Thermoelectricity

Introduction

A TEC (Thermo-Electric Cooler) is an electrically driven, solid-state heat pump in the form of a plate (fig. 1). In use, the input and output sides of the plate usually are thermally connected to different parts of the surrounding environment with thick pieces of aluminum metal. Aluminum conducts heat so readily that these so-called "thermal reservoirs" will have an almost uniform temperature.

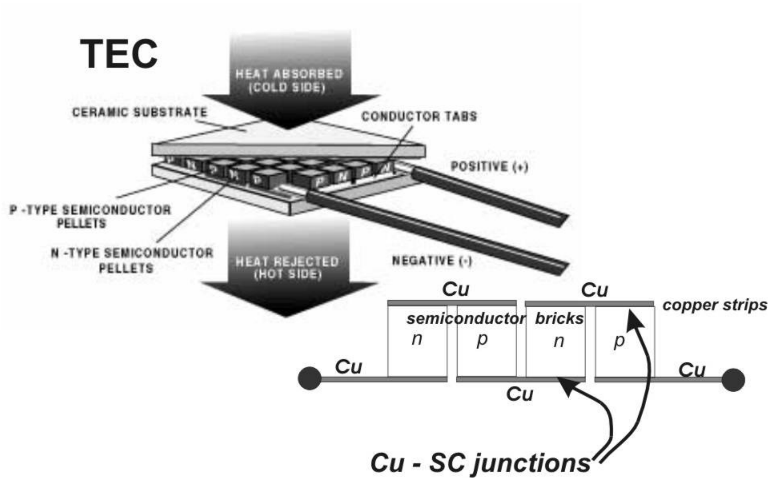

Figure 1: A semiconductor thermoelectric cooling module (TEC) (left). Internally, it consists of alternating pairs of metal-semiconductor-metal thermocouple junctions (right). (From www.peltier-info.com)

A TEC is an array of metal-to-semiconductor thermocouple junctions. If one side of the TEC is at a different temperature than the other, a potential difference will be observed between its leads (called the Seebeck voltage, V_s). And if a suitable DC electrical current is passed through the TEC, the temperature of one side of the plate will drop with respect to the temperature of the other side. In steady operation, a TEC can suck heat from a cool environment on the input side and discharge heat (a greater amount of heat) to a warmer environment on the other side. This is a defining characteristic of this system: this type of heat transfer is commonly seen in car refrigerators (electric coolers) and solid state physics experiments.

Such a device is called a "heat pump" because it causes thermal energy to be moved from a cooler temperature to a warmer one, rather than the natural case of heat flowing from higher to lower temperature. There is, of course, a penalty for frustrating nature's normal habits, and this is a necessary input of electrical power. Heat pumps are just the reverse of heat engines. In a classic heat engine, some amount of heat is input at high temperature, and a fraction of that amount is output at lower temperature, while the difference between the input output heat energies appears as mechanical (or some other kind of) work. In a heat pump or electric cooler, work energy is input to the device, which causes an amount of thermal energy to be taken into the device at some low temperature and a larger amount (the sum of the input heat and electrical energies) to be output at a higher temperature.

The second law of thermodynamics states that entropy (the heat energy transported divided by the absolute temperature at which it moves) must increase or (at best) remain constant in the process. The ideal case (no entropy change) is called a reversible process. Normal heat flow (heat energy moving from higher to lower temperature) always increases entropy.

The Seebeck and Peltier effects that a TEC exploits arise from the free (or partially free) electrons that allow charge to move through a conductive solid. The charge carriers also transport heat very effectively, this being in addition to whatever heat flows through the crystalline frame of the solid by lattice vibrations (called phonons). Especially in situations where different conductive media are in contact with one another, couplings arise between heat flow and current flow, and temperature difference and potential difference. A temperature difference can generate a potential difference (Seebeck effect), and a current flow can generate a heat flow (Peltier effect): the two effects are reciprocal, **not** independent.

In this experiment there are many effects that need to be considered: for simplicity we will list off each effect individually with an explanation, then follow it up with combining the ideas into what the experiment entails.

