Thermoelectric Energy Conversion

Objective: The objective of this laboratory is for you to explore how thermoelectric materials can convert thermal energy to electrical, and vice versa.

Terminology Clarification: Thermoelectric Devices are often called Peltier Devices. Both terms will be used in this lab report.

Pre-Lab

Read: Simple Experiments with a Thermoelectric Module (Compass)
Look Up:
Voltage limit of Heater:
Voltage limit of Peltier Device:
Temperature limit of module:

Equipment Needed:

- Thermoelectric module containing
    - Heater
    - Peltier/Thermoelectric device (TE)
    - Integrated Heat Exchanger
- Thermocouples for measuring temperature on both sides of the TE
- Two dc power supplies
- Multi-meter
- Two breadboards and wires
- EasySense Software
- Variable resistor
- Validyne USB2250 Data Acquisition Board

Laboratory Safety

Required Personal Protective Equipment

- Safety glasses with side shields
- Long Pants
- Closed toed shoes

Safety Concerns:

Electricity—potential for shock
Consider all circuits "hot" unless proven otherwise.
Keep the body, or any part of it, out of the circuit.
Never touch an exposed live wire.
Always turn off the power supply first before adjusting circuit.
Currents above 10mA can paralyze or "freeze" muscles. Currents more than 75mA can cause a rapid, ineffective heartbeat—death will occur in a few minutes unless a defibrillator is used.

Introduction

Most large-scale conversion of thermal-to-electrical energy uses a gas cycle of some type. For example, heat generated by burning coal is used to vaporize water that drives a turbine and generator. The air conditioner in your apartment uses electrical energy to run a compressor to condense a refrigerant. The electrons and holes in a semiconductor can also be used to convert heat to electrical power or the electrons and holes can be used to move heat against a temperature gradient. Semiconductors that do this relatively efficiently are referred to as good thermoelectrics. The best thermoelectric material for use near room temperature is Bi_2Te_3 and related alloys; for many decades, researchers have been looking for something better without success. In this lab, you will measure the efficiency of a Bi_2Te_3 based thermoelectric module and compare this efficiency of the module to the theoretical limit, i.e., the efficiency of the Carnot cycle.

Experimental Setup:

Figure 1a shows a schematic of the inside of the thermoelectric module you will be using in this lab. Figure 1b shows the circuit diagram corresponding to the setup that has already been wired for you. It is a simple series circuit containing the power supply, Peltier device/heater, and a resistor. A resistor has been included in each circuit to enable the calculation of the current using Ohm's Law. Please familiarize yourself with the labels for the different values on each diagram.

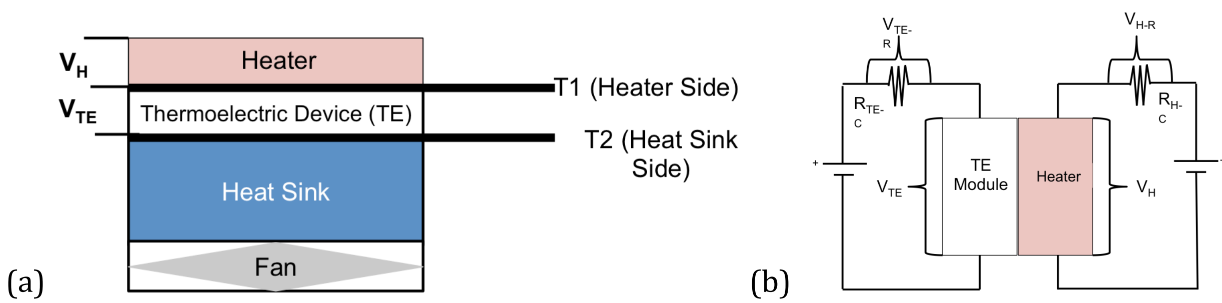


Figure 1: Basic TEC Lab Diagrams
(a): Thermoelectric module diagram
(b): TEC Lab Circuit Diagram

Experiment Guidelines and Restrictions:

Maximum voltage for items connected to the Validyne data acquisition system: 10V

Maximum temperature of module: 80°C

Maximum voltage for heater: 20V

Let T1 and T2 equilibrate in between each step. If taking too much time, set a timer and note this in your lab report

Be consistent with equilibration times (if possible) for each experiment.

