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Supplementary Material to "Development of a low-cost system for energy conversion coefficient measurements based on thermomagnetic phenomena"

1 Appendices

1.1 Arduino Code - Temperature Reading and relay controler

Description of the Arduino code used to measure the temperature difference between two points of the experimental system will be described.

```
    // Definition of the analog pins for the NTC sensors
const int ntcPin1 = A0; // Pin for the first NTC sensor
const int ntcPin2 = A1; // Pin for the second NTC sensor

    // Definition of the relay pin
const int relayPin = 7; // Digital pin for the relay module
// Temperature difference limit for heater activation
const float deltaT − limit = 5.0; // Temperature difference limit for heater activation

    // NTC 10K parameters
const float Rref = 10000.0; // Reference resistance (10K)
const float T0 = 298.15; // Reference temperature in Kelvin (25°C)
const float Beta = 3950.0; // Beta coefficient of the NTC
const float R0 = 10000.0; // Resistance of the NTC at T0 (10K)

    void setup()
// Initialize serial communication
Serial.begin(9600);

    // Set the relay pin as output
pinMode(relayPin, OUTPUT);
digitalWrite(relayPin, LOW); // Ensure the relay starts off

    void loop()
// Read the analog values from the sensors
int adcValue1 = analogRead(ntcPin1);
int adcValue2 = analogRead(ntcPin2);

    // Convert the analog values to resistance
float Rntc1 = Rref / (1023.0 / adcValue1 - 1.0);
float Rntc2 = Rref / (1023.0 / adcValue2 - 1.0);

    // Calculate the temperature in Kelvin using the NTC equation
float T1 = 1.0 / (1.0/T0 + (1.0/Beta) * log(Rntc1/R0));
float T2 = 1.0 / (1.0/T0 + (1.0/Beta) * log(Rntc2/R0));

    // Convert Kelvin to Celsius
float Tc1 = T1 - 273.15;
```

```
float Tc2 = T2 - 273.15;

        // Calculate the temperature difference
float deltaT = abs(Tc1 - Tc2);

        // Control the relay based on the temperature difference
if (deltaT > deltaT-limit)
digitalWrite(relayPin, HIGH); // Turn on the heater
else
digitalWrite(relayPin, LOW); // Turn off the heater


        // Send the data to the user interface via serial communication
Serial.print(Tc1); // Temperature from sensor 1
Serial.print(",");
Serial.print(Tc2); // Temperature from sensor 2
Serial.print(",");
Serial.print(deltaT); // Temperature difference
Serial.print(",");
Serial.println(digitalRead(relayPin)); // Relay state

        // Wait for 0.5 seconds before repeating
delay(500);
```

1.2 User interface

The user interface was developed using open-source Python, with the goal of being simple and intuitive. All parameters are clearly displayed and can be easily controlled by the user through specific buttons. The results can be saved in various file formats, as specified by the user.

Below the funcionlities of each botton is present:

Current (A): This function allows control of the current supplied to the system's heating cartridge. The user can enter the desired value or use the arrows to increase the current in increments of 0.1 A. The system limits the current to prevent the cartridge from being overloaded and burning out.

Heat ON and Heat OFF buttons: These buttons can be used to turn the system's current on or off.

Stop and Save button: This button allows the user to interrupt the measurement process and immediately sends a command to save the current data from the graphs into a file in a format previously chosen by the user.

Data Directory Path button: The data can be saved in different formats, such as .txt, .dat, or .csv, for further analysis.

