','Err_Rohm     (%)','Err_rTC1
(%)','Err_rTC2 (%)',...
    'Err_rTCSo     (%)','Err_rTCSi     (%)','Err_hSO     (%)','Err_S
(%)','Err_lambdaTE (%)','Err_alphaTE (%)',...
    'Err_lambdaM  (%)','Err_alphaM  (%)','Err_lambdaC  (%)','Err_alphaC
(%)','Err_lambdaSo (%)',...
    'Err_alphaSo (%)'};

ini=0; ini_2=0;

freq1=struct1(:,1)';
Zreal_meas1=struct1(:,2)';
Zimag_meas1=struct1(:,3)';
Zmod_meas1=sqrt(struct1(:,2).^2+struct1(:,3).^2)';
Zphase_meas1=atan2(struct1(:,3),struct1(:,2))';

plot(Zreal_meas1,-
Zimag_meas1,':k','Marker','.','MarkerEdgeColor','k','MarkerSize',10)
grid on; axis equal
legend('Expermental data')
xlabel('Real Z (\Omega)')
```

```
ylabel('-Imag Z (\Omega)')


struct2=struct1;

disp('Follow the instructions below to select the impedance data range to fit/simulate:')

disp(' ')

disp('1.- Magnify the plot to clearly see the initial point of the data range to be fitted/simulated.')

disp('2.- Press enter.')

disp('3.- Move the mouse and click so the data to be fitted is included in the top right quadrant.')

disp('4.- Magnify again the plot to clearly see now the final point of the data range to be fitted/simulated.')

disp('5.- Press enter.')

disp('6.- Move the mouse and click so the data to be fitted is included in the bottom left quadrant (you can click out of the white zone of the plot if needed).')

stop1=input('\nPress enter to continue...');

pts(1,:)=ginput(1);

stop1=input('\nPress enter to continue...');

pts(2,:)=ginput(1);

fileli=0;

for iii=1:length(freq1)

    if struct1(iii,2)<min(pts(1,1),pts(2,1))

        struct2(iii-fileli,:)=[];

        fileli=fileli+1;

    elseif struct1(iii,2)>max(pts(1,1),pts(2,1))

        struct2(iii-fileli,:)=[];

        fileli=fileli+1;

    elseif -struct1(iii,3)<min(pts(1,2),pts(2,2))

        struct2(iii-fileli,:)=[];

        fileli=fileli+1;

    elseif -struct1(iii,3)>max(pts(1,2),pts(2,2))

        struct2(iii-fileli,:)=[];

        fileli=fileli+1;

    end
```

```
end


freq2=struct2(:,1)';

Zreal_meas2=struct2(:,2)';

Zimag_meas2=struct2(:,3)';


if length(freq2)<11

    war_ning=warndlg('The fitting needs, at least, 11 frequency points!','Warning');

    uiwait(war_ning);

end


hold off

plot(Zreal_meas1,-Zimag_meas1,':k','Marker','.','MarkerEdgeColor','k','MarkerSize',10)

hold on

plot(Zreal_meas2,-Zimag_meas2,'-r','Marker','.','MarkerEdgeColor','b','MarkerSize',10)

grid on; axis equal

legend('Expermental data','Selected data')

xlabel('Real Z (\Omega)')

ylabel('-Imag Z (\Omega)')


while 1

    clc

    choice1=questdlg('Would you like to change the selected frequency range?',...

        'Range selection','Initial point','Final point','No','No');

    switch choice1

        case 'Initial point'

            disp('Follow the instructions below to select the impedance data range to fit/simulate:')

            disp(' ')

            disp('1.- Magnify the plot to clearly see the initial point of the data range to be fitted/simulated.')

            disp('2.- Press enter.')
```

```
            disp('3.- Move the mouse and click so the data to be fitted is included in the top right quadrant.')

            stop1=input('\nPress enter to continue...');

            pts(1,:)=ginput(1);

        case 'Final point'

            disp('Follow the instructions below to select the impedance data range to fit/simulate:')

            disp(' ')

            disp('1.- Magnify the plot to clearly see the final point of the data range to be fitted/simulated.')

            disp('2.- Press enter.')

            disp('3.- Move the mouse and click so the data to be fitted is included in the bottom left quadrant (you can click out of the white zone of the plot if needed).')

            stop1=input('\nPress enter to continue...');

            pts(2,:)=ginput(1);

        case 'No'

            break;

    end

    struct2=struct1;

    fileli=0;

    for iii=1:length(freq1)

        if struct1(iii,2)<min(pts(1,1),pts(2,1))

            struct2(iii-fileli,:)=[];

            fileli=fileli+1;

        elseif struct1(iii,2)>max(pts(1,1),pts(2,1))

            struct2(iii-fileli,:)=[];

            fileli=fileli+1;

        elseif -struct1(iii,3)<min(pts(1,2),pts(2,2))

            struct2(iii-fileli,:)=[];

            fileli=fileli+1;

        elseif -struct1(iii,3)>max(pts(1,2),pts(2,2))

            struct2(iii-fileli,:)=[];

            fileli=fileli+1;

        end
```

```
    end


    freq2=struct2(:,1)';

    Zreal_meas2=struct2(:,2)';

    Zimag_meas2=struct2(:,3)';


    if length(freq2)<11

        war_ning=warndlg('The fitting needs, at least, 11 frequency
points!','Warning');

        uiwait(war_ning);

    end


    hold off

    plot(Zreal_meas1,-
Zimag_meas1,':k','Marker','.','MarkerEdgeColor','k','MarkerSize',10)

    hold on

    plot(Zreal_meas2,-Zimag_meas2,'-
r','Marker','.','MarkerEdgeColor','b','MarkerSize',10)

    grid on; axis equal

    legend('Expermental data','Selected data')

    xlabel('Real Z (\Omega)')

    ylabel('-Imag Z (\Omega)')

end


w=2*pi*freq2;

Zmod_meas2=sqrt(struct2(:,2).^2+struct2(:,3).^2)';

Zphase_meas2=atan2(struct2(:,3),struct2(:,2))';


opts.Interpreter = 'tex';

dims=[1 100];


ff=figure('Resize','off');

left_sep=20;

long_sep=1300;

alt_sep=20;
```

```
uicontrol(ff,'Style','text','Position',[10 350 540 60],'String',strcat('Select the properties you want to fit and press "Continue".',...

' Then, non-selected properties will take a fixed value that you should provide next (an initial value should be also provided for the properties to fit).',...

' If you want to run a simulation leave everything deselected.'));

LL_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 320 long_sep alt_sep],'String',...

    'Inductance (L)');

Rohm_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 300 long_sep alt_sep],'String',...

    'Ohmic resistance (Rohm)');

rTC1_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 280 long_sep alt_sep],'String',...

    'Thermal contact resistivities between thermoelements and metallic strips (rTC1)');

rTC2_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 260 long_sep alt_sep],'String',...

    'Thermal contact resistivities between metallic strips and ceramics (rTC2)');

rTCSo_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 240 long_sep alt_sep],'String',...

    'Thermal contact resistivity between ceramic and heat source (rTC,So)');

rTCSi_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 220 long_sep alt_sep],'String',...

    'Thermal contact resistivity between ceramic and heat sink (rTC,Si)');

h_SO_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 200 long_sep alt_sep],'String',...

    'Convection at the top of the liquid (hSo)');

S_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 180 long_sep alt_sep],'String',...

    'Average Seebeck coefficient of the thermoelements (S)');

k_TE_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 160 long_sep alt_sep],'String',...

    'Thermal conductivity of the thermoelements (lambdaTE)');

alpha_TE_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 140 long_sep alt_sep],'String',...
```

```
    'Thermal diffusivity of the thermoelements (alphaTE)');

k_cu_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep      120
long_sep alt_sep],'String',...

    'Thermal conductivity of the metallic strips (lambdaM)');

alpha_cu_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep  100
long_sep alt_sep],'String',...

    'Thermal diffusivity of the metallic strips (alphaM)');

k_C_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep        80
long_sep alt_sep],'String',...

    'Thermal conductivity of the ceramics (lambdaC)');

alpha_C_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep    60
long_sep alt_sep],'String',...

    'Thermal diffusivity of the ceramics (alphaC)');

k_SO_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep       40
long_sep alt_sep],'String',...

    'Thermal conductivity of the heat source (lambdaSo)');

alpha_SO_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep   20
long_sep alt_sep],'String',...

    'Thermal diffusivity of the heat source (alphaSo)');

hh=uicontrol('Position',[445                  15                   100
30],'String','Continue','Callback','uiresume(ff)');

uiwait(ff);

fit_prop=[LL_aux.Value  Rohm_aux.Value  rTC1_aux.Value  rTC2_aux.Value
rTCSo_aux.Value rTCSi_aux.Value...

    h_SO_aux.Value   S_aux.Value   k_TE_aux.Value   alpha_TE_aux.Value
k_cu_aux.Value alpha_cu_aux.Value...

    k_C_aux.Value alpha_C_aux.Value k_SO_aux.Value alpha_SO_aux.Value];

close(ff);


prompt_0={'Inital temperature (Ti) in K:','Inductance (L) in H:','Ohmic
resistance (Rohm) in \Omega:',...

    'Thermal contact resistivities between thermoelements and metallic
strips (r_{TC1}) in m^{2}K/W:',...

    'Thermal contact resistivities between metallic strips and ceramics
(r_{TC2}) in m^{2}K/W:',...

    'Thermal  contact  resistivity  between  ceramic  and  heat  source
(r_{TC,So}) in m^{2}K/W:',...

    'Thermal  contact  resistivity  between  ceramic  and  heat  sink
(r_{TC,Si}) in m^{2}K/W:',...
```

```
    'Convection coefficient at the top of the liquid (h_{So}) in W/m^{2}K:'};
dlgtitle_0='Estimated values';
definput_0={'297','1.5e-7','2.4','1.20395e-5','0','1e-30','2.0453e-4','30'};
answer_0=inputdlg(prompt_0,dlgtitle_0,dims,definput_0,opts);
if isempty(answer_0)==1
    error('Cancelled');
end
Ti=str2num(answer_0{1});
LL=str2num(answer_0{2});
Rohm=str2num(answer_0{3});
RC1=str2num(answer_0{4});
RC2=str2num(answer_0{5});
rTCSo=str2num(answer_0{6});
rTCSi=str2num(answer_0{7});
h_SO=str2num(answer_0{8});
prompt_1={'Number of couples:','Length of the thermoelements (L) in m:',...
    'Thickness of the metallic strips (L_{M}) in m:','Thickness of the ceramics (L_{C}) in m:',...
    'Average area of the thermoelements (A) in m^{2}:','Ratio area legs/strips (\eta_{M}):',...
    'Filling factor of the thermoelectric module (\eta):','Length of the heat source (L_{So}) in m:'};
dlgtitle_1='Geometry';
definput_1={'70','1.6e-3','0.3e-3','0.7e-3','1.05e-3*1.05e-3','0.56','0.26','2.13e-3'};
answer_1=inputdlg(prompt_1,dlgtitle_1,dims,definput_1,opts);
if isempty(answer_1)==1
    error('Cancelled');
end
N=str2num(answer_1{1});
L_TE=str2num(answer_1{2}); %m
L_cu=str2num(answer_1{3}); %m
L_C=str2num(answer_1{4}); %m
```

