Thermoelectric Generator Characterization

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***Abstract*—Thermoelectric generators (TEGs) are solid-state devices that exploit the Seebeck effect to generate electric current from a temperature difference. The objective of this paper is to develop an automated system to collect data on TEGs and characterize the internal resistance and Seebeck coefficient of a new fiber-based flexible TEG design.**

I. INTRODUCTION

TEG are mainly used in the context of energy harvesting, both on an industrial scale (generally large amounts of energy from chemical reactions) and for low power electronic devices (e.g., batteryless or hybrid systems). Wearable electronics, i.e., powering devices with body heat, is becoming popular in this field. However, having rigid TEGs was a limitation for developments in this field, as they are particularly uncomfortable when worn, a problem solved by the development of **flexible TEG modules** [1]. These use fiber-based materials that allow the TEG to be bent and adapted to curved surfaces, such as an arm.
Currently, the TEG model we received has no characterization, so it is not possible to know how it behaves in terms of efficiency and power generated. Characterization is essential to understand how the TEG behaves under real conditions and to be able to use it in a power generation system. The efficiency of a TEG is governed by the dimensionless figure of merit **Zero Temperature Difference** (**ZT**), which depends on the material's **Seebeck coefficient, electrical conductivity and thermal conductivity**. Improvements in any of these parameters can lead to enhanced performance, but they often involve trade-offs, such as increased electrical conductivity leading to higher thermal conductivity, which can reduce the temperature gradient needed for power generation. The ideal TEG has a high Seebeck coefficient, high electrical conductivity, and low thermal conductivity. The best way to characterize a TEG is to **measure the open-circuit voltage and the current generated with a load resistor**. These data can be used to fit the Seebeck model and find the internal parameters of the TEG.

II. RELATED WORK

The most complete work on TEG is the paper of Tohidi, Holagh and Chitsaz [2] where the authors describe in details the working principle of TEG, the efficiency and the limitations of these devices, starting from thermodynamics principles then focusing on fabrication designs, modeling the TEG as a semiconductor device (also in [3]). One of the most relevant statements is that the **maximum output power of a TEG is achieved when the load resistance equals the internal resistance of the module**, useful when designing actual circuits or find the maximum efficiency of the TEG (related to the figure of merit). Then they explore the possible applications, especially in industrial processes and in the automotive sector (e.g., recovering waste heat from the engine).
We found 3 examples of TEG characterization in the literature, which basically follow the same principles with minor variations.

- Oswaldo Hideo Ando Junior, Nelson H. Calderon and Samara Silva de Souza developed in their work [4] a system to recover the energy from the waste heat of industrial processes. In these cases, the temperature difference is quite high, so the TEG can generate a significant amount of power. In particular they used a configuration of 10 TEG modules in series and 20 in parallel, reaching a **maximum power output of 29W** with a temperature difference of 80°C.
- The same strategy was employed by [5] for characterization, namely measuring with an open circuit and a load resistor. The resulting model of the TEG was linear, both for the internal resistance and the Seebeck coefficient. Ultimately, the **SPICE model** of the TEG was obtained, thus enabling its use in simulations.
- Finally, [6] uses also the same approach, with the additional collection of data regarding thermal conductivity. Their methodology was based on steady-state principles, specifically **insulating the TEG with the heater** and logging the energy required to heat the TEG under load.

III. DESCRIPTION OF THE WORK FOR THE PROJECT

The project was divided into two parts: **developing an automatic system** to get the TEG measurements and **fitting the data** to find the TEG parameters. To have a complete characterization, two types of data are needed: the open-circuit voltage that is measured at the ends of the TEG when a temperature difference is applied and the current that flows through a load resistor.
The tools needed for the acquisition are the following:

- The **STM32 NUCLEO-F401RE board**.
- The **heating and cooling control circuit board**. We used a prototype board on a matrix board.
- **One TEG module** with fan and heatsink on one side and the heating resistor on the other one.
- **Two thermocouples** (installed on the hot and cold sides). We used the MAX6675 module.
- **One bench power supply** (at least rated at $40W$).
- A PC with our **GUI application** to control MCU settings.