Seebeck effect

The Seebeck effect is the conversion of temperature differences directly into electricity. A temperature difference causes a potential difference between two conducting materials: as a consequence, current flows. Consider two wires, A and B, made of two different materials, with their tips soldered together to form a simple circular loop: we will label the junctions 0 and 1. Because of the different chemical composition of the two wires, they will have different average electron densities ρ_A, ρ_B when maintained at the same temperature (this depends, for example, on how many free electrons each molecule in the material's lattice has): assume that $\rho_A < \rho_B$. As soon as we connect the two wires, the electrons will start to move around to re-distribute equally over the whole circuit and correct the electron imbalance originally present due to the chemical composition of the wires: because $\rho_A < \rho_B$, the electrons will flow from B to A. Hence locally, near the junctions, there will be an "excess" of positive charges on the side of material B (as compared to the usual electron density ρ_B) and a similar excess of negative charges on the side of material A, thus creating a net electric field at each junction, E_0 and E_1.

Now let us introduce a temperature difference between the two junctions, keeping one at a temperature T_0 and the other at T_1 so that $T_0 > T_1$. Increasing the temperature simply gives the electrons more kinetic energy to move around: they will be moving more quickly to correct the overall charge imbalance at the site with the higher temperature, i.e. at junction 0. Hence the excess of positive and negative charges at 0 will be greater, resulting a larger field than at 1. Now that there is a net electric field in the loop, the current starts to flow. As we have claimed earlier, a temperature difference led to potential difference and production of electric current.

Peltier effect

The Peltier effect is the inverse of the Seebeck effect: an electric current passing through a loop made of two different materials results in a temperature difference between the two junctions. consider the same situation as in the previous section, with wires A and B. There is the same charge excess at the junctions as described in the previous section: however, this time the electrons are forced through the junctions in some particular direction. The junction at which the electron flow coincides with the direction of the local electric field is cooled down, as the electrons “use up” the energy offered by the existing potential difference; meanwhile, at the other junction the electrons flow against the local field, doing work and introducing heat into the junction, and heating it up as a consequence.

Ohmic heating

Ohmic heating is simply the process of heat production in a circuit when the current flows through a circuit element that possesses a non-zero resistance: according to Joule heating law, the heat production per unit time, P, is given by

$$P = I^2 R$$

where I is the current and R is the resistance of the circuit element. In the case of the TEC, it heats up both the thermal sink and the thermal reservoir.

Apparatus

A diagram of the refrigeration device (TEC) and its surroundings is provided in fig. 2. The TEC is sandwiched between an aluminum block and an aluminum heat sink. These two "thermal reservoirs" (at temperatures T_{in} and T_{out}, in units of Kelvin) pass heat into and out of the TEC through its surfaces at rates P_{in} and P_{out} (positive flow is defined to be the direction from input reservoir to output, units J/s = W). We shall often refer to the aluminum block being cooled as the "thermal reservoir", and to the aluminum heat dissipator as the "heat sink".

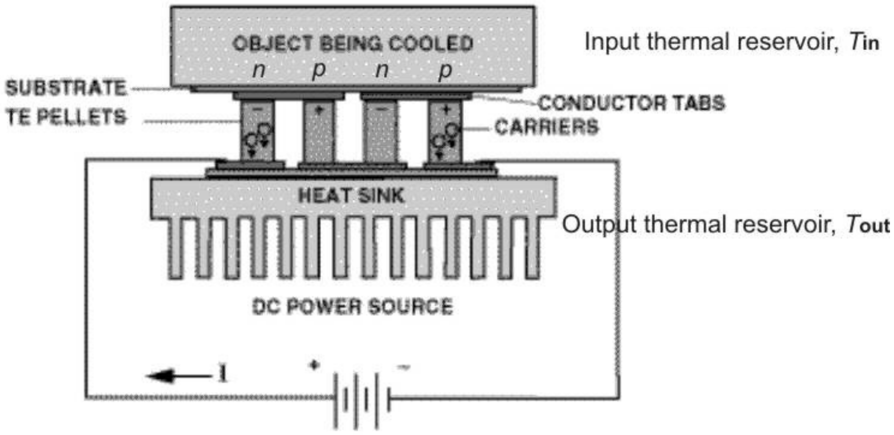

Figure 2: Schematic diagram of how a TEC can be used to cool an object. In our experiment, heat is supplied electrically to the input reservoir by resistive dissipation and heat is removed from the output reservoir by a forced flow of air. (Illustration from www.peltier-info.com.)

The TEC consists of multiple pairs of metal-semiconductor-metal junctions in which the semiconductor type is alternated. The thermocouple pairs are connected electrically in series and thermally in parallel (Figures 1, 2 and 3).