```
A_te=str2num(answer_1{5}); %m2
eta_M=str2num(answer_1{6});
eta_C=str2num(answer_1{7});
L_SO=str2num(answer_1{8}); %m
prompt_2={'Average Seebeck coefficient of the thermoelements (S) in V/K:',...
    'Thermal conductivity of the thermoelements (\lambda_{TE}) in W/(mK):',...
    'Thermal diffusivity of the thermoelements (\alpha_{TE}) in m^{2}/s:',...
    'Thermal conductivity of the metallic strips (\lambda_{M}) in W/(mK):',...
    'Thermal diffusivity of the metallic strips (\alpha_{M}) in m^{2}/s:',...
    'Thermal conductivity of the ceramics (\lambda_{C}) in W/(mK):',...
    'Thermal diffusivity of the ceramics (\alpha_{C}) in m^{2}/s:',...
    'Thermal conductivity of the heat source (\lambda_{So}) in W/(mK):',...
    'Thermal diffusivity of the heat source (\alpha_{So}) in m^{2}/s:'};
dlgtitle_2='Material properties';
definput_2={'212e-6','1.5345','1.2e-6','400','1.1e-4','24.0933','0.1e-4','400','1.1e-4'};
answer_2=inputdlg(prompt_2,dlgtitle_2,dims,definput_2,opts);
if isempty(answer_2)==1
    error('Cancelled');
end
S=str2num(answer_2{1}); %V/K
k_TE=str2num(answer_2{2}); %W/mK
alpha_TE=str2num(answer_2{3}); %m2/s
k_cu=str2num(answer_2{4}); %W/mK
alpha_cu=str2num(answer_2{5}); %m2/s
k_C=str2num(answer_2{6}); %W/mK
alpha_C=str2num(answer_2{7}); %m2/s
k_SO=str2num(answer_2{8}); %W/mK
alpha_SO=str2num(answer_2{9}); %m2/s
```

```
while 1
    if ini>0
        hold off
        plot(Zreal_meas1,-
Zimag_meas1,':k','Marker','.','MarkerEdgeColor','k','MarkerSize',10)
        hold on
        plot(Zreal_meas2,-Zimag_meas2,'-
r','Marker','.','MarkerEdgeColor','b','MarkerSize',10)
        grid on; axis equal
        legend('Expermental data','Selected data')
        xlabel('Real Z (\Omega)')
        ylabel('-Imag Z (\Omega)')

        while 1
            clc
            choice1=questdlg('Would you like to change the selected
frequency range?',...
                'Range selection','Initial point','Final
point','No','No');
            switch choice1
                case 'Initial point'
                    disp('Follow the instructions below to select the
impedance data range to fit/simulate:')
                    disp(' ')
                    disp('1.- Magnify the plot to clearly see the
initial point of the data range to be fitted/simulated.')
                    disp('2.- Press enter.')
                    disp('3.- Move the mouse and click so the data to
be fitted is included in the top right quadrant.')
                    stop1=input('\nPress enter to continue...');
                    pts(1,:)=ginput(1);
                case 'Final point'
                    disp('Follow the instructions below to select the
impedance data range to fit/simulate:')
                    disp(' ')
                    disp('1.- Magnify the plot to clearly see the final
point of the data range to be fitted/simulated.')
```

```
                    disp('2.- Press enter.')
                    disp('3.- Move the mouse and click so the data to be fitted is included in the bottom left quadrant (you can click out of the white zone of the plot if needed).')
                    stop1=input('\nPress enter to continue...');
                    pts(2,:)=ginput(1);
                case 'No'
                    break;
            end
            struct2=struct1;
            fileli=0;
            for iii=1:length(freq1)
                if struct1(iii,2)<min(pts(1,1),pts(2,1))
                    struct2(iii-fileli,:)=[];
                    fileli=fileli+1;
                elseif struct1(iii,2)>max(pts(1,1),pts(2,1))
                    struct2(iii-fileli,:)=[];
                    fileli=fileli+1;
                elseif -struct1(iii,3)<min(pts(1,2),pts(2,2))
                    struct2(iii-fileli,:)=[];
                    fileli=fileli+1;
                elseif -struct1(iii,3)>max(pts(1,2),pts(2,2))
                    struct2(iii-fileli,:)=[];
                    fileli=fileli+1;
                end
            end

            freq2=struct2(:,1)';
            Zreal_meas2=struct2(:,2)';
            Zimag_meas2=struct2(:,3)';

            if length(freq2)<11
                war_ning=warndlg('The fitting needs, at least, 11 frequency points!','Warning');
                uiwait(war_ning);
```

```
            end


            hold off

            plot(Zreal_meas1,-
Zimag_meas1,':k','Marker','.','MarkerEdgeColor','k','MarkerSize',10)

            hold on

            plot(Zreal_meas2,-Zimag_meas2,'-
r','Marker','.','MarkerEdgeColor','b','MarkerSize',10)

            grid on; axis equal

            legend('Expermental data','Selected data')

            xlabel('Real Z (\Omega)')

            ylabel('-Imag Z (\Omega)')

        end


        w=2*pi*freq2;

        Zmod_meas2=sqrt(struct2(:,2).^2+struct2(:,3).^2)';

        Zphase_meas2=atan2(struct2(:,3),struct2(:,2))';


        ff=figure('Resize','off');

        uicontrol(ff,'Style','text','Position',[10       350       540
60],'String',strcat('Select the properties you want to fit and press
"Continue".',...

        ' Then, non-selected properties will take a fixed value that
you should provide next (an initial value should be also provided for
the properties to fit).',...

        '  If  you  want  to  run  a  simulation  leave  everything
deselected.'));

        LL_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep
320 long_sep alt_sep],'String',...

            'Inductance (L)');

        Rohm_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep
300 long_sep alt_sep],'String',...

            'Ohmic resistance (Rohm)');

        rTC1_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep
280 long_sep alt_sep],'String',...

            'Thermal contact resistivities between thermoelements and
metallic strips (rTC1)');
```

```
        rTC2_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 260 long_sep alt_sep],'String',...
            'Thermal contact resistivities between metallic strips and ceramics (rTC2)');
        rTCSo_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 240 long_sep alt_sep],'String',...
            'Thermal contact resistivity between ceramic and heat source (rTC,So)');
        rTCSi_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 220 long_sep alt_sep],'String',...
            'Thermal contact resistivity between ceramic and heat sink (rTC,Si)');
        h_SO_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 200 long_sep alt_sep],'String',...
            'Convection at the top of the liquid (hSo)');
        S_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 180 long_sep alt_sep],'String',...
            'Average Seebeck coefficient of the thermoelements (S)');
        k_TE_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 160 long_sep alt_sep],'String',...
            'Thermal conductivity of the thermoelements (lambdaTE)');

alpha_TE_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep  140 long_sep alt_sep],'String',...
            'Thermal diffusivity of the thermoelements (alphaTE)');
        k_cu_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 120 long_sep alt_sep],'String',...
            'Thermal conductivity of the metallic strips (lambdaM)');

alpha_cu_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep  100 long_sep alt_sep],'String',...
            'Thermal diffusivity of the metallic strips (alphaM)');
        k_C_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep 80 long_sep alt_sep],'String',...
            'Thermal conductivity of the ceramics (lambdaC)');

alpha_C_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep    60 long_sep alt_sep],'String',...
            'Thermal diffusivity of the ceramics (alphaC)');
```

```
        k_SO_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep
40 long_sep alt_sep],'String',...
            'Thermal conductivity of the heat source (lambdaSo)');

alpha_SO_aux=uicontrol(ff,'Style','checkbox','Position',[left_sep   20
long_sep alt_sep],'String',...
            'Thermal diffusivity of the heat source (alphaSo)');
        hh=uicontrol('Position',[445              15              100
30],'String','Continue','Callback','uiresume(ff)');
        uiwait(ff);
        fit_prop=[LL_aux.Value      Rohm_aux.Value      rTC1_aux.Value
rTC2_aux.Value rTCSo_aux.Value rTCSi_aux.Value...
            h_SO_aux.Value         S_aux.Value         k_TE_aux.Value
alpha_TE_aux.Value k_cu_aux.Value alpha_cu_aux.Value...
            k_C_aux.Value       alpha_C_aux.Value       k_SO_aux.Value
alpha_SO_aux.Value];
        close(ff);


definput_0={num2str(Ti),num2str(LL),num2str(Rohm),num2str(RC1),num2str
(RC2),num2str(rTCSo),num2str(rTCSi),num2str(h_SO)};
        answer_0=inputdlg(prompt_0,dlgtitle_0,dims,definput_0,opts);
        if isempty(answer_0)==1
            error('Cancelled');
        end
        Ti=str2num(answer_0{1});
        LL=str2num(answer_0{2});
        Rohm=str2num(answer_0{3});
        RC1=str2num(answer_0{4});
        RC2=str2num(answer_0{5});
        rTCSo=str2num(answer_0{6});
        rTCSi=str2num(answer_0{7});
        h_SO=str2num(answer_0{8});

definput_1={num2str(N),num2str(L_TE),num2str(L_cu),num2str(L_C),num2st
r(A_te),num2str(eta_M),num2str(eta_C),num2str(L_SO)};
        answer_1=inputdlg(prompt_1,dlgtitle_1,dims,definput_1,opts);
        if isempty(answer_1)==1
```

```
            error('Cancelled');
        end
        N=str2num(answer_1{1});
        L_TE=str2num(answer_1{2}); %m
        L_cu=str2num(answer_1{3}); %m
        L_C=str2num(answer_1{4}); %m
        A_te=str2num(answer_1{5}); %m2
        eta_M=str2num(answer_1{6});
        eta_C=str2num(answer_1{7});
        L_SO=str2num(answer_1{8}); %m

definput_2={num2str(S),num2str(k_TE),num2str(alpha_TE),num2str(k_cu),num2str(alpha_cu),num2str(k_C),num2str(alpha_C),num2str(k_SO),num2str(alpha_SO)};
        answer_2=inputdlg(prompt_2,dlgtitle_2,dims,definput_2,opts);
        if isempty(answer_2)==1
            error('Cancelled');
        end
        S=str2num(answer_2{1}); %V/K
        k_TE=str2num(answer_2{2}); %W/mK
        alpha_TE=str2num(answer_2{3}); %m2/s
        k_cu=str2num(answer_2{4}); %W/mK
        alpha_cu=str2num(answer_2{5}); %m2/s
        k_C=str2num(answer_2{6}); %W/mK
        alpha_C=str2num(answer_2{7}); %m2/s
        k_SO=str2num(answer_2{8}); %W/mK
        alpha_SO=str2num(answer_2{9}); %m2/s
    end
    ini=ini+1;


    OPTIONS=optimset('Display','off','TolX',1e-50,'TolFun',1e-50,'MaxIter',500);
    refine=min(struct2(:,2))*0.9;
    Zmod_meas2_ref=sqrt((struct2(:,2)-refine).^2+struct2(:,3).^2)';
```

```
    guesspars=[LL Rohm RC1 RC2 rTCSo rTCSi h_SO S k_TE alpha_TE k_cu
alpha_cu k_C alpha_C k_SO alpha_SO];

    limlow=guesspars; limhigh=guesspars;

    en_ter=find(fit_prop==1);

    limlow(en_ter)=0; limhigh(en_ter)=1e9;


    pass.w=w; pass.N=N; pass.Ti=Ti; pass.L_TE=L_TE; pass.L_cu=L_cu;
pass.L_C=L_C; pass.A_te=A_te; pass.eta_M=eta_M; pass.eta_C=eta_C;
pass.L_SO=L_SO; pass.freq2=freq2;