The data acquisition procedure is organized as follows.

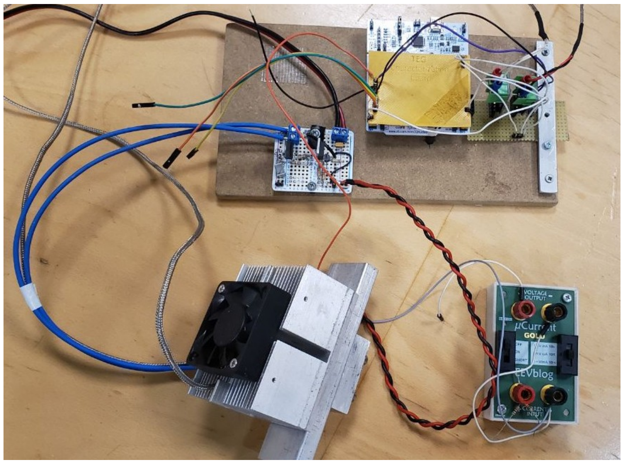

Fig. 1. A photo of the used materials

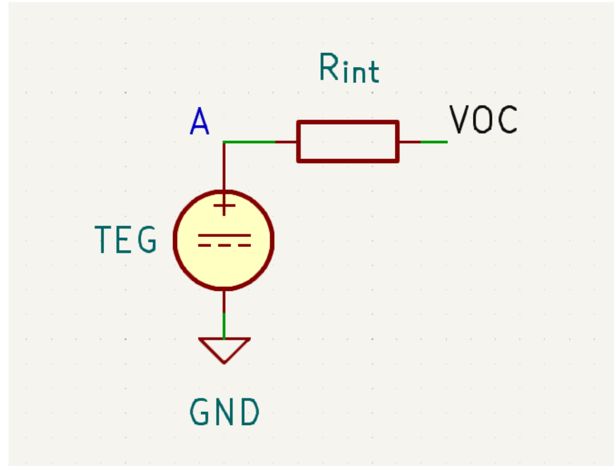

Fig. 2. TEG model in open circuit configuration

1) Power the heating and cooling circuit, connect the STM32 NUCLEO board to the PC and open the control GUI.
2) Set the two target temperatures from the PC and start.
3) Save the acquired data (voltages, currents and temperatures) in CSV format on the PC.

The STM32 uses the UART in DMA mode to communicate with the PC, the SPI to read data from the thermocouples (MAX6675 module), the ADC to read the voltage from the TEGC, and the PWMs to control the fan and temperature of the heating resistor.

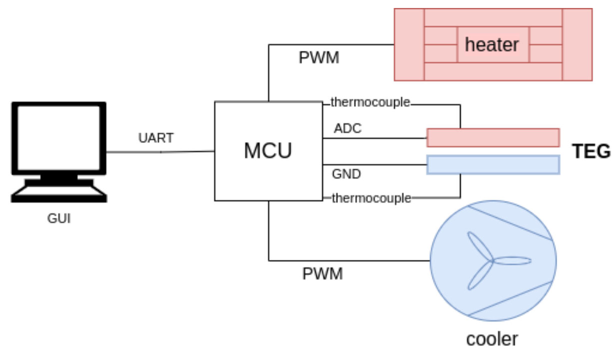

Fig. 3. Open circuit voltage measurement diagram

A. Measurements

TEG characterization requires us to estimate the Seebeck coefficient and the internal resistance. The method we used allowed us to estimate the two parameters with two different type of measurements. The first one is the open-circuit voltage measurement, which allows us to estimate the Seebeck coefficient. The second one is the current measurement, which is needed to define the internal resistance. In this second test we depend on the already estimated Seebeck coefficient.