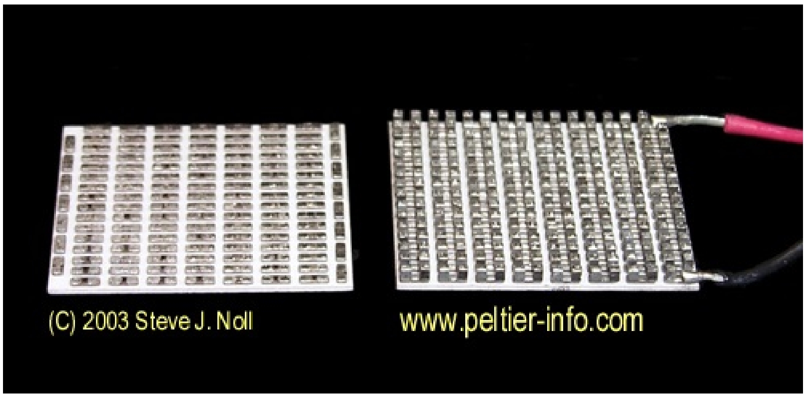

Figure 3: (Right) TEC with one face removed:- bismuth telluride bricks, doped with impurities to be p or n semiconductors. (Left) copper connection strips and top surface. (Illustration from www.peltier-info.com)

Although the materials connecting the surfaces of the TEC between the junctions are p and n semiconductors, the device contains only metal-to-semiconductor junctions. Thus, a TEC does not exhibit the non-linear voltage versus current characteristic of a semiconductor diode (which requires a $p-n$ junction). It acts like a battery (the thermocouple voltage) in series with a small ohmic resistance; and a potential difference of only a few volts applied across the TEC can cause an ampere level current to flow through it. The device itself is symmetrical; so the direction of current flow determines the direction of heat flow from one surface of the TEC to the other.

Theory

In our experiment, heat is supplied at a controlled rate to the "input" thermal reservoir, by passing an electric current through a pair of resistors attached to it (total resistance $R_h = 2.0\ \Omega$; $P_{in} = I_h V_h = I_h^2 R_h$). The input reservoir is only poorly connected to the air environment, so the heat flow into the TEC (P_{in}) will be closely equal to the amount of resistive heating of the reservoir. (Of course, if the input reservoir is at a very different temperature than ambient air, it will receive or lose heat at a small rate, but this can be neglected, at least initially).

The total flow of electrical power into the TEC is $P_d = V_d I_d$ where, respectively, V_d and I_d are the total voltage across the device and the current flowing through it. This power is used in two ways: as electrical work ($V_s I_d$) done to overcome the TECs Seebeck voltage V_s, and as ohmic power dissipation which heats the TEC ($I_d^2 R_d$). The first part drives the Peltier heat pump; the second part heats the TEC, and is an undesired side effect.

The output thermal reservoir is a fan-cooled, finned, aluminum heat sink which dissipates P_{out} into the air environment. To do this, the heat sink's temperature (T_{out}) must rise a few degrees above the ambient air temperature (T_0).

The input reservoir gets (nearly) all its heat from the heating resistors (R_h). Thus $P_{in} = R_h I_h^2$, if the temperatures of the TEC and its thermal reservoirs are not changing, i.e. if the system is in equilibrium. Conservation of energy requires that $P_{out} = P_{in} + P_d$.

The temperature at the input and output of the TEC are monitored in the input and output thermal reservoirs. Locations of the electrical connection points and the temperature monitoring points in the apparatus are shown in fig. 4, along with all necessary circuitry. The modelling equations are provided in fig. 5.

Set-up

The setting up of the experimental apparatus can be tricky. We outline here a step-by-step procedure. First take the TEC and plug it into the power outlet, then take the current balance and plug it into the Variac transformer, then plug the Variac transformer into the power outlet. Connect the current balance, using banana plugs, to the resistor ports labelled in fig. 4, and connect a ammeter (AC settings) in series to this circuit. Connect a second ammeter (DC setting) in series to the two red (positive) ports and, as in fig. 4, and connect a voltmeter (DC setting) in parallel to the negative (black) port and one of the red ports. Connect the filter capacitors to the **positive** port of the ammeter (DC setting), and to the **negative** port of the voltmeter (DC setting).