Week 1 Experiments: Peltier Current and Solid-State Heat Pumps

Part 1: Peltier Cooling

Explore Peltier cooling and heating by applying current to the thermoelectric module in both directions, i.e., measure the steady-state temperature drop across the module as a function of electrical current. Keep in mind that the Peltier heat current is linear in the electrical current but Joule heating due to the finite resistance of the thermoelectric materials is quadratic in the current. You will want to use the fan to keep one side of the module near room temperature. Make sure that you find the minimum cold-side temperature so that you can estimate the effective value of the thermoelectric figure-of-merit for this module from the maximum cooling.

Figure 2 contains a diagram showing the direction of heat flowing through the system in this experiment and the circuit diagram for Part 1.

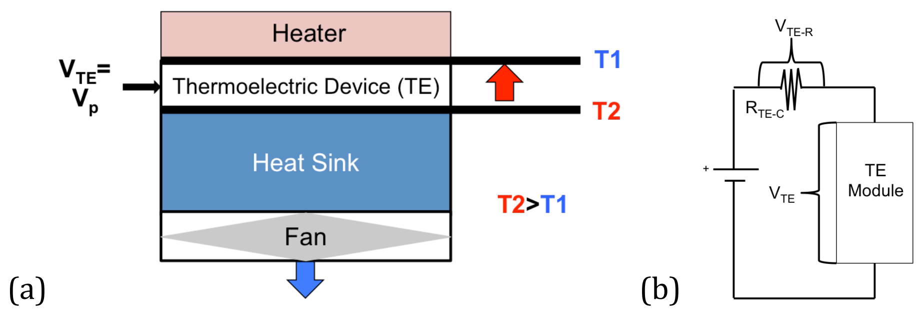


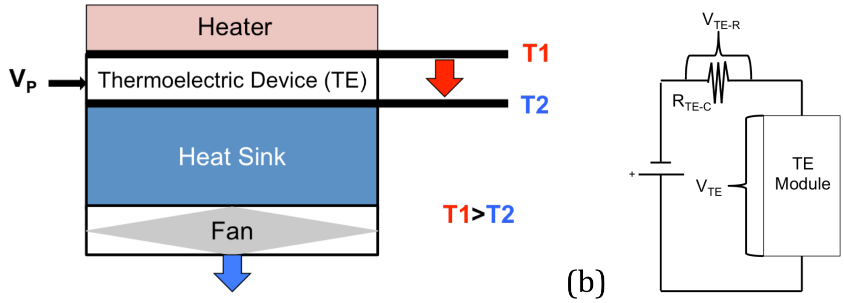
Figure 2: Part 1 Diagrams
(a) Heat Flow for Part 1 (b) Circuit Diagram for Part 1

1. Confirm wiring of setup is accurate using the circuit diagram.
2. Turn on Fan
3. Open EasySense software and begin data acquisition (see end of lab for more details on software)
4. Turn on module power supply
5. Increase current in increments of 0.05A until lowest value of T1 is achieved as shown by the EasySense Software *Wait until the temperature is stabilized before increasing to the next current (usually 1-3 minutes)
   *Do not exceed maximum 10V for Validyne system

Inputs for Part 1	**Outputs for Part 1**		**Measured Values for Part 1**				
V_P (V_{TE})	T_1	T_2	T_1	T_2	V_{TE}	V_{TE-R}	R_{TE-C}

Part 2: Peltier Heating

Figure 3 shows the heat flow diagram and circuit for Part 2. Notice the differences from the Part 1 diagrams.