    Simplified_2=@(val)
abs((abs(fitequation(val(1),val(2),val(3),val(4),val(5),val(6),val(7),
val(8),val(9),val(10),val(11),val(12),val(13),val(14),val(15),val(16),
pass))-Zmod_meas2)./Zmod_meas2)+...

abs((abs((fitequation(val(1),val(2),val(3),val(4),val(5),val(6),val(7)
,val(8),val(9),val(10),val(11),val(12),val(13),val(14),val(15),val(16)
,pass))-refine)-Zmod_meas2_ref)./Zmod_meas2_ref);



[fittedpars,resnorm,residual,exitflag,output,lambda,jacobian]=lsqnonli
n(@(parlist)Simplified_2...
    (parlist),guesspars,limlow,limhigh,OPTIONS);


    jacobianet=jacobian(:,en_ter);

    Cov=resnorm*inv((jacobianet'*jacobianet))/(length(residual)-
length(en_ter));

    Std=sqrt(diag(Cov));

    relativeErr=Std./fittedpars(en_ter)'*100;


    if isempty(en_ter)

        disp('ATENTION: All parameters were fixed and only a simulation
is shown!')

    else

        gg={'---','---','---','---','---','---','---','---','---','---
','---','---','---','---','---','---'};

        disp('RESULTS OF THE FITTING:')

        disp(' ')

        val_err=0;
```

```
        if fit_prop(1)==1
            val_err=val_err+1;
            gg{1}=num2str(relativeErr(val_err));
            disp(['Inductance (L) = ' num2str(fittedpars(1)) ' H' '
Error = ' num2str(relativeErr(val_err)) ' %'])
        end
        if fit_prop(2)==1
            val_err=val_err+1;
            gg{2}=num2str(relativeErr(val_err));
            disp(['Ohmic resistance (Rohm) = ' num2str(fittedpars(2)) '
Ohm' '          Error = ' num2str(relativeErr(val_err)) ' %'])
        end
        if fit_prop(3)==1
            val_err=val_err+1;
            gg{3}=num2str(relativeErr(val_err));
            disp(['Thermal contact resistivities between TE legs and
metallic strips (rTC1) = ' num2str(fittedpars(3)) ' m^2K/W' '
Error = ' num2str(relativeErr(val_err)) ' %'])
        end
        if fit_prop(4)==1
            val_err=val_err+1;
            gg{4}=num2str(relativeErr(val_err));
            disp(['Thermal contact resistivities between metallic
strips and ceramics (rTC2) = ' num2str(fittedpars(4)) ' m^2K/W' '
Error = ' num2str(relativeErr(val_err)) ' %'])
        end
        if fit_prop(5)==1
            val_err=val_err+1;
            gg{5}=num2str(relativeErr(val_err));
            disp(['Thermal contact resistivity between ceramic and heat
source (rTC,So) = ' num2str(fittedpars(5)) ' m^2K/W' '         Error =
' num2str(relativeErr(val_err)) ' %'])
        end
        if fit_prop(6)==1
            val_err=val_err+1;
            gg{6}=num2str(relativeErr(val_err));
```

```
            disp(['Thermal contact resistivity between ceramic and heat sink (rTC,Si) = ' num2str(fittedpars(6)) ' m^2K/W' '         Error = ' num2str(relativeErr(val_err)) ' %'])

        end

        if fit_prop(7)==1

            val_err=val_err+1;

            gg{7}=num2str(relativeErr(val_err));

            disp(['Convection coefficient at the top of the liquid (hSo) = ' num2str(fittedpars(7)) ' W/m^2K' '         Error = ' num2str(relativeErr(val_err)) ' %'])

        end

        if fit_prop(8)==1

            val_err=val_err+1;

            gg{8}=num2str(relativeErr(val_err));

            disp(['Average Seebeck coefficient of the thermoelements (S) = ' num2str(fittedpars(8)) ' V/K' '         Error = ' num2str(relativeErr(val_err)) ' %'])

        end

        if fit_prop(9)==1

            val_err=val_err+1;

            gg{9}=num2str(relativeErr(val_err));

            disp(['Thermal conductivity of the thermoelements (lambdaTE) = ' num2str(fittedpars(9)) ' W/(mK)' '         Error = ' num2str(relativeErr(val_err)) ' %'])

        end

        if fit_prop(10)==1

            val_err=val_err+1;

            gg{10}=num2str(relativeErr(val_err));

            disp(['Thermal diffusivity of the thermoelements (alphaTE) = ' num2str(fittedpars(10)) ' m^2/s' '         Error = ' num2str(relativeErr(val_err)) ' %'])

        end

        if fit_prop(11)==1

            val_err=val_err+1;

            gg{11}=num2str(relativeErr(val_err));

            disp(['Thermal conductivity of the metallic strips (lambdaM) = ' num2str(fittedpars(11)) ' W/(mK)' '         Error = ' num2str(relativeErr(val_err)) ' %'])
```

```
        end
        if fit_prop(12)==1
            val_err=val_err+1;
            gg{12}=num2str(relativeErr(val_err));
            disp(['Thermal diffusivity of the metallic strips (alphaM)
=  '  num2str(fittedpars(12))  '  m^2/s'  '                  Error  =  '
num2str(relativeErr(val_err)) ' %'])
        end
        if fit_prop(13)==1
            val_err=val_err+1;
            gg{13}=num2str(relativeErr(val_err));
            disp(['Thermal conductivity of the ceramics (lambdaC) = '
num2str(fittedpars(13))  '  W/(mK)'  '                  Error  =  '
num2str(relativeErr(val_err)) ' %'])
        end
        if fit_prop(14)==1
            val_err=val_err+1;
            gg{14}=num2str(relativeErr(val_err));
            disp(['Thermal diffusivity of the ceramics (alphaC) = '
num2str(fittedpars(14))  '  m^2/s'  '                  Error  =  '
num2str(relativeErr(val_err)) ' %'])
        end
        if fit_prop(15)==1
            val_err=val_err+1;
            gg{15}=num2str(relativeErr(val_err));
            disp(['Thermal conductivity of the heat source (lambdaSo) =
'  num2str(fittedpars(15))  '  W/(mK)'  '                  Error  =  '
num2str(relativeErr(val_err)) ' %'])
        end
        if fit_prop(16)==1
            val_err=val_err+1;
            gg{16}=num2str(relativeErr(val_err));
            disp(['Thermal diffusivity of the heat source (alphaSo) = '
num2str(fittedpars(16))  '  m^2/s'  '                  Error  =  '
num2str(relativeErr(val_err)) ' %'])
        end
        disp(' ')
```

```
        disp('To reduce fitting errors, consider fixing some parameters and/or modify the selected frequency range.')

        disp('In case you saved the results, check them with the above values (the .xls file may confuse "," and ".").')

        disp('You can also contact us if you need help (teslab@uji.es)!')

    end



Z1=fitequation(fittedpars(1),fittedpars(2),fittedpars(3),fittedpars(4),fittedpars(5),fittedpars(6),fittedpars(7),fittedpars(8),fittedpars(9),fittedpars(10),...

fittedpars(11),fittedpars(12),fittedpars(13),fittedpars(14),fittedpars(15),fittedpars(16),pass);


    hold off

    plot(Zreal_meas1,-Zimag_meas1,':k','Marker','.','MarkerEdgeColor','k','MarkerSize',10)

    hold on

    plot(Zreal_meas2,-Zimag_meas2,'-r','Marker','.','MarkerEdgeColor','b','MarkerSize',10)

    hold on

    plot(real(Z1),-imag(Z1),'-','Color',[0 0.5 0],'Marker','.','MarkerEdgeColor',[0 0.5 0],'MarkerSize',10)

    axis equal; grid on

    legend('Experimental data','Selected data','Fitting')

    xlabel('Real Z (\Omega)')

    ylabel('-Imag Z (\Omega)')

    figure

    subplot(2,1,1)

semilogx(freq1,Zmod_meas1,':k','Marker','.','MarkerEdgeColor','k','MarkerSize',10)

    hold on

    semilogx(freq2,Zmod_meas2,'-r','Marker','.','MarkerEdgeColor','b','MarkerSize',10)

    hold on
```

```
    semilogx(freq2,abs(Z1),'-','Color',[0                          0.5
0],'Marker','.','MarkerEdgeColor',[0 0.5 0],'MarkerSize',10)

    grid on

    legend('Experimental data','Selected data','Fitting')

    xlabel('Frequency (Hz)')

    ylabel('Magnitude (\Omega)')

    subplot(2,1,2)

semilogx(freq1,Zphase_meas1,':k','Marker','.','MarkerEdgeColor','k','M
arkerSize',10)

    hold on

    semilogx(freq2,Zphase_meas2,'-
r','Marker','.','MarkerEdgeColor','b','MarkerSize',10)

    hold on

    semilogx(freq2,angle(Z1),'-','Color',[0                        0.5
0],'Marker','.','MarkerEdgeColor',[0 0.5 0],'MarkerSize',10)

    grid on

    legend('Experimental data','Selected data','Fitting')

    xlabel('Frequency (Hz)')

    ylabel('Phase (rad)')


    if max(fit_prop)>0

        choice2=questdlg('Would you like to save the results in a .xls
file?',...

            'Save','Yes','No','No');

        switch choice2

            case 'Yes'

ee={num2str(fittedpars(1)),num2str(fittedpars(2)),num2str(fittedpars(3
)),num2str(fittedpars(4)),num2str(1/fittedpars(5)),num2str(fittedpars(
6)),...

num2str(fittedpars(7)),num2str(fittedpars(8)),num2str(fittedpars(9)),n
um2str(fittedpars(10)),num2str(fittedpars(11)),num2str(fittedpars(12))
,...

num2str(fittedpars(13)),num2str(fittedpars(14)),num2str(fittedpars(15)
),num2str(fittedpars(16)),...
```

```
gg{1},gg{2},gg{3},gg{4},gg{5},gg{6},gg{7},gg{8},gg{9},gg{10},gg{11},gg
{12},gg{13},gg{14},gg{15},gg{16}};
                dd=[dd;ee];
                ini_2=1;
            case 'No'
        end
    end

    stop2=input('\nTo stop (and create the .xls file, if applicable)
type "exit"... To continue just press enter...\n','s');
    if
strcmp(stop2,'exit')||strcmp(stop2,'Exit')||strcmp(stop2,'EXIT')||strc
mp(stop2,'"exit"')
        break;
    end
    close all
end

if ini_2==1
    real_name_file=name_file(1:length(name_file)-4);
    xlswrite(real_name_file,dd)
end

choice3=questdlg('Would you like to save the last fitted data in a .xls
file?',...
    'Save','Yes','No','No');
switch choice3
    case 'Yes'
        writematrix([freq2',real(Z1)',imag(Z1)'],'Fitted_data.csv')
    case 'No'
end

function
Ztotal=fitequation(LL,Rohm,RC1,RC2,rTCSo,rTCSi,h_SO,Sbck,k_TE,alpha_TE
,k_cu,alpha_cu,k_C,alpha_C,k_SO,alpha_SO,pass)
```

```
w=pass.w;   N=pass.N;   Ti=pass.Ti;   L_TE=pass.L_TE;   L_cu=pass.L_cu;
L_C=pass.L_C;   A_te=pass.A_te;   eta_M=pass.eta_M;   eta_C=pass.eta_C;
L_SO=pass.L_SO;