B. Voltage open circuit measurement (VOC)

The open-circuit voltage (VOC) is the voltage measured at the ends of the TEG with no load connected, in our case, we can measure a voltage only when there is a temperature difference between the TEG surfaces. With this test we want to measure the voltage generation of the TEG alone, and neglect the effect of the internal resistance. The only way to measure point A in figure 2, is to have zero current passing through R_{int}. To make a measurement without absorbing current, we can exploit the fact that the ADC is constructed to have high impedance, and so will limit the current to $5nA$. With this in mind we can neglect this currents and assume that the measurement is done directly in point A.
TEG voltage is generated by the Seebeck effect, and it is proportional to the temperature difference between the hot and cold sides of the TEG, so with this test we can directly estimate the coefficient without considering other factors.
The VOC is given by the following equation:

$$V_{OC} = S \cdot \Delta T \tag{1}$$

where S is the Seebeck coefficient of the TEG and ΔT is the temperature difference between the hot and cold sides. The Seebeck coefficient is a material property that characterizes the voltage generated by a temperature difference, it will be used to calculate the power outut of the TEG.

C. Current measurement

The current generated by the TEG can be measured by attaching a known load resistor to the TEG and is described by the following equation:

$$I = \frac{V_{OC}}{R_{int} + R_{load}} \tag{2}$$

where I is the current generated by the TEG, V_{OC} is the open-circuit voltage of the TEG, R_{int} is the internal resistance of the TEG, and R_{load} is the load resistor attached to the TEG. In the equation the only unknown is R_{int} in fact the load resistance is chosen, I is the measured quantity and V_{OC} is instead calculated by equation 1.
The difficult part is to do the current measurement from the microcontroller, in fact it has no direct interface to measure

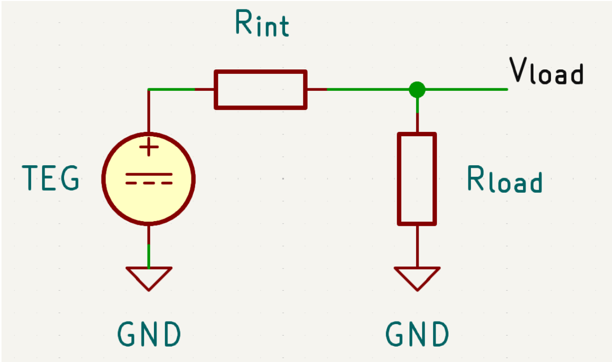

Fig. 4. TEG model with a resistive load

it, so one way is to measure the voltage drop on a known resistance, and use $I = \frac{\Delta V}{R}$ to calculate the current. A shunt is a device that does this exact thing. The microcontroller's ADC has a resolution of 12 bits and the voltages are between 0 and 3.3, so, as shown here 3, the resolution is of $0.8mV$.

$$Resolution = \frac{3.3V}{2^{12}} = \frac{3.3V}{4096} = \approx 0.0008V \tag{3}$$

To effectively measure we used an external module, the **microCurrent**, to amplify the signal then read by the MCU's ADC. This module has a tunable amplification circuit that allows to change the expected scale and resolution to fit the expected currents range.

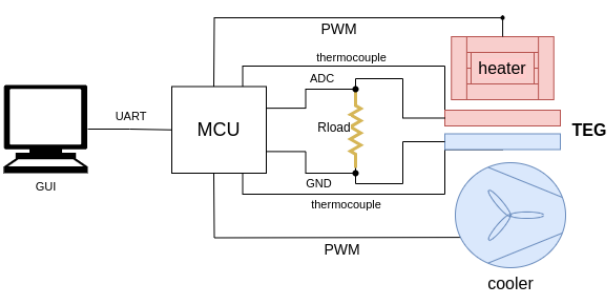

Fig. 5. Current measurement diagram with a resistive load

D. Hot side temperature control

For every measurement we need a temperature difference between the two sides of the TEG, so we need to control the temperature of the hot side. We used a **wire wound resistor with a current control**. The circuit (in Figure 6) involves a MOSFET driven by a NPN transistor. As a load resistor we used a wire wound resistor of 18 effective ohms (measured with the multimeter). Both SPICE simulation and actual measurements confirm a maximum current of $1.4A$ on the load resistor, with a maximum power around $35W$ as shown here 4.