Now you have your apparatus ready. However, it is important to do a system check before you begin to take any measurements. To perform a system check, follow the instructions below. If at any stage you cannot complete the check due to a failure of the apparatus, proceed to the table of possible fixes below the instructions.

1. Turn on the TEC with no power in the Variac transformer. Make sure that the aluminum finned side (heat sink) is the 'hot' side (this is the side with the fan). Make sure that the input thermal reservoir is getting colder as time increases (this step does not need to be performed for a long period: if you see the system cooling, everything is fine).

2. Turn on the TEC device, and allow the temperature difference between the two plates to reach a few degrees. Turn the Variac transformer on and turn the dial so that it has a power output of 5 W. To d this, note the reading on the ammeter (AC setting), connected to the current balance. The current balance outputs a constant 5 V by the transformer, therefore by turning the dial you only change the current. Use this and calculate what the current has to be to provide a power output of 5 W, and turn the dial to the appropriate setting. If the temperature of the input thermal reservoir does not change (or the cooling process is not slowing down), turn the dial on the Variac transformer to its maximum power output. This should result in the temperature increase for both the thermal reservoir and the heat sink.

3. Turn off the Variac and run the system until the thermal reservoir reaches around 0°C; monitor the thermal reservoir's temperature. If the temperatures reaches a low value(around 273.13 K) and continues to decrease then the system is fine. Please note that sometimes at some negative values of temperature, the thermometers fail to register the correct temperature — their reading start to spontaneously increase. Keep a close eye on the temperature when it reaches negative values (around $-5°$).

4. Run the TEC as in (3) again, but this time introduce 1 W of power into the system, to ensure complete control of the variables.

The next section contains the possible ways to fix your system. If none of these work, seek help from the TA or the Technologist:

1. Unplug the filter capacitors. Their only function is to filter out the noise produced by the TEC. If you do unplug the capacitors, please note that you are introducing additional error into your measurement of the DC current and DC voltage, which you have to account for in the data taking process. Remember to note in your lab manual if you remove these capacitors and explain what error they introduce into the system and what effect it has on the variables of the TEC.

2. Turn on the TEC in the incorrect configuration you currently have, and check the wires periodically to see if they get hot. If they get hot then you have wired

something incorrectly or may need to change the banana plug for a new one. Try both techniques if neither work move on to step 3.

3. Allow the TEC to be turned on and let it run for about 15 minutes, check the temperature of the thermal reservoir and the heat sink and test these values for several thermometers, if they are showing different results seek help from the Technologist.
4. Remove all wires from the system, and re-wire the set up. This may seem tedious and useless, but sometimes fixes the issues with the system.

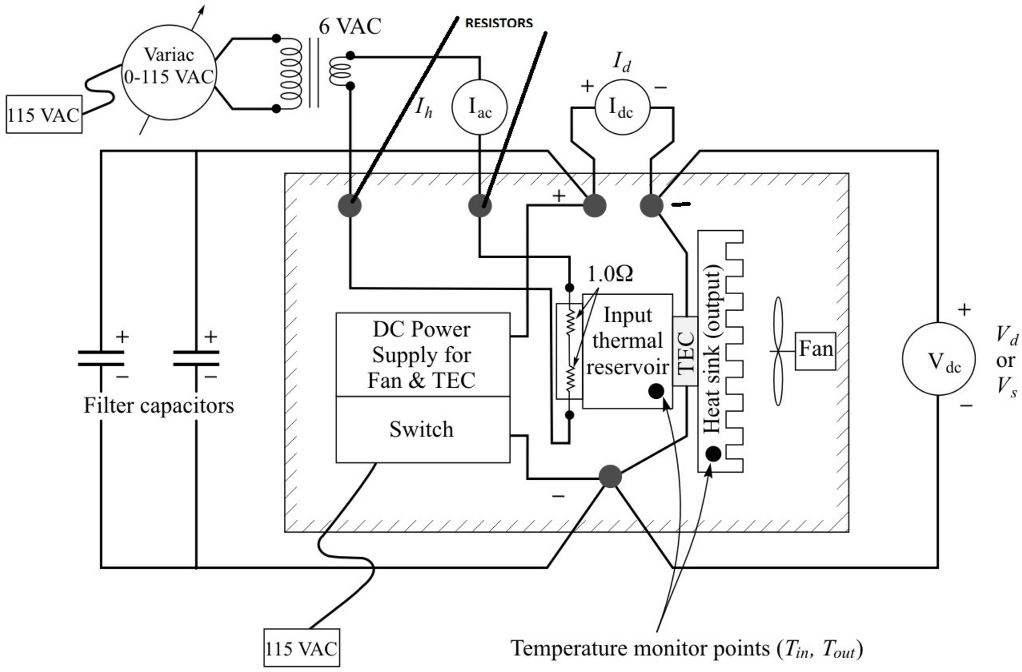

Figure 4: Connection points on the experiment assembly.