ZLP=1i*w.*LL;


exp_plus=(1+exp(-2*((1i*w./(alpha_TE/(L_TE^2))).^0.5)))/2;

exp_minus=(1-exp(-2*((1i*w./(alpha_TE/(L_TE^2))).^0.5)))/2;

ZTOT5t_exp=k_TE*A_te/L_TE*(1i*w./(alpha_TE/(L_TE^2))).^0.5;

exp_simp=exp(-((1i*w./(alpha_TE/(L_TE^2))).^0.5));

Flux=Sbck*Ti;


x1=sqrt(A_te/eta_C)/2+sqrt(A_te)/2;                    y1=sqrt(A_te)/2;
x2=sqrt(A_te/eta_C); y2=sqrt(A_te/eta_C)/2;

njj=(1:100)';

mjj=(1:100);

mat_njj=repmat(njj,1,length(mjj));

mat_mjj=repmat(mjj,length(njj),1);


for each_w=1:length(w)

    w_aux_nn=repmat(w(each_w),length(njj),1);

    w_aux_mm=repmat(w(each_w),1,length(mjj));

    w_aux=repmat(w(each_w),length(njj),length(mjj));

    gamma_nn=sqrt((njj*pi/x2).^2+(1j*w_aux_nn/alpha_C));

    gamma_mm=sqrt((mjj*pi/y2).^2+(1j*w_aux_mm/alpha_C));

gamma_sq=sqrt((mat_njj*pi/x2).^2+(mat_mjj*pi/y2).^2+(1j*w_aux/alpha_C)
);

    num_nn=x2*y1*sin(njj*pi*x1/x2).^2;

    num_mm=y2*x1*sin(mjj*pi*y1/y2).^2;

    num_sq=x2*y2*sin(mat_njj*pi*x1/x2).^2.*sin(mat_mjj*pi*y1/y2).^2;



par_RSo_nn=(k_C.*gamma_nn.*tanh(gamma_nn.*L_C)+(1/rTCSo))./(k_C.*gamma
_nn+(1/rTCSo).*tanh(gamma_nn.*L_C));
```

```
par_RSo_mm=(k_C.*gamma_mm.*tanh(gamma_mm.*L_C)+(1/rTCSo))./(k_C.*gamma
_mm+(1/rTCSo).*tanh(gamma_mm.*L_C));

par_RSo=(k_C.*gamma_sq.*tanh(gamma_sq.*L_C)+(1/rTCSo))./(k_C.*gamma_sq
+(1/rTCSo).*tanh(gamma_sq.*L_C));
    den_sqSo_nn=x1*y2*pi^2*njj.^2.*gamma_nn.*par_RSo_nn;
    den_sqSo_mm=y1*x2*pi^2*mjj.^2.*gamma_mm.*par_RSo_mm;
    den_sqSo=x1*y1*pi^4*mat_njj.^2.*mat_mjj.^2.*gamma_sq.*par_RSo;

ZSC4NS2TMSo(each_w)=4*(eta_M/(k_C*A_te))*sum(sum(num_sq./den_sqSo))+2*
(eta_M/(k_C*A_te))*sum(num_nn./den_sqSo_nn)...
        +2*(eta_M/(k_C*A_te))*sum(num_mm./den_sqSo_mm);



par_RSi_nn=(k_C.*gamma_nn.*tanh(gamma_nn.*L_C)+(1/rTCSi))./(k_C.*gamma
_nn+(1/rTCSi).*tanh(gamma_nn.*L_C));

par_RSi_mm=(k_C.*gamma_mm.*tanh(gamma_mm.*L_C)+(1/rTCSi))./(k_C.*gamma
_mm+(1/rTCSi).*tanh(gamma_mm.*L_C));

par_RSi=(k_C.*gamma_sq.*tanh(gamma_sq.*L_C)+(1/rTCSi))./(k_C.*gamma_sq
+(1/rTCSi).*tanh(gamma_sq.*L_C));
    den_sqSi_nn=x1*y2*pi^2*njj.^2.*gamma_nn.*par_RSi_nn;
    den_sqSi_mm=y1*x2*pi^2*mjj.^2.*gamma_mm.*par_RSi_mm;
    den_sqSi=x1*y1*pi^4*mat_njj.^2.*mat_mjj.^2.*gamma_sq.*par_RSi;

ZSC4NS2TMSi(each_w)=4*(eta_M/(k_C*A_te))*sum(sum(num_sq./den_sqSi))+2*
(eta_M/(k_C*A_te))*sum(num_nn./den_sqSi_nn)...
        +2*(eta_M/(k_C*A_te))*sum(num_mm./den_sqSi_mm);
end


RTC14NS2TM=RC1/A_te;
RTC24NS2TM=RC2*eta_M/A_te;
ZWaM4NS2TM=(L_cu*eta_M/(k_cu*A_te)).*(1i*w./(alpha_cu/(L_cu^2))).^-
0.5.*coth((1i*w./(alpha_cu/(L_cu^2))).^0.5);
ZWCTM4NS2TM=(L_cu*eta_M/(k_cu*A_te)).*(1i*w./(alpha_cu/(L_cu^2))).^-
0.5.*tanh((1i*w./(alpha_cu/(L_cu^2))).^0.5);
ZWCTC4NS2TM=(L_C*eta_C/(k_C*A_te)).*(1i*w./(alpha_C/(L_C^2))).^-
0.5.*tanh((1i*w./(alpha_C/(L_C^2))).^0.5);
```

```
ZWa4NS2TM=(L_C*eta_C/(k_C*A_te)).*(1i*w./(alpha_C/(L_C^2))).^-
0.5.*coth((1i*w./(alpha_C/(L_C^2))).^0.5);

RhSO4NS2TM=eta_C/(h_SO*A_te);

ZWaSo4NS2TM=(L_SO*eta_C/(k_SO*A_te)).*(1i*w./(alpha_SO/(L_SO^2))).^-
0.5.*coth((1i*w./(alpha_SO/(L_SO^2))).^0.5);

ZWCTSO4NS2TM=(L_SO*eta_C/(k_SO*A_te)).*(1i*w./(alpha_SO/(L_SO^2))).^-
0.5.*tanh((1i*w./(alpha_SO/(L_SO^2))).^0.5);


RTC4NS2TMSo=eta_C*rTCSo/A_te;

ZChSO=(L_SO*eta_C/(k_SO*A_te))^2/RhSO4NS2TM.*(1i*w./(alpha_SO/(L_SO^2)
)).^-1;

ZWaSoMNoConv=(ZWaSo4NS2TM.^-1+RhSO4NS2TM.^-1).^-1+(ZWCTSO4NS2TM.^-
1+ZChSO.^-1).^-1;

ZTOT3=RTC24NS2TM+ZSC4NS2TMSo+(ZWa4NS2TM.^-
1+(RTC4NS2TMSo+ZWaSoMNoConv).^-1).^-1+(ZWCTC4NS2TM.^-1+...


((L_C*eta_C/(k_C*A_te)).^2./(RTC4NS2TMSo+ZWaSoMNoConv).*(1i*w./(alpha_
C/(L_C^2))).^-1).^-1).^-1;

ZSo=RTC14NS2TM+((ZWaM4NS2TM.^-1+ZTOT3.^-1).^-1+(ZWCTM4NS2TM.^-1+...


((L_cu*eta_M/(k_cu*A_te)).^2./ZTOT3.*(1i*w./(alpha_cu/(L_cu^2))).^-
1).^-1).^-1);


RTC4NS2TMSi=eta_C*rTCSi/A_te;

ZCTC4NS2TM=(L_C*eta_C/(k_C*A_te))^2/RTC4NS2TMSi.*(1i*w./(alpha_C/(L_C^
2))).^-1;

ZTOT5=RTC24NS2TM+ZSC4NS2TMSi+(ZWa4NS2TM.^-1+RTC4NS2TMSi.^-1).^-
1+(ZWCTC4NS2TM.^-1+ZCTC4NS2TM.^-1).^-1;

ZTOT6_1=(L_cu*eta_M/(k_cu*A_te)).^2./ZTOT5.*(1i*w./(alpha_cu/(L_cu^2))
).^-1;

ZSi=RTC14NS2TM+(ZWaM4NS2TM.^-1+ZTOT5.^-1).^-1+(ZWCTM4NS2TM.^-
1+ZTOT6_1.^-1).^-1;


Temp0_num=Flux.*exp_plus+Flux.*exp_minus./ZTOT5t_exp./ZSi-
Flux.*exp_simp;

Temp0_den=ZTOT5t_exp.*exp_minus+exp_plus./ZSi+exp_plus./ZSo+exp_minus.
/ZTOT5t_exp./ZSi./ZSo;

Temp0=Temp0_num./Temp0_den;

TempL_num=Flux*exp_simp-Temp0.*exp_simp./ZSo-exp_plus*Flux;

TempL_den=ZTOT5t_exp.*exp_minus+exp_plus./ZSi;
```

```
TempL=TempL_num./TempL_den;


