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Thermo-mechatronic Lab — Characterization of Thermoelectric Generators

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Abstract

Most mechanical engineering programs offer separate classes on mechatronics, renewable energy, and thermal systems. However, due to high academic loads, there are few opportunities for students to work on hands-on activities involving thermal systems and, less so, on activities that combine elements of these domains. This lack of hardware experience with thermal systems has been expressed by senior students during the Senior Exit interviews at the FAMU-FSU College of Engineering. To alleviate this problem without increasing course load, we are proposing a mechatronic lab to teach students foundational mechatronics concepts such as analog to digital conversion, signal conditioning, sensor interfacing, data logging, data analysis, and circuit assembly while staying within the context of characterization of thermoelectric generators.

The thermoelectric devices selected provide an opportunity to explore thermal and electrical phenomena that can be both sensed and visualized in a classroom environment without the need for expensive instrumentation. The experiments conducted tend to catalyze ideas for new concepts and serve as a starting point for further exploration of thermoelectricity as a mechanism for direct energy conversion.

The paper details the hardware components and designs so other instructors can easily reproduce them. Additionally, it provides a series of suggested lab activities.

Keywords-

Mechatronics; Thermal Systems; Engineering Labs; Arduino; Energy Conversion; Renewable Energy

I. Introduction

Introductory mechatronics courses focus on the following microcontroller topics: configuration of general-purpose input and outputs (GPIOs), control of DC motors, analog to digital conversion, pulse width modulation, and serial communication. It is often the case that these concepts have a clear connection with areas such as robotics and control. However, more effort should be put forward towards integrating this class with other subfields such as material science, and the thermal area. These cross-curricular connections would help reinforce key concepts covered in those more theoretical courses by making them more tangible via hands-on experiments. Additionally, since at the same time students will be learning the mechatronics concepts, there is no added course load.

Previous efforts have been made to standardize and improve mechatronics and robotics curriculum [1-4]. Additionally, relevant interdisciplinary mechatronics projects within the realm of mechanical engineering include the design and evaluation of miniature turbines[5], and the utilization of swaying devices for energy harvesting[6]. In this work, we focus on developing lab activities to teach the mechatronics concepts while staying focused on thermo-electric generation. The paper is structured as follows: Section II, details proposed lab activities to develop the essential skillset needed to perform a characterization of a TEG. Section III, provides background on thermo-electricity and describes a TEG characterization experiment that builds up on the concepts of Section II. Finally, Section IV, includes conclusions and directions for future work.

II. Fundamental Lab Activities

A. Thermistors

Thermistors are passive devices that change their resistance as a function of temperature. A typical way to interface a thermistor with a microcontroller consists in the use of a voltage divider, where one resistor (R_1) is fixed and connected in series with the thermistor (R_{th}).

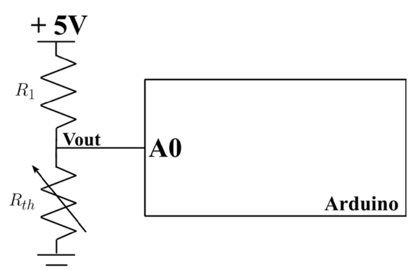


Figure 1 Thermistor interface circuit.

The output of the divider, labeled Vout in the circuit of Fig. 1 is then connected to an analog input Channel of the Microcontroller. In this experiment we employ channel zero (A_0). The ADC of microcontroller being used (ATmega 2560) has 10-bit resolution. When designing the voltage divider, it is common practice to select the fixed resistor with a value that is close to the thermistor resistance at nominal temperature. In this experiment, we employ the NTC thermistor NTCLE300E3502SB.