$$(1.4A)^2 * 18\Omega = 35W \tag{4}$$

The circuit has reverse logic, so when the MCU pin is grounded the mosfet is activated and 1.4 A of current flows

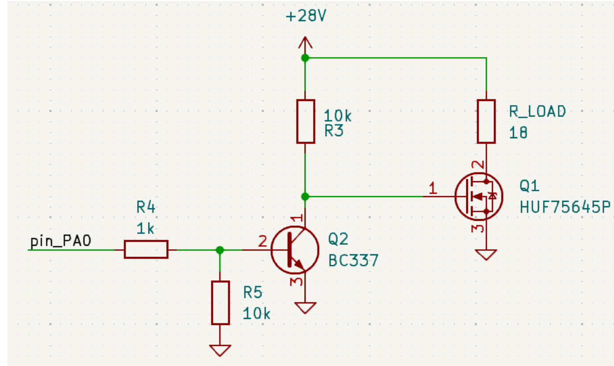

Fig. 6. Current control circuit

through, but when it is at 3.3V it stops. R3 and R5 are chosen according to this configuration, R4 is only a protection resistor for the MCU pin.

E. Cold side temperature control

To maintain a constant temperature, a **heatsink** was positioned on the cold side of the TEG. Subsequently, a fan was incorporated into the system to facilitate cooling of the aluminum, which proved particularly advantageous during steady-state acquisitions. This approach enabled the temperature of the hot side to be maintained at a stable level through the PID on the heater, the temperature of the cold side to be kept stable by the fan, and the delta to remain constant. A 12V fan with a PWM control was utilized. The power supply was the same as that used for the heater, and a voltage regulator with the appropriate resistors was employed to provide a 12V power supply. The PID was tuned to control the fan, but we found out that it was preferable to run the fan constantly in steady-state measurements or to turn it off in measurements with equal delta temperatures but different average temperatures.

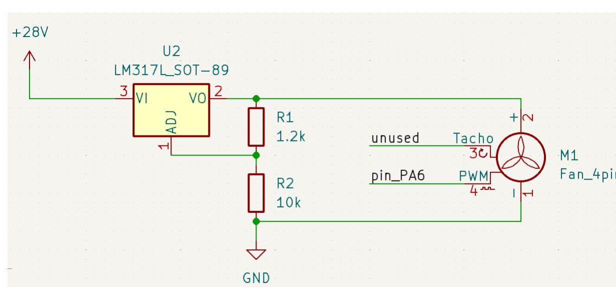

Fig. 7. Cooling control circuit

F. Acquisition process

The MCU accepts via UART the following commands:

- **setpoint hot_side**: set the hot side temperature in Celsius degrees
- **duty duty_cycle**: set the duty cycle of the PWM controlling the fan, from 0 to 1
- **pid kp ki kd**: set the PID parameters

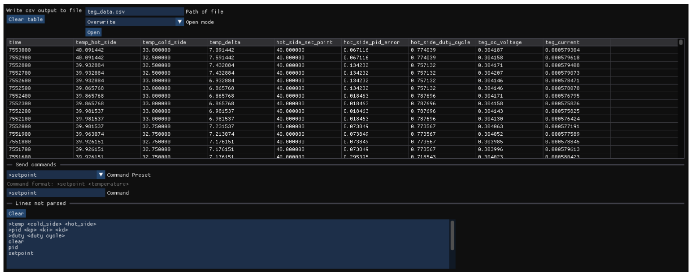

Fig. 8. Sending the settings to the MCU

The GUI application was developed in C++ using the **Dear ImGui** library and it allows to control the MCU parameters, plot the acquired data and save it in CSV format.