Ztotal=ZLP+Rohm+2*N*Sbck*(Temp0-TempL);
end
```

2. Annex 2: Technical data sheets

TE module

TEC Specification Sheet

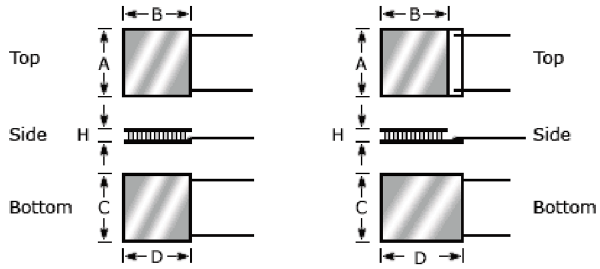
CUSTOM THERMOELECTRIC
Your Thermoelectric Partner

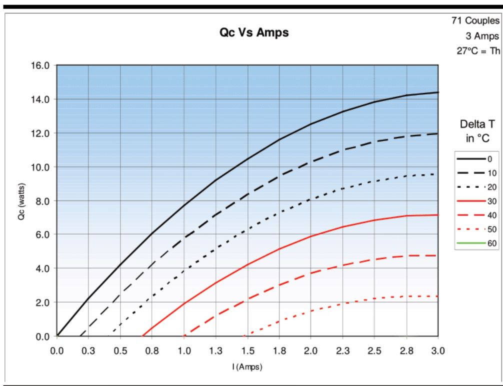
Part #	I_{max} (Amps)	Q_{max} (Watts)	V_{max} (Volts)	DT_{max} (°C)	T_{max} (°C)
07111-5L31-03CJ	3.0	14.4	8.6	67°C	125°C

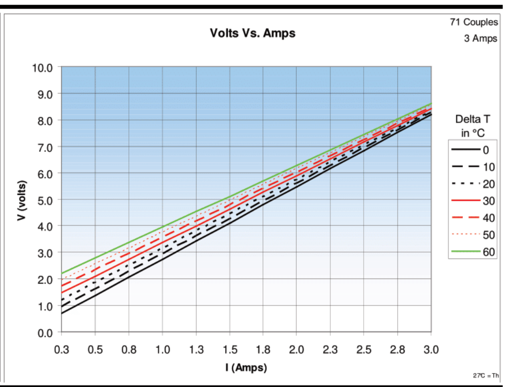
Lapped

Top Plate				Bottom Plate				Metallized Height		Lapped Height	
A		B		C		D		H		H	
mm	in	mm	in	mm	in	mm	in	mm	in	mm	in
23.00	0.91	23.00	0.91	23.00	0.91	23.00	0.91	NA	NA	3.6	.142

Weight (w/o leads)
7 grams







Tel. **443-926-9135** FAX: 443-926-9137 WEB: **www.customthermoelectric.com** E-mail: **temodule@customthermoelectric.com**
All technical information and data in this document is based on tests and measurements and is believed to be accurate and reliable. Product testing by the purchaser is recommended in order to confirm expected results for specific applications. Materials and specifications are subject to change without notice. REV. 4-15-2007

Thermal Grease

Thermal Grease

FEATURES

- Wide operating temperature range
- Excellent thermal conductivity even at high temperatures
- Low in toxicity
- White colour enables treated parts to be easily identified
- Low evaporation weight loss
- Chemically inert (not chemically reactive)
- Shock absorbent
- Moisture repellent with long-term stability

Metal Oxide Thermal Paste, 0.65W/m·K

RS Stock No.: 554-311

RS Professionally Approved Products bring to you professional quality parts across all product categories. Our product range has been tested by engineers and provides a comparable quality to the leading brands without paying a premium price.

Thermal Grease

Product Description

This thermal grease adhesive provides an excellent heat transfer between semiconductor devices and heat sinks. It is based on a silicone oil and therefore offers a wide operating temperature range and excellent stability at high temperatures. Improves electrical isolation when used in the normal way with insulating washers and reduce time lag in thermostats. This heat sink compound is recommended where the efficient and reliable thermal coupling of electrical and electronic components is required, or between any surface where thermal conductivity or heat dissipation is important.

General Specifications

Material	Metal Oxide
Chemical Component	Powdered Metal Oxides, Silicone Oil
Colour	White
Pack Size	20mL
Thermo-conductive Component	Powdered metal oxides
Application	Overclocking and high performance CPUs, CPU die and its integrated heat spreader, Solder

Electrical Specifications

Specific Resistance	1 x 10_{14} Ohms/cm
Thermal Conductivity	0.65W/m·K
Dielectric Strength	16 kV/mm

Mechanical Specifications

Penetration	310
Weight Loss after 96 hours @ 100°C	<1%
Density @ 20°C	2.0 g/cm3

Thermal Grease

Operation Environment Specifications

Maximum Operating Temperature	+200°C
Minimum Operating Temperature	-40°C
Operating Temperature Range	-40°C to +100°C

Approvals

Compliance/Certifications	RoHS-2 Compliant (2011/65/EU)

Potentiostat PGSTAT302N

Potential range in volt	-10 V to 10 V
Compliance voltage range in volt	± 30
Maximum current in ampère	± 2
Number of current ranges	9
Number of current ranges remarks	10 nA to 1 A
Modular instrument	true
Maximum number of modules	8
Analog integrator	false
Multichannel instrument	false
Maximum number of channels	1
Potential and current accuracy	V: ± 0.2% ± 2 mV
Potential resolution	0.3 µV (gain 1000)
Current resolution	0.0003% (of current range)
Maximum bandwidth in Hz	1 MHz
Input impedance in Ohm	1 TOhm
Dimensions in mm (W/H/D)	520/160/420
Dimensions remark	Without cables and accessories
Weight of the instrument in kg	18

Luzar antifreezer

SUC. DE CARMELO PEREZ MARTINEZ S.L.
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Carpemar

LUZAR ORGÁNICO 50%

DOCUMENTACIÓN TÉCNICA

Características:

Nuevo anticongelante-refrigerante de **fórmula completamente orgánica**:

- No contiene Nitritos, Nitratos ni aminas. No se forman nitrosaminas (potenciales agentes cancerigenos)
- Exento de silicatos. Se puede almacenar por periodos de tiempo más largos.
- No contiene Boratos ni Benzoatos.
- No contiene fosfatos, cuestionados por sus implicaciones medioambientales.

Formulación 100% orgánica: Se degrada más lentamente que los Anticongelantes-Refrigerantes convencionales y alarga los periodos de cambio notablemente.

- Descenso del Punto de Congelación y aumento del Punto de Ebullición.
- Nula formación de espuma.
- Su color amarillo fluorescente ayuda en la detección de fugas.
- Protege al radiador, la bomba y todo el circuito de refrigeración de la corrosión, especialmente formulado para el aluminio y sus aleaciones.

Propiedades:

Apariencia	Líquido Transparente
Color	Amarillo-Fluorescente
Tª de Congelación[1]	-37,0ºC
Tª de Ruptura[2]	-43,0ºC
Tª de Protección[3]	-40,0ºC
Punto de ebullición a 1 bar	109ºC
Punto de ebullición a 2 bares	137ºC
pH a 20ºC	8,5-9,5
Flash point	>100ºC
Densidad a 20ºC	1,07-1,08 g/cc
Viscosidad a 20ºC	4,17 mPas
Capacidad Calorífica a 20ºC	3,32 KJ/KgK
Coeficiente de expansión térmica	0,00048 1/K
Reserva alcalina	min. 5 ml HCl 0,1N

[1] *El punto de congelación según la norma ASTM D 1177 indica la temperatura a la que aparece el primer cristal.*
[2] *La normativa DIN 51583 marca el punto a partir del cual el producto deja de fluir. El producto está totalmente congelado y existe aumento de volumen, con lo que la integridad del circuito está en peligro.*
[3] *Entre la temperatura de congelación y la temperatura de ruptura existe una mezcla de cristales de hielo y fluido sin congelar que fluye sin aumentar el volumen, sin causar daños en la instalación.*

Rev: 05-13 1 de 7

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Protección contra la corrosión:

Las mezclas etilenglicol-agua son más corrosivas que el agua por lo que no pueden usarse sin los aditivos antioxidantes que garanticen la integridad del circuito.

A continuación se muestran los resultados del ensayo correspondiente a la normativa ASTM D 3306 en el que se evalúa la corrosión sobre diferentes metales. A modo comparativo se incluyen los resultados para la mezcla sin aditivos y para el agua pura.