The output voltage of the divider is given by

$$V_{out} = V_{in}\left(\frac{R_{th}}{R_{th}+R_f}\right). \quad (1)$$

From Eq. 1, one can solve for the thermistor resistance given that we can measure $V_{out} = \frac{5*2^N-1}{ADC_{reading}}$ and R_1 is known. In this setup, $R_1 = 4.7k\Omega$, which is close to the thermistor resistance at $25°C$ $(5.0k\Omega)$. *N* is the number of bits of the ADC. Then, by manipulating the Steinhart-Hart equation[7], the temperature of the thermistor is given by

$$T = \left(\frac{1}{T_N} + \frac{\ln\left(\frac{R_{th}}{R_N}\right)}{B}\right)^{-1}, \quad (2)$$

where R_N is the thermistor's resistance at $25°C$, $T_N = 25 + 273.15$, and B is the beta value of the thermistor between 25 and 85°C.

Suggested lab activities

a) Sketch a general trend of Vout vs R_{th}.

b) Sketch a general trend of Vout vs R_{th} if the position of the thermistor and the fixed resistor are flipped.

c) If the Analog to Digital converter were 12 bits, what would be the set of possible numbers generated by the ADC?

d) Assemble the circuit of Fig. 1 on the breadboard and interface it with the microcontroller to estimate the local ambient temperature.

e) Based on your experiments, does the resistance of the thermistor increase or decrease with temperature?

f) List some limitations of thermistors and comment on alternative temperature sensors.

B. Instrumentation Amplifier

Several sensors often produce signals with very small magnitudes. Therefore, if they were to be connected directly to an Analog to Digital converter, the outputs would be lumped together towards the lower output values of the ADC. An option to better utilize the span of the ADC is to employ an Instrumentation Amplifier.

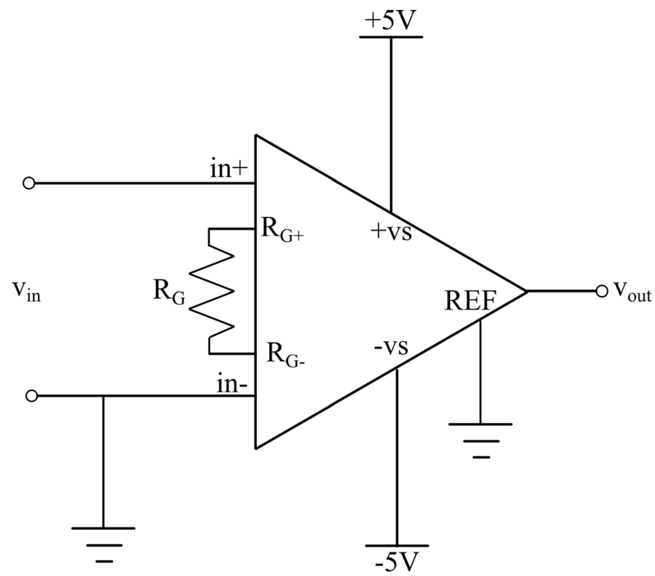


Figure 2 Instrumentation Amplifier (IA). In this lab, the Analog Devices AD623 IA is employed.

The output voltage of the amplifier is given by

$$Vout = G(vin) + vref \tag{3}$$

Where $RG = 100k\Omega(G - 1)$ and G is the desired gain.

Suggested lab activities

a) Assemble the circuit of Fig. 2.

b) Using an external power supply to feed an input voltage Vin of 0.1V. Then select values for R_G to amplify the input voltage by 10 and 40. Make approximations to commercially available resistors. Measure and report the output voltage of the amplifier.

c) Propose an application not discussed here, where you consider that an instrumentation amplifier would be useful.

C. Controlling Loads (e.g., heaters, fans, motors)

A convenient way to control the speed of fans or the voltage applied to devices such as heaters or fans is called Pulse Width Modulation (PWM). Essentially, the load is connected and disconnected at intervals specified either by a user or a control law. Normally, the connected time (ON time) of the signal is varied. The ratio of the ON time and the period of the PWM signal is known as the duty cycle and is usually expressed as a percentage.

Besides a PWM signal, a digital switch (e.g., a transistor) is needed to connect the load being controlled and support its current demands. Among the several possible digital switches, power MOSFET transistors are common choices due to their ability to handle large currents[8]. MOSFETs are employed here as voltage-controlled switches where a high signal at the Gate of the transistor results in a very small resistance to electrical flow between the Drain (D) and the Source (S) terminals. When this occurs, the load is energized. If the load is inductive, such as a motor or an electromagnet, it is recommended to add a flyback diode in parallel with the load to suppress voltage spikes that appear when the load is rapidly turned off.