We carried out the acquisitions in the same environment, thus maintaining the same conditions for all acquisitions. We justify the time used for the development of the application as it was very useful both for acquiring accurate data and for quickly noticing any errors or dirty data so that we could stop and correct, saving time later.

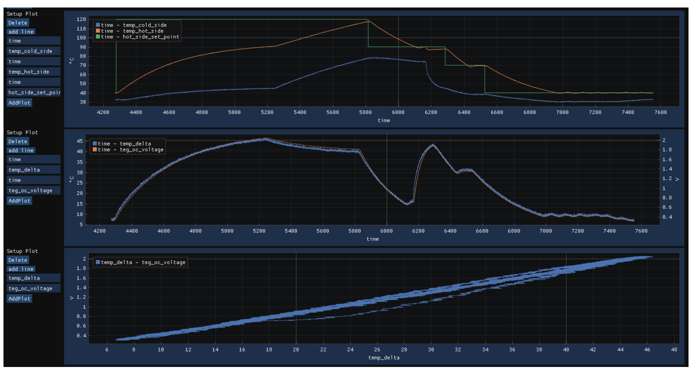

Fig. 9. Real time plots from the GUI application

IV. Experimental results

We estimate the internal resistance and the Seeback coefficient with a MATLAB script.

A. Fitting Seeback coefficient

The **Seebeck coefficient** (also known as thermopower, thermoelectric power, and thermoelectric sensitivity) of a material is a measure of the magnitude of an induced thermoelectric voltage in response to a temperature difference across that material, as induced by the Seebeck effect [7], which is described by the equation 5. It is one of the components of the figure of merit, which measures the overall efficiency of a thermoelectric device.

$$S = \frac{\Delta V}{\Delta T} \tag{5}$$

As described in section III-B, we can assume that we are measuring directly point A in figure 2. In this way, the voltage measured is dependent only on the Seeback coefficient, which in itself depends on the delta temperature between hot and cold. In MATLAB the model is written as follows:

```
% Seeback inline function
% T is a vector of mean temperature between hot and cold surfaces
seeback_coeff_mdl = @(coeffs, T)(coeffs(1));
% Model of the Open Circuit Voltage
voc_mdl = @(seeback_coeffs, T)(seeback_coeff_mdl(seeback_coeffs, T(:,1)) .* T(:,2))
    ;
% Create data table
tbl = table(mean_surface_temperature, delta_surface_temperature, measured_voltage);
% Fit model with initial guesses for each coefficient
nlm = fitnlm(tbl, voc_mdl, [0.0, 0.01, 0.02, 0.01],'Options',statset('Display','
    final','Robust','On'));
```

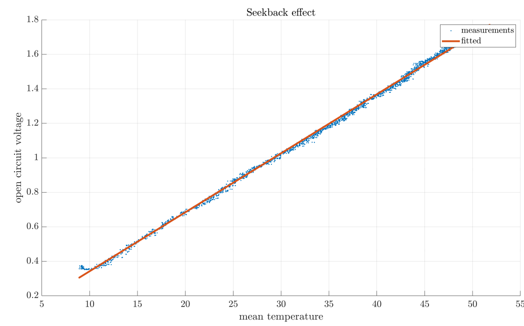

Fig. 10. Open circuit voltage mean temperature dependence

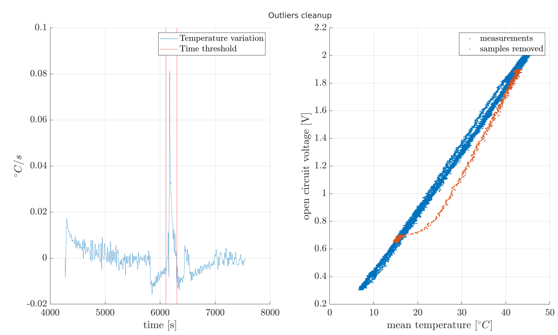

Fig. 11. Cleanup of outliers from an experiment contaimnation.