Comparativa de corrosión para diferentes metales y productos (mg/cm^2)				
Metal	**Agua**	**Etilenglicol 33% volumen en agua**	*Luzar Orgánico 50%*	**ASTM D 3306**
Aluminio	-1,10	-1,60	**- 0,20**	**Máx. 0,60**
Acero	-7,60	-15,20	**- 0,02**	**Máx. 0,30**
Cobre	-0,10	-0,28	**- 0,04**	**Máx. 0,30**
Hierro	-19,20	-27,30	**0,02**	**Máx. 0,30**
Latón	-0,10	-0,76	**- 0,03**	**Máx. 0,30**
Soldadura	-1,10	-13,50	**- 0,07**	**Máx. 0,60**

Los resultados obtenidos se presentan en mg/cm^2. Un resultado positivo indica una ganancia neta por la formación de una capa protectora estable sobre la superficie del metal. En la última columna se muestran los valores máximos de corrosión permitidos por la norma.

Especificaciones:

ASTM D-4985-94	UNE 26-361-88
ASTM D-3306-94	SAE J 1034
ASTM D-1177-65	MAN 324 SNF
INTA 157413	VOLVO 12 86 083
BS 6580	SCANIA TI 02-980813 T/B/M
FS O-A 548 D	MB 325.0
VW TL-774 D	

Materiales compatibles:

Luzar Orgánico 50% es compatible con los materiales habitualmente usados en circuitos térmicos. La siguiente tabla muestra plásticos, sellantes y elastómeros que son compatibles con el producto. Los datos han sido recogidos de bibliografía específica y ensayos propios.

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Nombre	Abreviatura
Hule-Caucho de isobuteno-isopropeno	IIR
Hule-Caucho de cloropropeno	CR
Hule-Caucho terpolímero de etileno-propildieno	EPDM
Elastómeros fluoro carbonados	FPM
Polisopropeno natural hasta 80ºC	NR
Hule-Caucho de poli(nitrilo-butadieno)	NBR
Poli-oximetileno	POM
Poliamida hasta 115ºC	PA
Poli-butileno	PB
Polietileno alta/baja densidad	PE-LD/PE-HD
Polietileno reticulado	VPE
Polipropileno	PP
Poli (tetrafluoroetileno)	PTFE
Poli (cloruro de vinilo) rígido	PVC h
Silicona	Si
Hule-Caucho de estireno-butadieno hasta 100ºC	SBR
Poliéster insaturado (termofijo)	UP

Resinas fenólicas, PVC plastificado y poliuretanos no son compatibles con *Luzar Orgánico 50%*.

El Zinc no es compatible con mezclas de glicoles y agua por lo que debe de ser evitado siempre que sea posible ya que podría ser atacado y disuelto por el etilenglicol.

Modo de empleo:

El producto se presenta listo para usar. No diluir ya que no se podrían garantizar sus propiedades anticorrosión.

Su formula orgánica exenta de silicatos permite largos periodos de inactividad de los equipos sin dar lugar a precipitaciones en forma de gel. De esta manera el circuito queda permanentemente protegido y se evitan precipitaciones que pueden dañar u obturar el circuito en la puesta en marcha.

Presentación:

El producto se suministra en contenedores IBC de 1.000 litros, bidones de 210 litros y envases de 5 litros.

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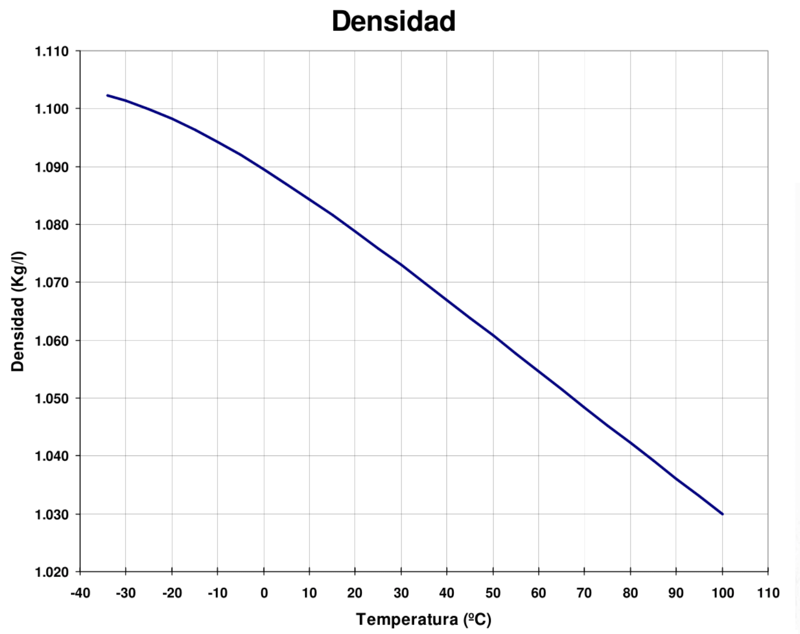

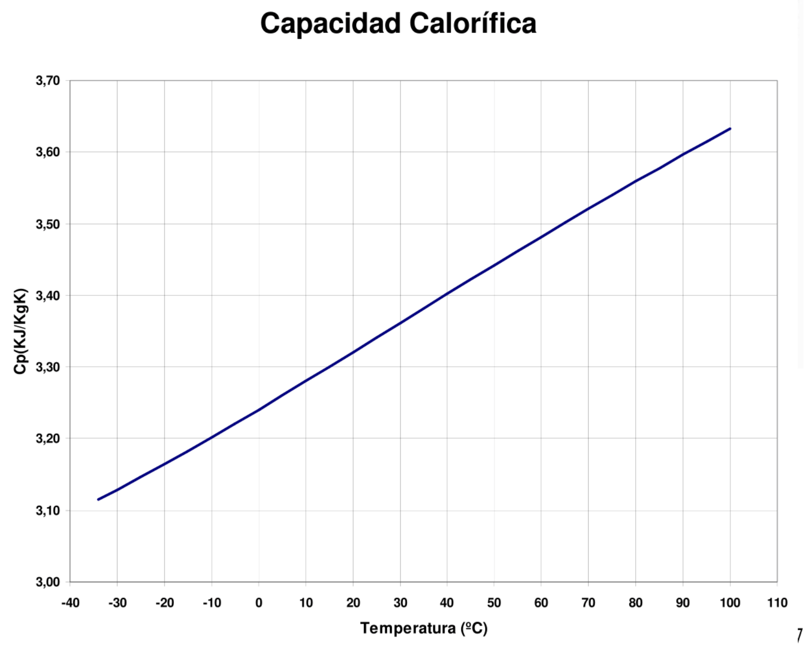

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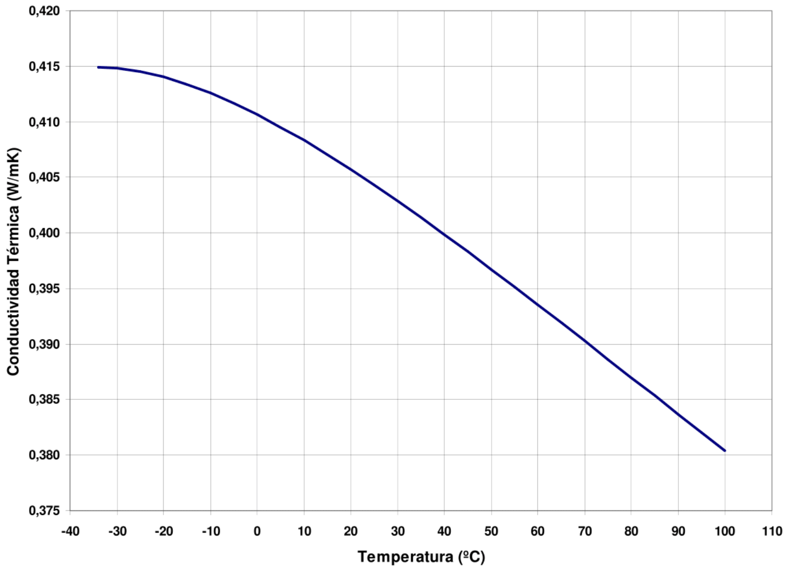
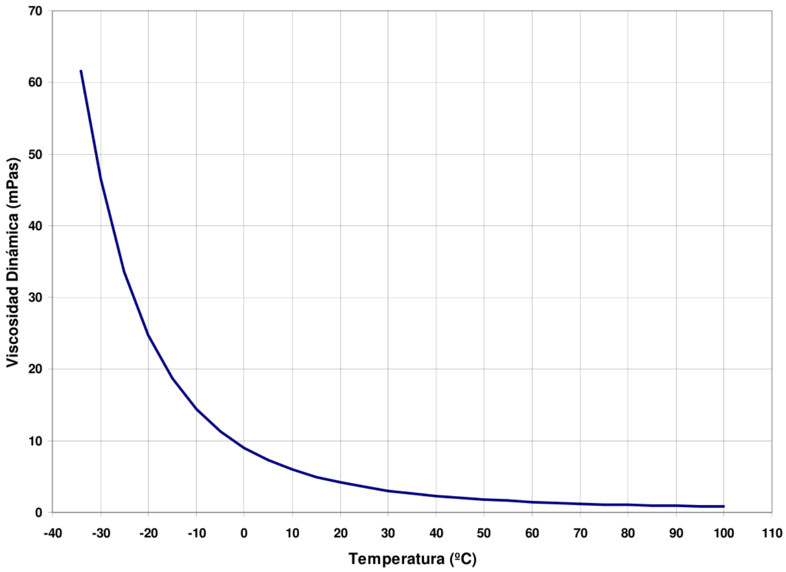
Conductividad Térmica



Viscosidad Dinámica



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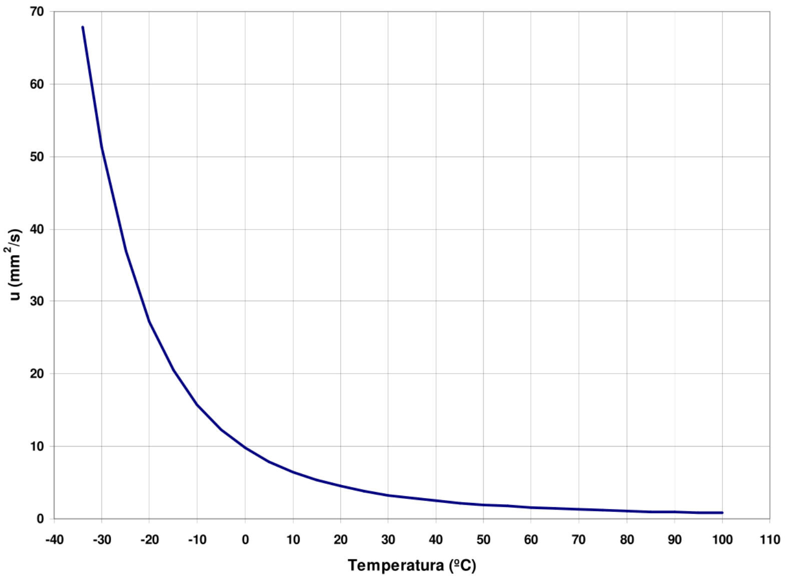
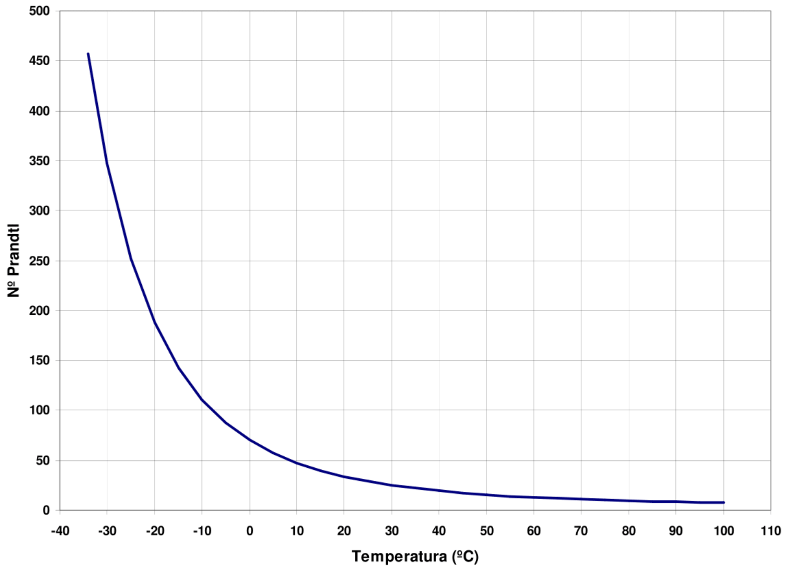
Viscosidad Cinemática



Nº Prandtl



Vacuum Pump

Technical Data

Displacement	
50Hz	5.8 m3h-1 / 3.4 ft3min-1
60Hz	7.0 m3h-1 / 4.1 ft3min-1
Speed (Pneurop 6602)	
50Hz	5.1 m3h-1 / 3.0 ft3min-1
60Hz	6.2 m3h-1 / 3.7 ft3min-1
Ultimate pressure	2.0 x 10-3 mbar / 1.5 x 10-3 Torr
Ultimate pressure GB I	3.0 x 10-2 mbar / 2.3 x 10-2 Torr
Ultimate pressure GB II	1.0 x 10-1 mbar / 7.5 x 10-2 Torr
Ultimate Pressure with Fomblin®	2.0 x 10-2 mbar / 1.5 x 10-2 Torr
Max inlet pressure for water vapour	50 mbar / 38 Torr
Max water vapour pumping rate – GB I	60 gh-1
Max water vapour pumping rate – GB II	220 gh-1
Max allowed outlet pressure	0.2 bar gauge / 2.8 psig
Max allowed inlet and gas ballast pressure	0.5 bar gauge / 7 psig
Motor power 50/60Hz	450 / 550W
Power connector 1-ph	IEC EN60320 C13
Nominal rotation speed 50/60Hz	1500 / 1800rpm
Weight (without oil)	25 kg / 55 lb
Oil capacity min/max	0.42/0.7 litres
Recommended oil	Ultragrade 19
Inlet flange	NW25
Exhaust flange	NW25
Noise level	48 dB(A) @ 50 Hz
Operating temperature range	12 – 40 °C

III Drawings

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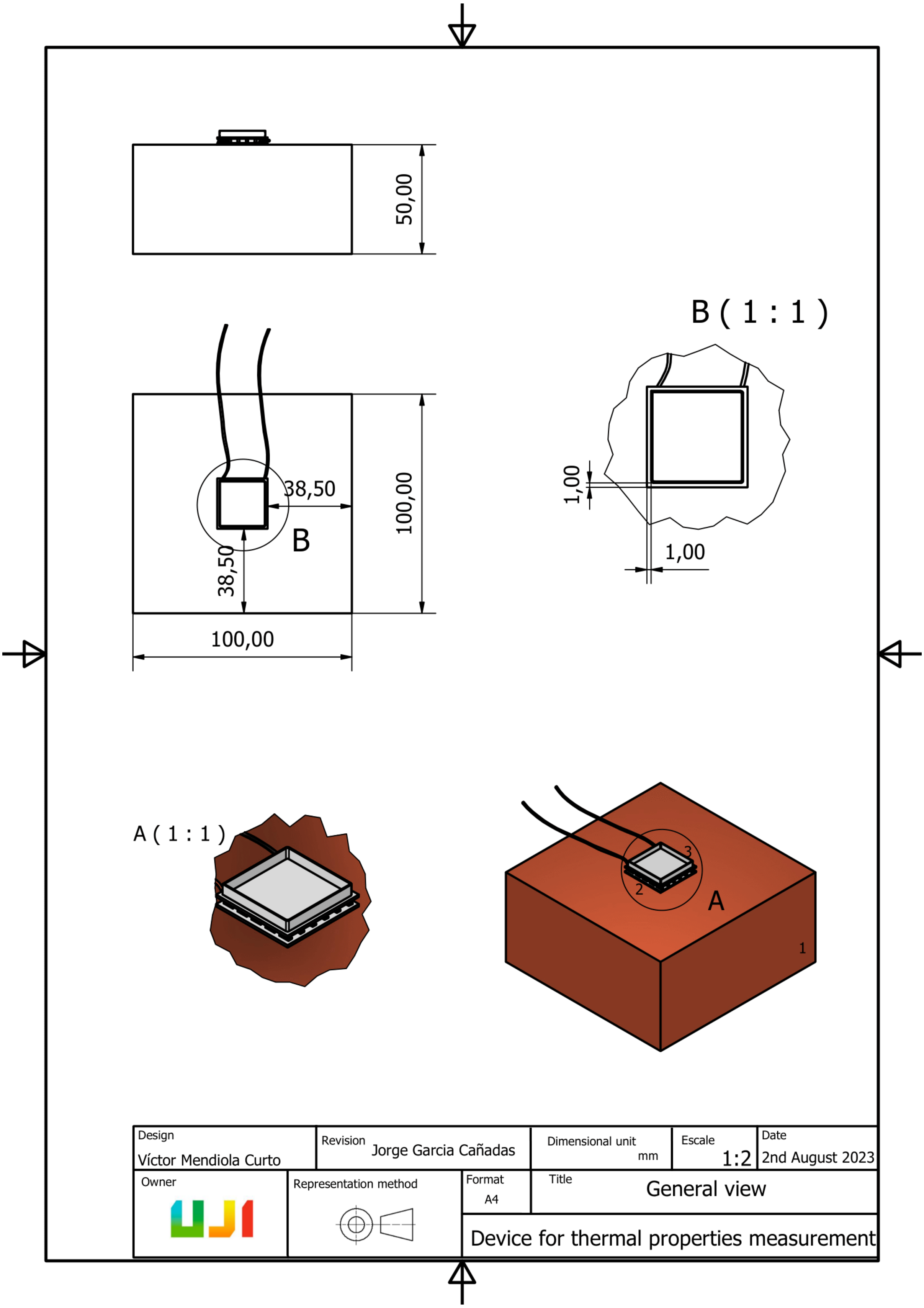
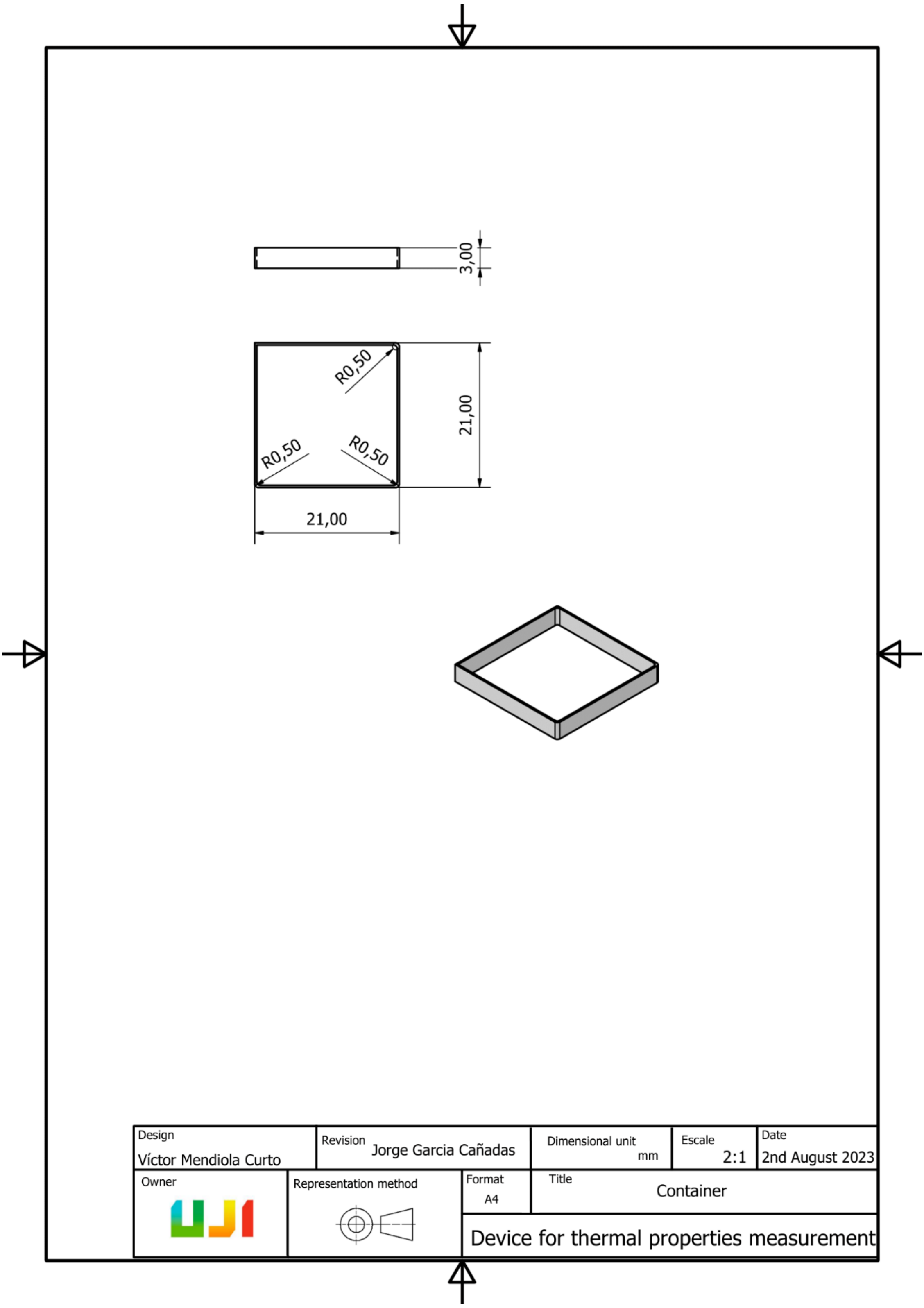
1. General device view



2. Container


3,00
R0,50
R0,50
R0,50
21,00
21,00
Design
Víctor Mendiola Curto
Revision
Jorge Garcia Cañadas
Dimensional unit
mm
Escale
2:1
Date
2nd August 2023
Owner
Representation method
Format
A4
Title
Container
Device for thermal properties measurement

IV Specifications

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1. Introduction

This document sets out both the conditions to be followed in each part of the project and the technical requirements and specifications to be met by the components and the software used.

It is important that the work methodology be as precise as possible, as maximum rigor is required in a study of this type. Slight changes can have a significant impact on the measurements. Not adhering rigorously to the description below could compromise the result obtained.

2. Components

TE Module

A TE module with the following thermal and electrical specifications is required:

1) Input amperage: $I_{max} = 3{,}0\ A$
2) Maximum heat that can be absorbed: $Qc_{max} = 14{,}4\ W$
3) Voltage at I_{max}: $V_{max} = 8{,}6\ V$
4) Difference in temp. between sides: $DT_{max} = 67°C$
5) Maximum temp: $T_{max} = 125°C$

Regarding the dimensions, the employed module must have ceramic plates on both sides (cold and hot) that are square-shaped and measure 23x23 mm. It should also have a height of 3.6 mm. Furthermore, it should consist of a total of N=70 pairs of couples. The procedure to calculate the contact ratios has been explained in section 4.2.1 of the report; it is important to verify the module dimensions to obtain accurate ratios.

The module must have soldering material attached to one of its faces to connect it to the heat sink. This material should be acquired from Custom TEs, with the reference number ref. 07111-5L31-03CJ-T1.

Heat sink