A typical control circuit is shown in Fig. 3.

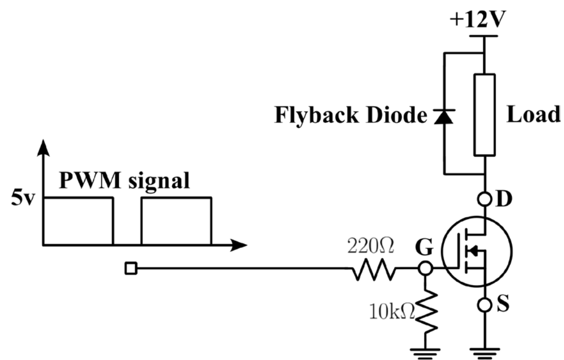


Figure 3 Controlling loads with an N-channel power MOSFET transistor (GQP30N06L) and Pulse Width Modulated signals.

Suggested activities

a) Assemble the circuit of Fig. 3 and use a 12V fan as the load.

b) Write microcontroller code to command different speeds to the fan by using PWM signals of different duty cycles e.g., 0, 50, and 100%.

D. Serial Communication

Depending on the students programming experience, they are tasked with writing, using their language of choice, computer code to read serial data being sent by the microcontroller. The data should include a temperature reading obtained using a thermistor.

III. **Thermo-electricity and characterization of TEGs**

Thermo-electric Generators (TEGs)

As a culmination of the lab, an experiment combining the concepts learned in the previous activities is proposed. Here, the students assemble a thermo-mechatronic system comprised of a TEG, a resistive heater, a fan, two thermistors, a shunt resistor, and additional electronics to interface with a microcontroller. The experimental setup is depicted in Figure 4 and 9, and the complete circuit that students need to assemble is shown in Figure 8.

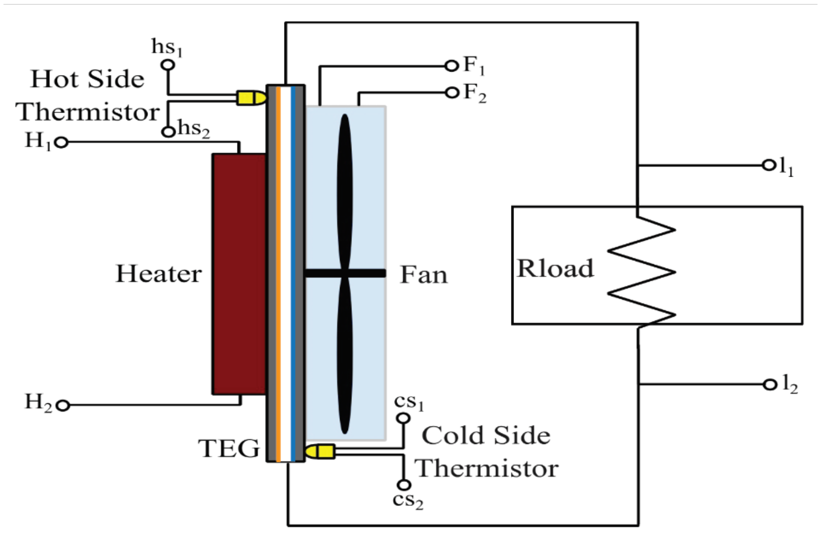
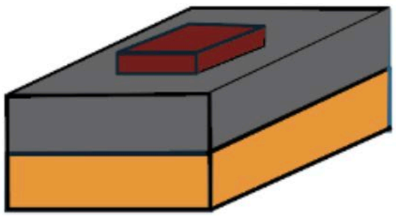


Figure 4 Depiction of setup to characterize a TEG. The setup comprises a resistive heater, a fan, two thermistors to monitor the hot and cold sides of the TEG, and a resistive load to estimate the power produced by the TEG. The orange and blue colors represent the hot and cold sides of the TEG, which is placed between to metallic based plates.