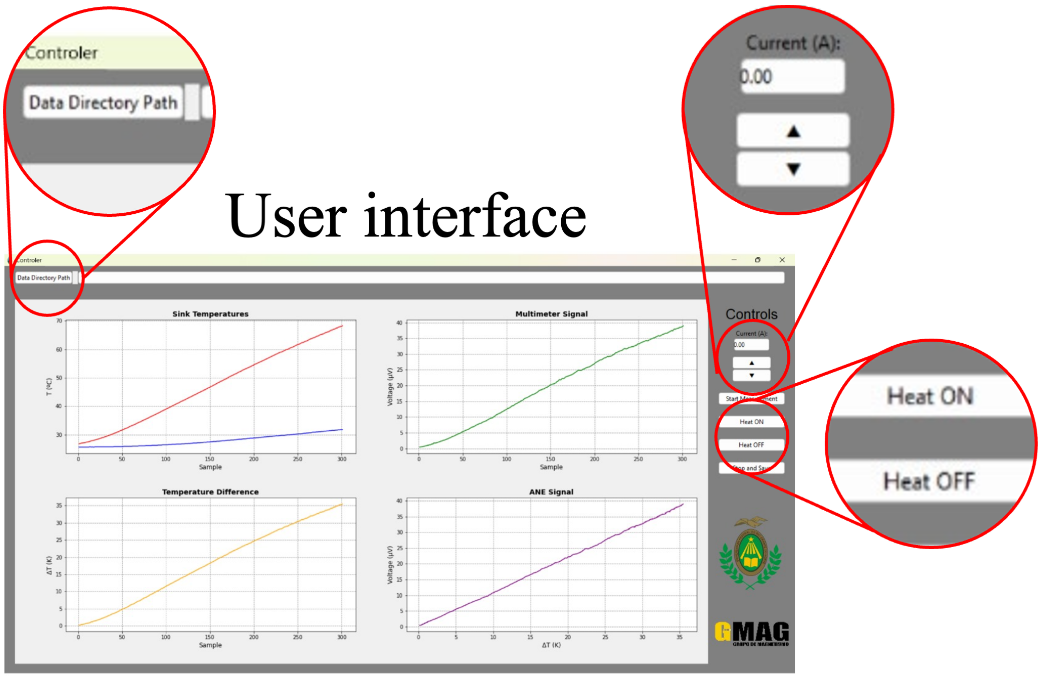

Figure 1: Image of the user interface proposed in this study.

1.3 Temperature measurements

Figure 2 depicts the temperature of the hot sink (T_h), temperature of the cold sink (T_c) and the temperature difference (D_T) as a function of time. In particular the data are related to the NiFe thin film, 60 nm thick (Fig. 2 (a)) and TAG (Fig. 2 (b)). Figure 2 (b) shows the temperature comparison between the NTC (hot sink) and the K-type thermocouple. In particular, these measurements were used to calibrate the NTC sensor and obtain the best values for the β constant.

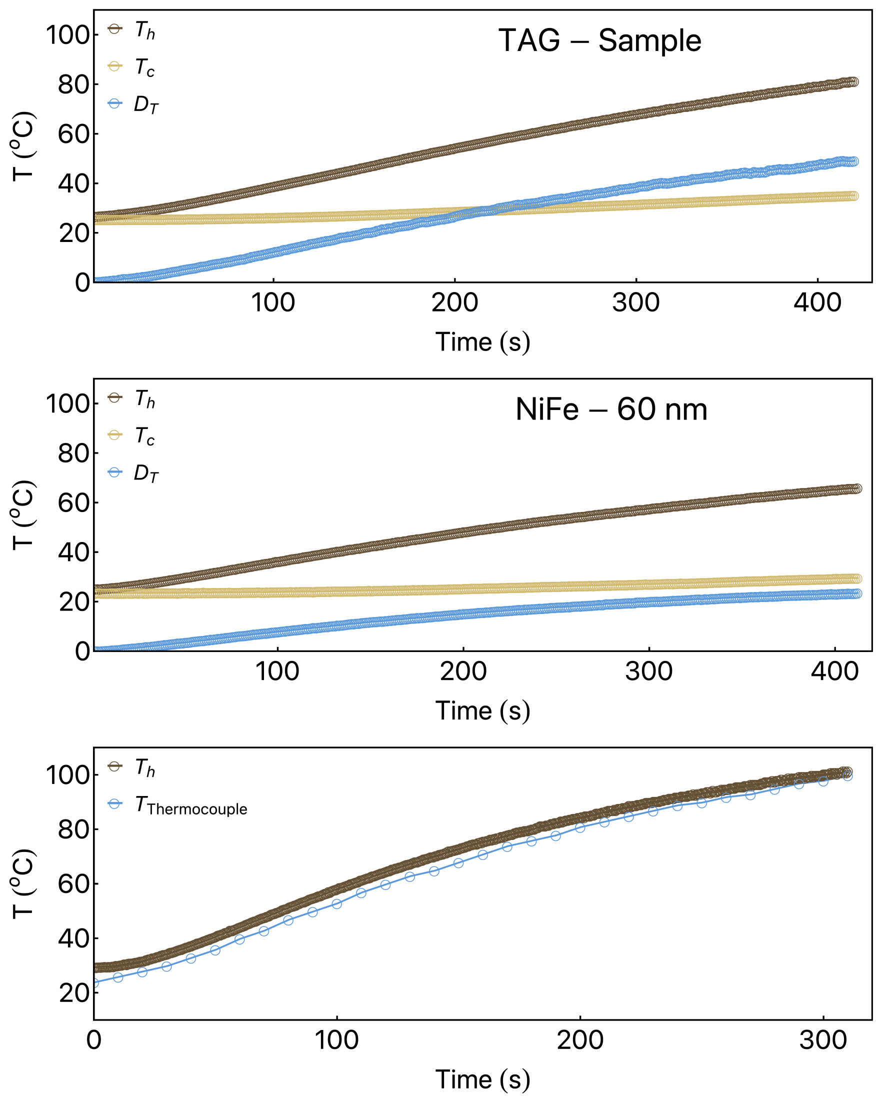

Figure 2: (a) Temperature of hot sink (T_h), cold sink (T_c) and temperature difference (D_T)between the NTC sensors obtained during the NiFe 60 nm thick thin film measurements. (b) Similar plot for the TAG sample. (c) Comparison between the T_h and a commercial K-type thermocouple used to calibrate the β constant in the system.