(a) (b)

Figure 3: Part 2 Diagrams
(a): Heat Flow Diagram (b) Circuit Diagram

1. Switch power supply lead direction (use circuit diagram to confirm correct direction of voltage)

2. Turn on Fan

3. Open EasySense and begin data acquisition in a new file

4. Turn on power supply and repeat 0.05A increment increases from Part 1.
   *You will not be able to reach the same amperage
   *Pay attention to the maximum T of the module and max voltage for the Validyne

Inputs for Part 2	**Outputs for Part 2**		**Measured Values for Part 2**				
V_P (V_{TE})	T_1	T_2	T_1	T_2	V_{TE}	$V_{TE\text{-}R}$	$R_{TE\text{-}C}$

Part 3: Peltier Coefficient

The Peltier coefficient (Π) descries the rate of thermal power transport that the Peltier device performs for a given electrical current (I) input. Ideally, the equation that relates the heat transport ($Q_{net,\ ideal}$) by the thermoelectric device is

$$Q_{net,ideal} = \Pi I_P \tag{1}$$

However there are other sources of heat transport via thermal diffusion and heat production via Joule heating within the device itself that leads to a more accurate equation, as shown below.

$$Q = \Pi I_P - \kappa \Delta T - \frac{1}{2} I_P^2 R_P \tag{2}$$

Where κ is the thermal diffusion coefficient, ΔT is the temperature different across the device, and R_P is the resistance of the device.

Today you will measure the Peltier coefficient of the module by balancing the Peltier current against the heat dissipated by the heater that is attached. To make the calculation simpler, we will be setting ΔT to zero to remove the κ term. Comment on why we would want to do this from a theoretical standpoint in your lab report.

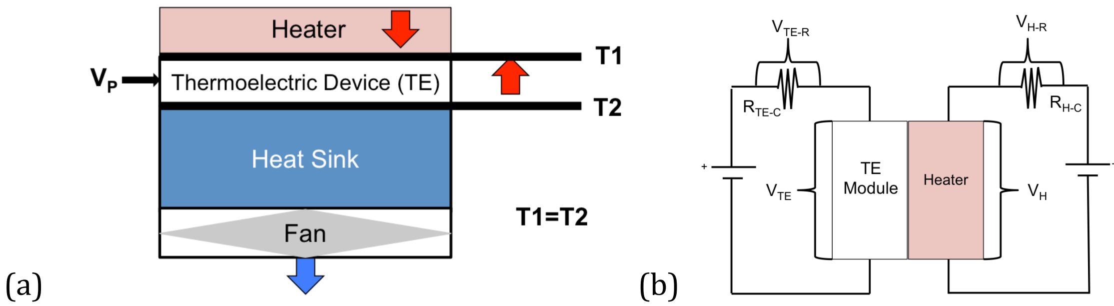


Figure 3: Part 3 Diagrams
(a): Heat Flow Diagram for Part 3 (b) Circuit Diagram for Part 3

1. Make sure the setup is in cooling mode (check circuit diagram)
2. Turn on Fan
3. Open EasySense and begin a new data acquisition
4. Select a low current and hold constant across the Peltier device. Start with a low current (ex: 0.05-0.1A)
5. Wait until ΔT has stabilized
6. Increase voltage to the heater slowly until T_1 and T_2 across the device is close to equal
   *ΔT<0.3°C is acceptable
7. Manually measure and record the voltage across the heater and the resistor within the heater circuit using the multi-meter
8. Manually record the T_1, T_2, the voltage across the Peltier, and the voltage across the resistor within the Peltier circuit.
9. Repeat this process for four other currents across the Peltier, increasing the heater power to balance.
   *Pay attention to maximum temperature and voltage constraints