As part of this activity, students also develop a thermal model of the experimental setup. For simplicity, the model assumes that the cold side of the TEG is maintained at a constant temperature Tc by means of a fan. The model then focuses on the heater, the hot-side base plate and the hot side of the TEG with the objective of obtaining the hot side temperature T_H.

The proposed activity consists in providing a simple set of coupled ODEs, obtained from treating the heater, base plate and hot-side as control volumes and using an energy balance. The system of ODEs is illustrated in Figure 5.



$$M_r Cp_r \frac{dT_r}{dt} = I_r^2 R_r - \frac{2k_r A_r}{H_r}(T_r - T_b) - h_\infty A_{rl}(T_r - T_\infty)$$

$$M_b Cp_b \frac{dT_b}{dt} = \frac{2k_b A_r}{H_b}(T_r - T_b) - h_\infty A_{bl}(T_b - T_\infty)$$

$$M_h Cp_h \frac{dT_h}{dt} = \left(\frac{k_r A_r}{H_b} + \frac{k_h A_h}{H_h}\right)(T_b - T_h) - h_\infty A_{hl}(T_h - T_\infty)$$

Figure 5 System of ODEs used to predict the hot-side temperature of the TEG

The symbols and suggested values (to be adapted according to specific setup) are described in Table 1.

Table 1. Variables and suggested values for system of ODEs.

Description	Symbol	Value
Resistance of the heater	R_r	6 Ω
Temperature of hot side of the TEG	T_h	variable
Temperature of the cold side of the TEG	T_c	Constant (293 K)
Current through resistor	I_r	I_r = 0.05 m
Area exposed to ambient temperature for each layer r, b, h	A_{il} $i = r, b, h$	*Arl = 0.0010* m^2 *Abl = 4.0e-04* m^2 *Ahl = 0.0010* m^2
Cross sectional area (for conduction between layers)	A_i $i = r, h$	A_r = *6.2500e-04* m^2 A_h = *6.2500e-04* m^2
Thickness of layer	H_i $i = r, b, h$	*Hr = 4 mm* *Hb = 4 mm* *Hh = 4 mm*
Thermal Conductivity	k_i $i = r, b, h$	K_r = 71.4000 W/(m K) K_b = 237 W/(m K) K_h = 1.4 W/(m K)
Mass of each layer	M_i $i = r, b, h$	M_r = 0.1 kg M_b = 0.007 kg M_h = 1.92e-5 kg
Specific heat of each layer	Cp_i $i = r, b, h$	C_{pr} = 900 J/(kg K) C_{pb} = 237 J/(kg K) C_{ph} = 1.4 J/(kg K)
Convective heat transfer coefficient to ambient	h_∞	$h_\infty = 10\ W/(m^2\ K)$

Once the students develop the system of coupled differential equations, they are tasked with generating a simulation of the temperature evolution of the system under the assumption that the input electrical power is computed using a proportional control law $P_{in} = K_p(T_{h,des} - T_h)$ and that the desired hot side temperature is 305K. The expected behavior of the key system's temperatures is shown in Figs. 6-7. This simulation utilizes the parameters of in Table 1.