A solid copper block is required. In this project, a block measuring 10x10x5 cm has been used to ensure proper heat dissipation. It is recommended to use a block of a similar size. If the block is larger, it may complicate the handling of the device during measurements and if it is smaller, it might not dissipate heat effectively.

Container

A steel *AISI304* container with a thickness of 0.3 mm, measuring 21x21 mm on the outside, and 3 mm in height is required. The dimensions can be found in the drawings section of this project.

Glue

Cyanoacrylate adhesive is needed to attach the container to the TE module. In this project, *Loctite Super GLUE-3* is used for this purpose.

3. Software

Nova 1.11.2

This software is used as a controller for the Autolab potentiostat. It gathers all impedance data and allows for subsequent exportation to be processed in MATLAB.

Picolog

Software used for recording and monitoring temperatures. This system enables real-time viewing of the recorded temperatures from thermocouples, with the ability to monitor up to 8 channels simultaneously. The sixth version of the software is utilized.

Microsoft Excel

Essential for preliminary calculations. Seebeck coefficients and ratios are obtained using this software, implementing the equations described in this project.

MATLAB

This software is necessary for deriving the parameters under study. The version used is *MATLAB R2020*.

4. Components and hardware

Potentiostat

An *Autolab PSTAT302N* potentiostat has been used for all impedance spectroscopy measurements.

Fig. 1 Potentiostat used in the project.[1]

The technical specifications of the device are as follows:

Potential range in volt	-10 V to 10 V
Compliance voltage range in volt	± 30
Maximum current in ampère	± 2
Number of current ranges	9
Number of current ranges remarks	10 nA to 1 A
Modular instrument	true
Maximum number of modules	8
Analog integrator	false
Multichannel instrument	false
Maximum number of channels	1
Potential and current accuracy	V: ± 0.2% ± 2 mV and i: ± 0.2% ± 0.2% of current range
Potential resolution	0.3 µV (gain 1000)
Current resolution	0.0003% (of current range)
Maximum bandwidth in Hz	1 MHz
Input impedance in Ohm	1 TOhm
Dimensions in mm (W/H/D)	520/160/420
Dimensions remark	Without cables and accessories
Weight of the instrument in kg	18

Fig. 2. Technical specifications of the potentiostat.[1]

Vacuum chamber

All measurements at room temperature have been conducted in a hermetic vacuum chamber measuring 400x400 mm, which also acts as a Faraday cage. This chamber was manufactured by Cryovac Anevac in 2016, and its reference number is 51617.

Vacuum pump

For measurements requiring a vacuum environment, an Edwards RV5 vacuum pump has been utilized. It has a throughput of 6.2 m^3/h and operates quietly, producing noise levels below 50dB. Further specifications can be found in the appendix.

Thermocouple data logger

A thermocouple data logger will be used to measure the temperatures. The model used is the TC-08 from Pico Technology and is capable of having 8 thermocouples at a time. It can measure over a wide temperature range from –270 to +1820 °C very precisely.

Fig. 3. Thermocouple data logger. [2]

Thermocouples

To measure the temperature, 4 K-type thermocouples long enough to go from the computer to the vacuum chamber have been used is a model SE030 with thermocouples cables of 1.5mm diameter and 2m long. The plug type is flat pin mini-plug.

Thermal Grease

To seal the ends of the thermocouples and reduce the effects of convection, RS PRO Thermal Grease model RS 554-311 with a conductivity of 0.65W/mK is used. More product information can be found in the annexes.

Micropipette

A calibrated micropipette is used to introduce the liquid into the container. It is necessary that it is accurate as all measurements are made with 1mL of liquid.

Heating plate

A magnetic stirrer with heating is used to carry out the soldering of the TE module. The one used in the project is an IKA model C-MAG HS 7 with a temperature range of between 50 and 500ºC.

Oven

The oven used in this project for the part where the material change is analysed is a *Labolan IDL CI80*. Its the temperature range goes from 5 to 80 ºC.

5. Experimental procedure

5.1. Setup building

Welding

1) Clean the copper block with soap and water and let it dry.
2) Place the block on the hot plate and raise the temperature to 115ºC.
3) Place a sample of the soldering material on top of the block and wait for it to melt, this is an indicator that it is ready for soldering.
4) Place the TE module on top of the block and press lightly for a few minutes to ensure that it is soldered correctly.
5) Turn off the board and let it cool at room temperature for at least 6 hours.

Glue the container

1) Clean the container with soap and water and dry it properly.
2) Clean the surface of the TE module with a cotton swab and acetone.
3) Place the container on the TE module.
4) Apply pressure by placing an object on the container to ensure that it does not move.
5) Apply the cyanoacrylate to the outer edges of the container, removing excess glue with a cotton swab.
6) When the glue has been properly applied, wipe off any excess glue and allow to dry for 24 hours.

5.2. Experimental procedure

In this section we will distinguish four experimental processes, explained in section 5 of the report. In each of these, certain parameters are extracted which must be implemented in the MATLAB code in order to finally find the thermal conductivity and diffusivity of the liquid under study.

Characterisation of the vacuum suspended module

1) The module must be placed inside the vacuum chamber hanging from the cables.
2) Connect the wires of the TE module to the pins of the potentiostat.
3) Carefully place a thermocouple on each side of the TE module with some thermal grease to seal the ends. This can be done with the help of a toothpick.
4) Close the chamber door and switch on the compressor.
5) The internal pressure should be 10-5 mbar. Set and wait for it to stabilise.
6) Measure with the potentiometer.
7) Switch off the compressor and wait for it to stabilise again at atmospheric pressure.
8) Disassemble the setup.