Inputs for Part 3		**Outputs for Part 3**		**Measured Values for Part 3**							
V_P (V_{TE})	V_H	T_1	T_2	T_1	T_2	V_{TE}	V_{TE-R}	R_{TE-C}	R_{H-C}	V_H	V_{H-R}

Analysis for Week 1

Part 1 & 2

- Plot ΔT vs. I_P for both cooling and heating mode on the same graph.
    - ΔT is chosen as the maximum per current interval (where the ΔT vs. time curve starts to plateau at each point)
- Comment on how the curves are different from one another. Can you quantify the difference? Explain what causes it.
    - Hint: Look at the terms in Equation 3. This should give you a hint on at least two other phenomena in our system besides the one we chose to investigate (Peltier Effect).
- Determine the maximum ΔT
- Calculate the figure of merit using the equation below

$$Z = 2\frac{\Delta T_{max}}{T_1^2}$$

- How does this compare to the expected Z value for Bi_2Te_3?

Part 3

- Plot Q vs. I_p
    - For this lab, we assume the power output of the heater is roughly equivalent to Q
- Fit the Q vs. I plot to a quadratic equation and use the coefficients from your fit to determine R and Π from equation 3

* BEFORE WEEK 2, CALCULATE $R_{Peltier}$

Week 2 Experiments: Seebeck Effect and Thermoelectric Power Generation

This week, there will be a variable resistor within the circuit. For Part 1.2, it should be set to 2.2. For Part 2.2, it will change (see instructions).

Part 1.2: Measuring the Seebeck Coefficient

The Seebeck coefficient relates the temperature difference across the device to the voltage output.

$$V = S * \Delta T$$

Figure 4 shows the heat flow and circuit diagram for Week 2 Part 1 experiment.

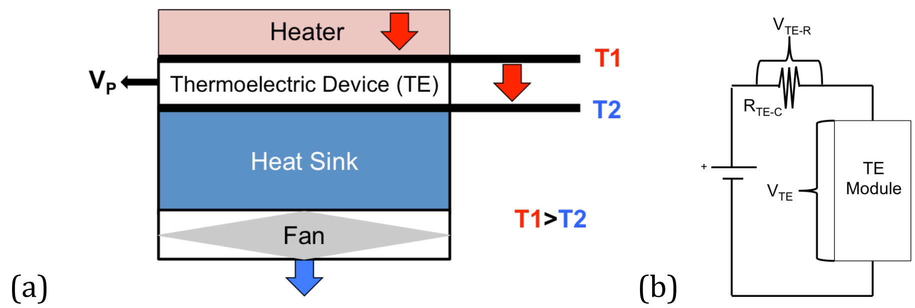


Figure 4: Part 1.2 Diagrams
(a) Heat Flow Diagram (b) Circuit Diagram

1. Turn Fan on
2. Open EasySense and start a new data acquisition
3. Turn on heater power supply and pick a voltage
4. Wait until the temperature has stabilized, then pick another voltage (five in total)

Inputs for Part 1.2	**Outputs for Part 1.2**		**Measured Values for Part 1.2**				
V_H	T_1	T_2	T_1	T_2	V_{TE}	V_{TE-R}	R_{TE-C}