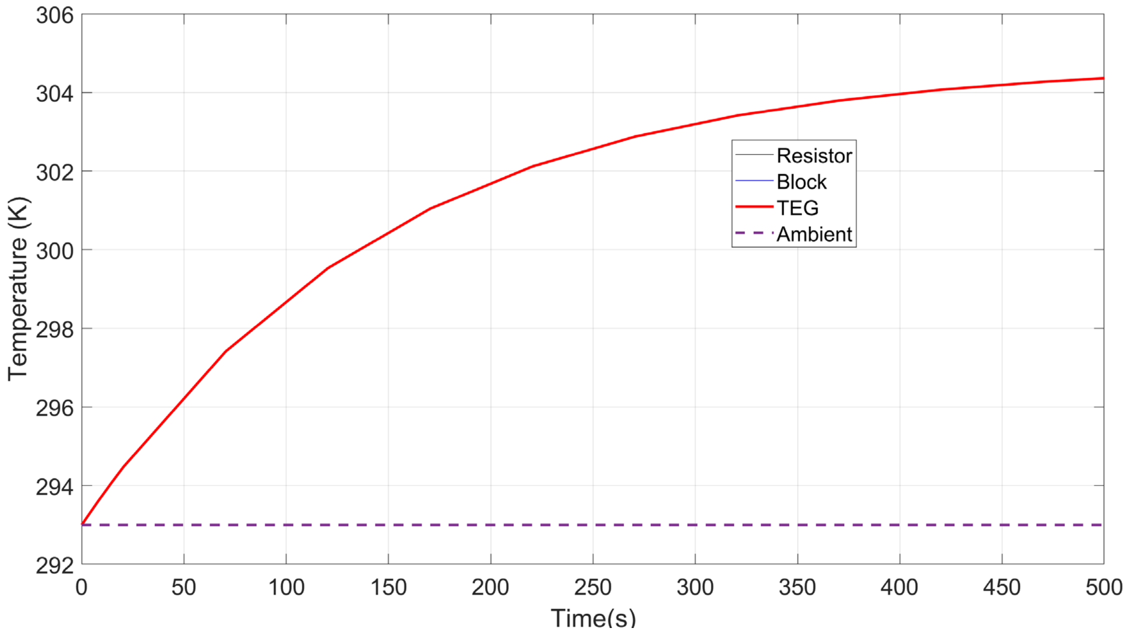


Figure 6. Evolution of key system's temperatures under closed-loop control. The desired TEG hot side temperature is 305K

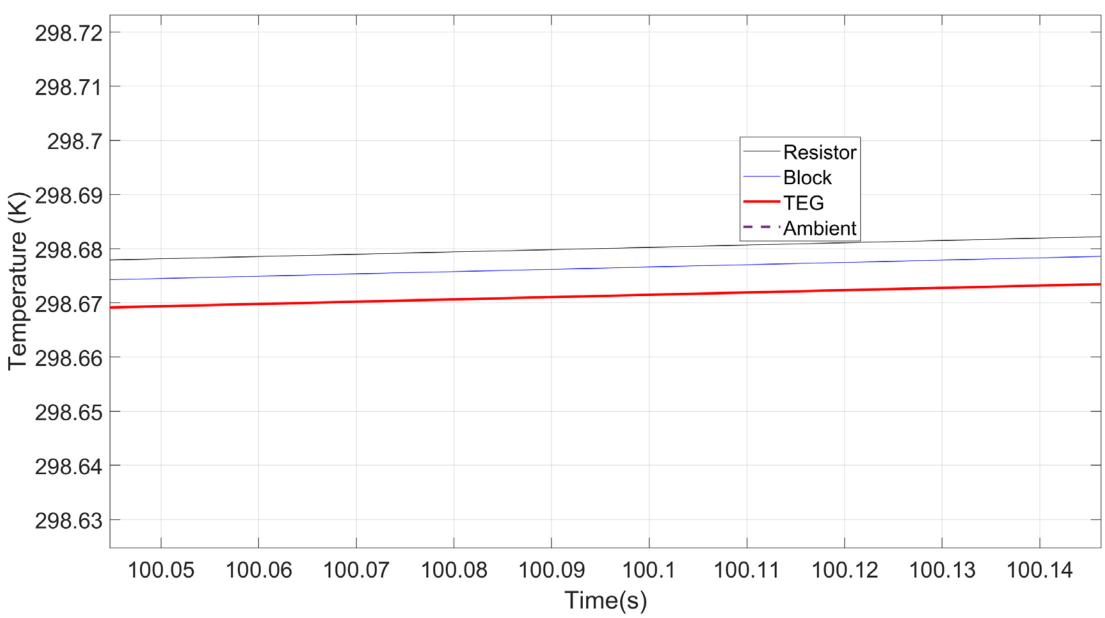


Figure 7 Evolution of system temperatures under closed-loop control (zoomed in version of Figure 6)

As a follow-up experiment the students can be asked to complete the ODE system by now accounting for all control volumes upto the cold side of the TEG.