1.4 Experimental Procedure Simulation for Students

Experiment – Thermoelectric Measurement

Objectives:
To understand one of the methods of converting thermal energy into electrical energy through measurements of the Anomalous Nernst Effect (ANE).

Specific Objectives:

- Understand concepts related to energy conversion.
- Understand modern physics concepts related to thermomagnetic phenomena;
- Develop skills and competence in the analysis of experimental data;
- Calculate the ANE coefficient for a ferromagnetic system.

Materials Used:

- ANE coefficient measurement system;
- Digital multimeter (5½ digits);
- Current source (9V – 100 mA);
- Computer for interface.

Theoretical Background

{\color{red} Thermomagnetic and thermoelectric phenomena involve the direct conversion of temperature differences within a material into electrical energy. These effects have attracted significant attention due to their high potential for technological applications, especially in the field of clean energy generation. Among the various thermoelectric effects, the Anomalous Nernst Effect (ANE) stands out for its ease of detection and its potential for converting waste heat into usable electrical power. The ANE occurs when a temperature gradient is applied perpendicular to the plane of a ferromagnetic material — that is, between its top surface and bottom. If the material exhibits spontaneous magnetization or is magnetized by an external magnetic field, an electric voltage can be generated across its lateral edges, as illustrated in Fig. 1(b). Mathematically, the phenomenon is represented by the following equation,

$$\vec{E}_{ANE} = -S_{ANE}\left(\hat{m} \times \vec{\nabla}T\right) \qquad (1)$$

Where $\hat{m}$ is the unit vector in the direction of magnetization $\vec{m}$ and S_{ANE} is the effective ANE. Considering that the sample is magnetically saturated during the entire measurement process and that the magnetization is aligned perpendicular to the electrical contacts as shown in Fig.1 (b), we can simplify Eq. 1 in the form,

$$|E|_{ANE} = -S_{ANE}\Delta T_a/t_a \quad (2)$$

where $\nabla \mathrm{T_a} = \Delta \mathrm{T_a}/\mathrm{t_a}$, and $\Delta \mathrm{T_a}$ is the temperature difference between the top and bottom parts of the thin film and substrate assembly, with total thickness t_a, i.e., $t_a = t_f + t_s$, where t_f is the thickness of the ferromagnetic film and t_s is the thickness of the substrate. Thus, the maximum voltage ($\mathrm{V_{max}}$) measured is given by the following expression:

$$\mathrm{V_{max}} = \mathrm{S_{ANE}}\Delta \mathrm{T_a}\mathrm{L}/\mathrm{t_a} \quad (3)$$

As we can observe, the voltage generated by the system should follow a linear behavior with the temperature difference ΔT_a. In other words,

$$V_{max} = \frac{S_{ANE}\mathrm{L}}{\mathrm{t_a}}\Delta T_a \quad (4)$$

Where L is the distance of the electric contacts. Consequently, if the V_{max} as a function of ΔT_a is measured, the angular parameter (AP) is related to the S_{ANE} through,

$$\mathrm{AP} = \frac{\mathrm{S_{ANE}}\Delta \mathrm{T_a}\mathrm{L}/\mathrm{t_a}}{\Delta \mathrm{T_a}} \quad (5)$$

Or

$$S_{ANE} = \frac{AP \cdot t_a}{L} \quad (6)$$

Therefore, it is possible to infer the S_{ANE} through the experimental data measured during the proposed experiment.

Experimental Procedure

Step 1: Insert the sample into the sample holder, ensuring good electrical contact between the sample and the gold spring contacts.

Step 2: Connect the electrical terminals to the digital multimeter (set to DC voltage mode). Ensure that both the Arduino module and the digital multimeter are connected to the computer.

Step 3: Open the software and select the directory where the data will be saved.

Step 4: Set the current for the heater and press the Heat ON button. The system will begin measuring the thermomagnetic voltage (ANE voltage) as a function of the temperature difference. Wait until the temperature at the hot sink (T_h) reaches approximately 80 °C, then press the Stop and Save button.

Step 5: Navigate to the selected directory and use a graphing program to plot the data.

Results and Discussion

Q1: Plot the experimental results and perform a curve fit to obtain the Angular Parameter (AP). It may be necessary to disregard the initial and final data points. Consider the period in which the desired linear behavior is observed.

Q2: Use Eq. (6) to calculate the effective ANE coefficient of the sample. Consider $t_a = 178\mu m$ (combined thickness of the glass slide and TAG ribbon). Also, use $L = 12\ mm$. Remember that the value of S_{ANE} must be expressed in μV/K. Note that a temperature variation in Kelvin is equivalent to a variation in Celsius degrees.

Q3: Compare the obtained ANE coefficient with values reported in the literature. Search online and find articles that discuss similar values for samples comparable to those used in this experimental procedure.

Q4: Discuss other methods of converting thermal energy into electrical energy that could be used for clean energy generation.

Q5: What are some other ways to turn heat into electricity that could be used as sources of clean energy? List and briefly explain at least two different methods..

Q6: Be creative! Imagine and describe a piece of equipment or a device that could work using the clean voltage generated by the ANE. What could it be used for?