Part 2.2: Seebeck Efficiency

*You will need $R_{Peltier}$ for this step

Part 2.2a: Fan On

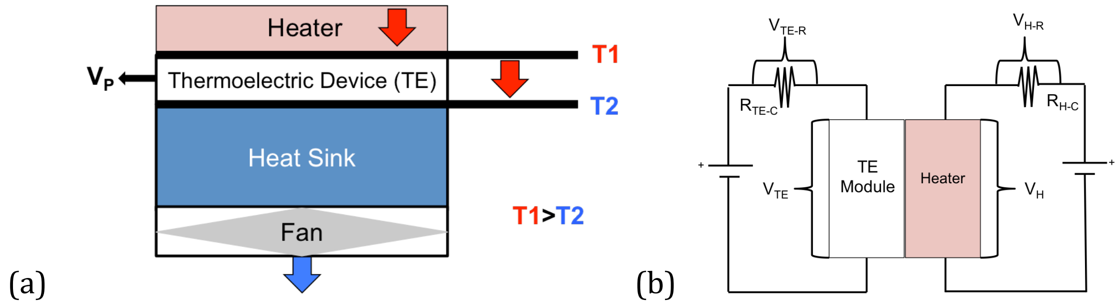


Figure 5: Part 2.2a Diagrams
(a) Heat Flow Diagram (b) Circuit Diagram

1. Turn Fan on
2. Set Rpeltier value to what you calculated in Part 3 on the variable resistor
3. Turn the power module for the Peltier device on to a low current (~0.01-0.03A).
4. Increase the heater power from 0-0.25A in increments of 0.05A
    a. Stop if the voltage or temperature gets too high
    b. Wait for the temperature to stabilize before increasing current
    c. If you cannot reach 0.25A, that's fine

Inputs for Part 2.2a		**Outputs for Part 2.2a**			**Measured Values for Part 2.2a**							
I_P	V_H	T_1	T_2	V_{TE}	T_1	T_2	V_{TE}	V_{TE-R}	R_{TE-C}	R_{H-C}	V_H	V_{H-R}

Part 2.2b: Fan off

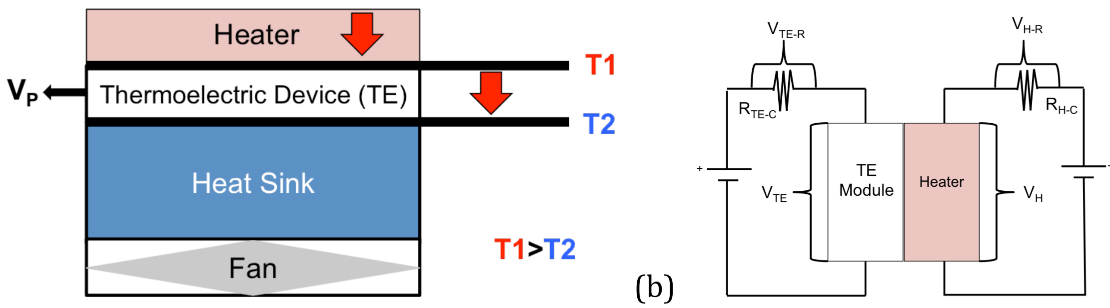
(a) 

Figure 6: 2.2b Diagrams
(a) Heat Flow Diagram (b) Circuit Diagram

1. Turn fan off
2. Turn the power module for the Peltier device on to a low current (~0.01-0.03A).
3. Increase the heater power from 0-0.25A in increments of 0.05A
    a. Stop if the voltage or temperature gets too high
    b. Wait for the temperature to stabilize before increasing current
    c. If you didn't reach 0.25A in Part 2.2a, stop at 0.2A for 2.2b

Inputs for Part 2.2b		**Outputs for Part 2.2b**			**Measured Values for Part 2.2b**								
I_P (V_{TE})	V_H	T_1	T_2	V_{TE}	T_1	T_2	V_{TE}	V_{TE-R}	R_{TE-C}	R_{H-C}	V_H	V_{H-R}	

Analysis for Week 2

Part 1.2

- Plot the temperature difference created by the heater (ΔT) vs. voltage generated in the module (V_{TE})
- Fit a linear equation to this data
    - Slope of the line is the Seebeck coefficient
- How does this compare to the expected/published value?

Part 2.2a & b

- Determine the power generated by the device/module
- Determine the power input from the heater
- Efficiency is the ratio of the output power to the input power
- Compare the efficiency with the fan off and on to the Carnot limit by plotting η vs. T_2/T_1 and plotting Efficiency values on this plot. *See Lecture slides for more details

$$\eta_{Carnot} = 1 - \frac{T_2}{T_1}$$