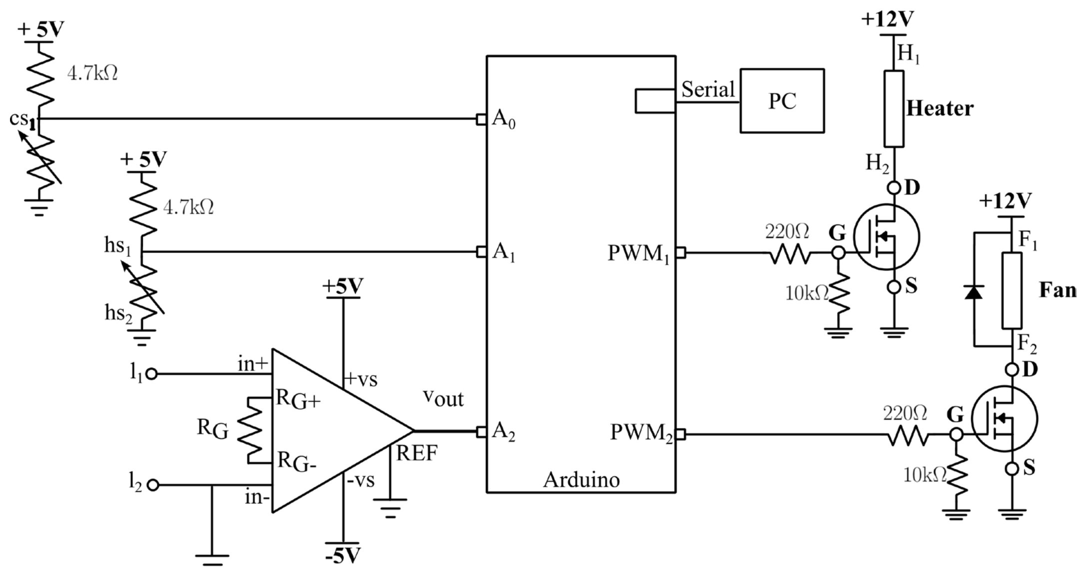


Figure 8 Electrical schematic to characterize the TEG.

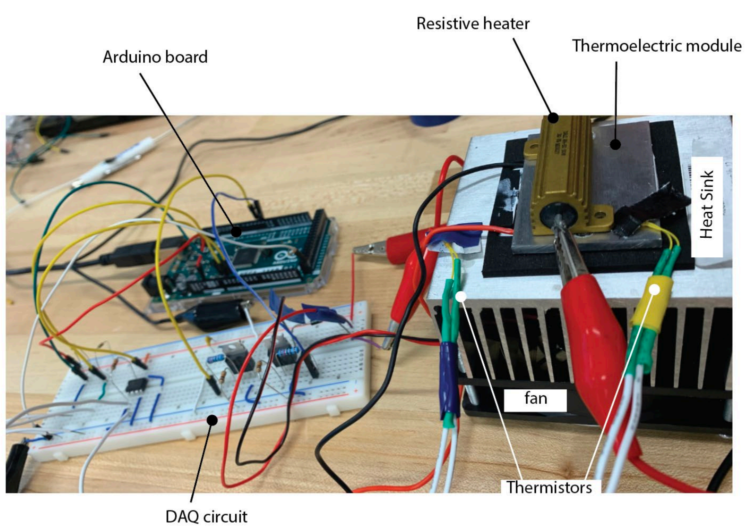


Figure 9 Experimental setup. A 12V fan is employed for the cold side of the TEG. For the heater, 2 3Ω 50W resistors are connected in series. A single 3Ω resistor is used as the load for the TEG.

By conducting the hardware experiment, the students will be able to acquire data to determine the primary variables relevant to characterize the thermoelectric device operation. In particular, the lab will include measures to determine the hot and cold side temperatures, the load current and voltage, and the electric power generation. It is also relatively straight forward to invert the operation of the thermoelectric unit so that it works as refrigerator or heat pump, which would allow for additional experiments relevant to thermal science and energy conversion courses.