An anomaly in the data stands out. As depicted in figure10, since the data are not superimposed on a line, it would appear that the Seebeck coefficient is not only dependent on the temperature difference, but also on the mean temperature. However, this is not true, because the Seeback coefficient is itself a constant of the material and from the shape. For this reason, we analyzed the data by focusing on the change in mean temperature over time, then filtered and derived with respect to time. The result shows a spike in the temperature variation, caused by some external event that contaminated the readings. We then removed the outliers and ran again the fitting, with the results shown in Figure 11.

B. Fitting internal resistance

We modeled the internal resistance as a constant plus a linear term dependent on the mean temperature. The equations used to fit the model are:

$$\begin{aligned} R_{int} &= R_{int_0} + R_{int_1} \cdot \overline{T} \\ V_{OC} &= S \cdot \Delta T \\ I &= \frac{V_{OC}}{R_{int} + R_{load}} \end{aligned} \tag{6}$$

The internal resistance was fitted with the following MATLAB code:

```
% Model of internal resistance
internal_resistance_mdl = @(internal_resistance_coeffs, mT_dT)(
      internal_resistance_coeffs(1) + internal_resistance_coeffs(2) * mT_dT(:,1));
% Model of current given a load resistance value
current_mdl = @(internal_resistance_coeffs, mT_dT_Voc)(mT_dT_Voc(:,3) ./ (
      load_value + internal_resistance_mdl(internal_resistance_coeffs, [mT_dT_Voc
      (:,1), mT_dT_Voc(:,2)])));

% Define residuals function (RMSE)
residuals = @(coeffs)(residuals_function(I, current_mdl(coeffs, [mT, dT, Voc])));

% Minimize residuals with contraints
default_options = optimoptions('fmincon');
fitted_internal_resistance_coeffs = fmincon(residuals, [0.5, 0],[],[],[],[], [0,
      0], [5, inf], [], default_options);
```

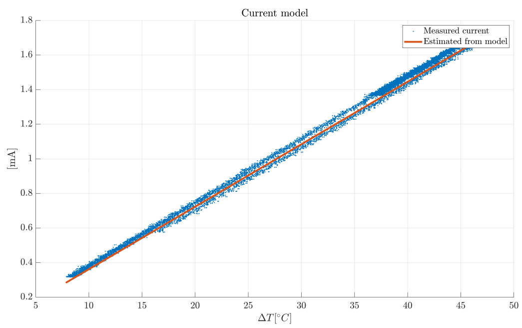

Fig. 12. Measured current vs model estimate.

V. Conclusion

We made measurements on three different types of TEG. The first two are classical TEG modules, and fitted results are in line with the online datasheets. The last one is a fibre-based TEG.

TEG model	Seebeck	Internal resistance
TEG MAT	0.034209	0.145028, 0.001342
TEG 12706	0.044441	2.299155, 0.083479
TEG VL25	0.007100	0.511499, 0.004171

From the results obtained, the best TEG is the TEG MAT, having the highest Seeback coefficient and lowest internal resistance. Here is the link to the project repository. In our project, we determined the internal resistance and Seebeck coefficient of the flexible fiber-based TEG. However, due to the unavailability of the requisite instrumentation, we were unable to collect the necessary data for determining the thermal conductivity. Nonetheless, this can be achieved by measuring the efficiency, as it is known that the maximum efficiency of the TEG is achieved by matching impedance and internal resistance. By determining the internal resistance, we can subsequently obtain the maximum efficiency, and thereby derive the figure of merit and the thermal conductivity.

In the future, it would be preferable to avoid setting temperatures manually. Instead, a cycle of temperatures should be set automatically by the microcontroller. This will allow for greater homogeneity in the dataset.

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