Characterisation of the welded setup

1) Place the setup inside the vacuum chamber.
2) Connect the cables of the TE module to the pins of the potentiostat.
3) Place one thermocouple on top of the copper block and one on the surface of the TE module.
4) Put thermal grease on the ends of both thermocouples.
5) Close the vacuum chamber door.
6) Measure with the potentiometer.
7) Dismantle the setup.

Analysis with liquids

1) Place the setup inside the vacuum chamber.

2) Connect the cables of the TE module to the pins of the potentiostat.
3) Clean the inside of the container with a cotton swab.
4) Carefully place 1mL of sample into the container using the calibrated micropipette.
5) Place the paper lid to reduce the effects of convection.
6) Measure with the potentiometer.
7) Open the door.
8) Carefully remove the lid.
9) Remove the liquid and clean the container.

Analysis of the phase change material in the oven

1) The procedure is the same as above but with everything in the oven.
2) When the door is opened and closed, wait long enough for the internal temperature to stabilise.

5.3. Other considerations

1) It is necessary to wear gloves when setting up the setup.
2) The temperature should be as constant as possible. Between each test, check the temperature by adjusting the thermostat and allowing it to stabilise. In the case of this project, the temperature has been 24.5 ± 0.5ºC always, except in the case of Phase Change material.
3) When carrying out the tests in the furnace with the PCMat, take precautions against burns with the oven.
4) When working with flammable or toxic liquids, take extreme precautions.

6. Measurements

For impedance measurements, the Nova 1.11 software is used, which monitors and records the data obtained via the potentiostat. For impedance analysis, the IS mode is selected.

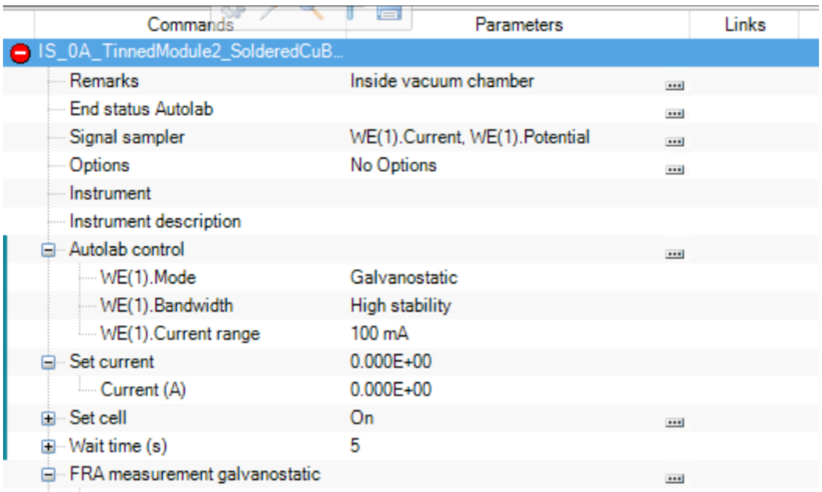

Fig. 4. Impedance spectroscopy selection.

To set the frequencies, the following parameters are available for all impedance spectroscopies in the drop-down menu of the "*FRA measurements galvanostatic*" option. 50 logarithmically distributed samples with frequencies between 0.002 and 10000 Hz are to be taken. A current intensity of 20mA will be used.

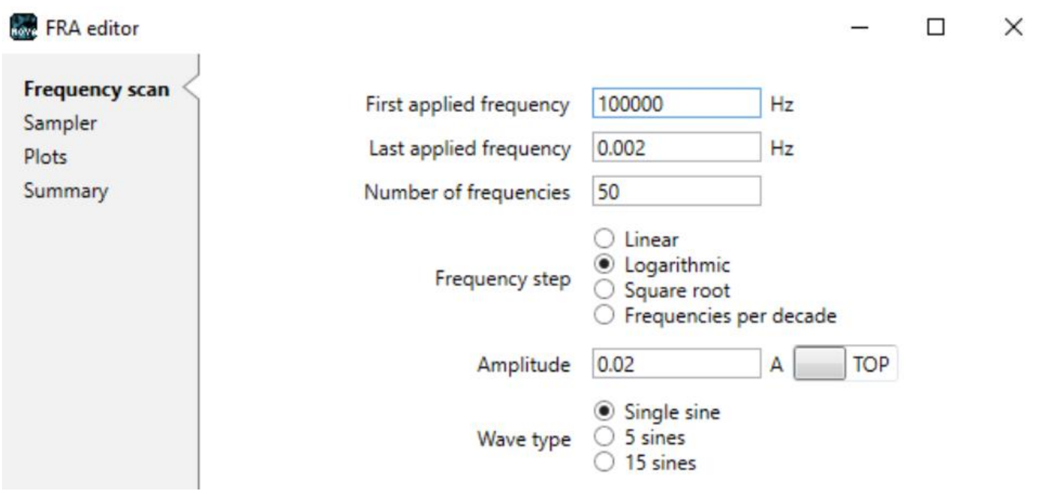

Fig. 5. Frequencies selection

On the other hand, 2 integration cycles are imposed to make the repeatability between analyses more accurate.

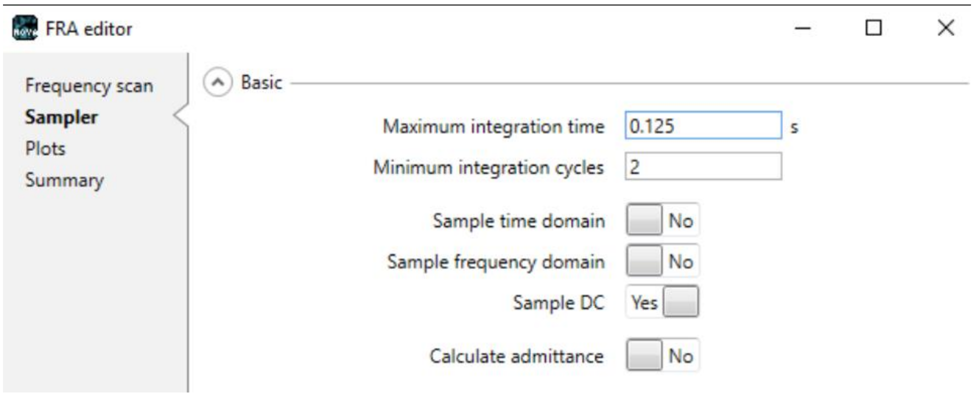

Fig. 6. Integration cycles selection.

Once the spectrum has been obtained, the impedance values are extracted in text format so that they can be introduced into the numerical calculation software with which the parameters will be obtained. Once they have been entered, the only thing to do is to follow the instructions provided by the code itself. The following image shows an example of the data.

100000	2.55541	0.15744
69643	2.55345	0.108158
48502	2.55256	0.0738611
33778	2.55307	0.0498604
23524	2.55404	0.0332763
16383	2.55527	0.0218908
11410	2.55657	0.0140584
7946	2.5566	0.00857426
5533.8	2.55762	0.0046773
3853.9	2.55842	0.00163315
2684	2.55926	-0.000653798
1869.2	2.56003	-0.00257944
1301.8	2.56115	-0.00417822
906.6	2.56248	-0.00534446
631.39	2.56423	-0.00613702
439.72	2.56634	-0.00658944
306.23	2.56842	-0.00691823
213.27	2.57061	-0.00729641
148.53	2.57285	-0.00759173
103.44	2.57491	-0.00843272
72.038	2.57661	-0.00897638
50.17	2.57843	-0.00978205
34.94	2.58053	-0.0107884

Fig. 7. In the left-hand column the frequencies. In the middle column, the real Z impedance. On the right the imaginary impedance.

7. References

[1] AutoLab PGSTAT302N. (2021, 14 noviember). Metrohm.

https://www.metrohm.com/en_gb/products/a/ut30/aut302n_s.html

[2] TC-08 ThermoCouple Data Logger | Pico Technology. (s. f.).

https://www.picotech.com/data-logger/tc-08/thermocouple-data-logger

V Budget

This document of the project presents the cost of the various parts of the project.

For the non-expendable items, a certain useful life has been considered from which the percentage of use corresponding to the project is calculated.

Section 1 contains the computing elements, the computer and the software used. In section 2 all the laboratory instrumentation, both the elements for impedance measurements and those used for the assembly of the apparatus. Section 3 shows the cost of the parts of the device. Finally, in section 4, the cost of the personnel working hours. See all the costs in Table 1.

Section	Quantity	Element	Description	Unit price (€)	Service life (months)	Time of use (months)	Percentage of use (%)	Total prices (€)
1	1	Lab computer	*Computer*	610,00 €	48	3	6,25%	38,13 €
	1	Calculation and text software	*Microsoft Office*	67,2 €/year	12	2	16,67%	11,20 €
	1	Numerical computing	*MatLab*	860 €/year	12	2	16,67%	143,33 €
	1	Impedance spectroscopy software	*Nova 11.2*	Inlcluded with potentiostat				0,00 €
	1	Thermal analysis software	*Picolog*	Inlcluded with data logger				0,00 €
							TOTAL S1	**192,66 €**
2	1	Potentiostat	*Autolab PSTAT302N*	12.578,36 €	80	2	2,50%	314,46 €
	1	Vacuum chamber	*Cryovac Anevac*	5.620,17 €	80	2	2,50%	140,50 €
	1	Vacuum pump	*Edwards RV5*	8.862,18 €	80	1	1,25%	110,78 €
	1	Thermocouple data logger	*TC 08 Pico Tech*	247,62 €	80	2	2,50%	6,19 €
	2	Thermocouples	*SE030 Pico Tech*	9,92 €				19,84 €
	1	Thermal grease	*RS PRO RS 554-311*	19,94 €				19,94 €
	1	Micropipette	*Transferpette*	255,00 €	80	2	2,50%	6,38 €
	1	Oven	*Labolan IDIL CI80*	834,00 €	80	1	1,25%	10,43 €
	1	Heating plate	*IKA C-MAG HS 7*	594,15 €	80	0,5	0,63%	3,71 €
	1	Cyanocrilate glue	*Loctite Super GLUE 3*	5,13 €				5,13 €
							TOTAL S2	**637,35 €**
3	1	TE module	*Custom thermoelectrics*	49,65 €				49,65 €
	1	Heat sink	*Copper block*	130,00 €				130,00 €
	1	Container	*Demetal SL*	16,83 €				16,83 €
							TOTAL S3	**196,48 €**
4	300	Student's labour	*Project realisation*	15,00 €				4.500,00 €
	30	Supervisor	*Project supervision*	45,00 €				1.350,00 €
							TOTAL S4	**5.850,00 €**
						TOTAL		**6.876,49 €**
						TOTAL+21% VAT		**8.320,55 €**

Table 1. Description and costs of each part of the project divided into sections.

The total cost of the work is **eight thousand three hundred twenty euros and fifty-five cents (8,320.55 €)**.