With the measured temperature gradient $(T_H - T_C)$ between the hot and cold sides of the thermoelectric unit, the current, I, the electrical power output, and the open circuit voltage, $V_{oc} = \alpha(T_H - T_C)$, it is possible to determine the average Seebeck coefficient, α, and the internal resistance of the device, R.

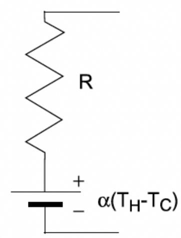


Figure 10 Electric representation of a thermoelectric unit with internal resistance R and Seebeck coefficient α .

The electrical power generated is given by,

$$P_E = \alpha(T_H - T_C)I - RI^2 \tag{4}$$

An example of the experimental result obtained with the proposed setup is shown in Fig. 11

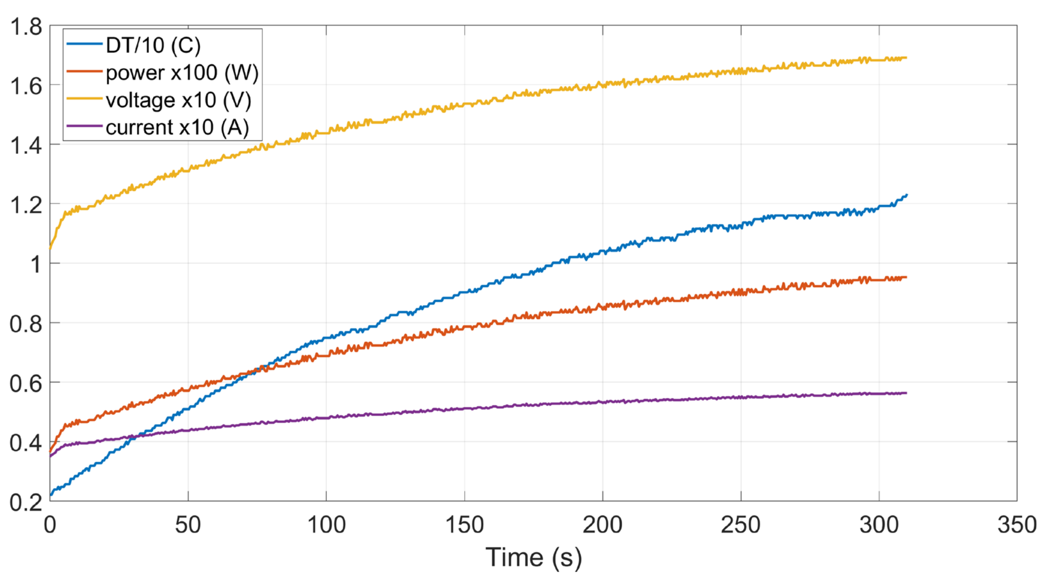


Figure 11 Experimental result of the characterization of the TEG. The plot illustrates evolution of the temperature gradient DT between the hot and cold sides, power, voltage, and current measured at the 3Ω load connected to the TEG.

Suggested Activities

a) Assemble the experimental setup of Fig.4 and the circuit of Fig. 6.

b) Write microcontroller code to read temperatures of both thermistors and the voltage across the load connected to the TEG. The code should send the collected data to a computer.

c) Use the collected data and develop plots of voltage, current, power and temperature gradient vs. time.

d) Provide conclusions of your experimental findings.

e) Describe an application of TEGs.

IV. Conclusion and Future Work

This work proposed a series of foundational mechatronic activities including thermistors, ADC, open loop control of fans and heaters, data logging, data analysis, circuit assembly, and thermoelectric generation. The suggested labs are expected to reinforce concepts both in mechatronics and thermal systems.

The most immediate course of action is to implement these lab activities in both mechatronics and sustainable energy classes. By having similar activities in two different classes, students would gain additional insights thanks to the spaced repetition. Additionally, we expect to collect student feedback on the lab activities and assess the efficacy of the labs.

An interesting extension to the current system would comprise adding control laws to regulate the temperatures of the hot and cold sides of the TEG. This activity would provide an opportunity to reinforce modeling of thermal systems, differential equations, and control systems.

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