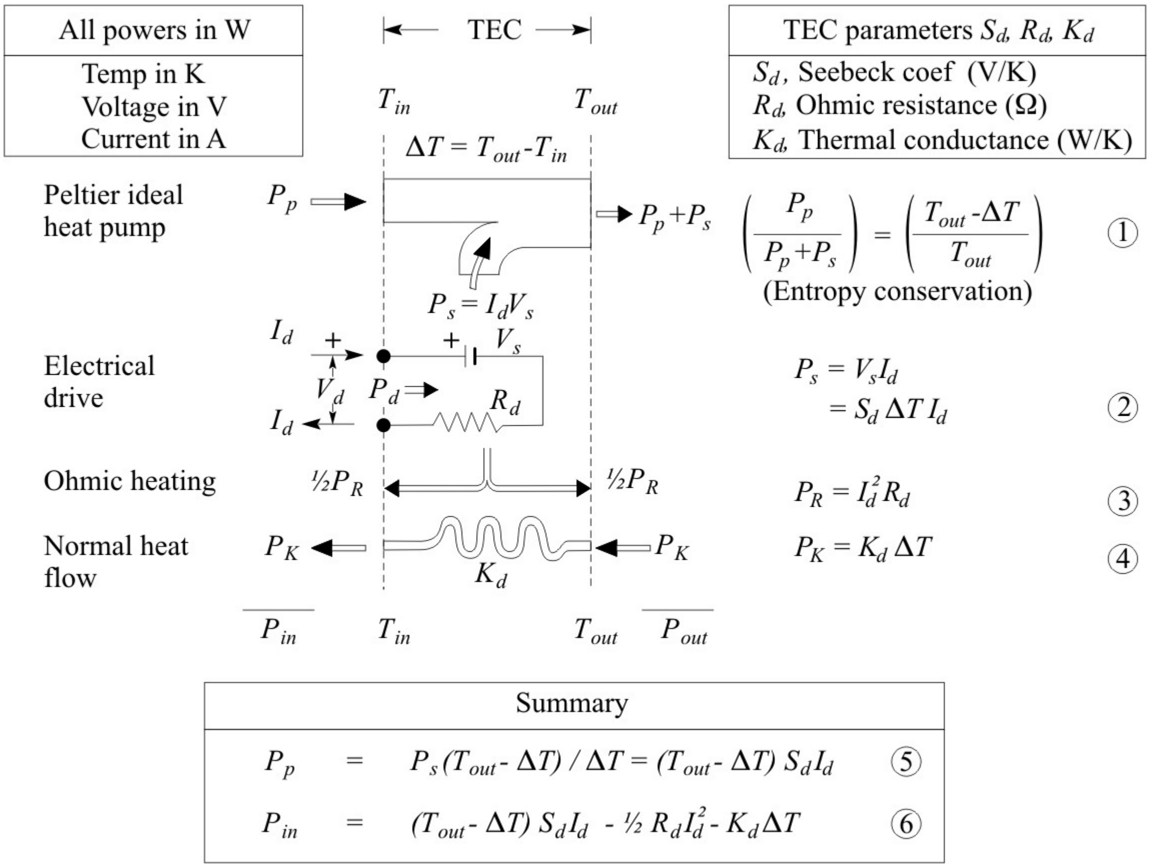

Figure 5: Phenomenological model of TEC behaviour.

Experiment

Creating a phenomenological physical model of a TEC

The aim here is to use basic macroscopic physical principles to interrelate different aspects of the TEC's performance. Included in the modelling equations are some unknown parameters that depend on the TEC's construction and its materials. If the values of these parameters can be estimated by a few experimental measurements, performance in other circumstances can be predicted. The standard phenomenological model of a TEC contains only three elements:

1. An ideal Peltier (Carnot) reversible heat pump which is just an ideal thermocouple working in reverse;
2. Ohmic resistive heating (in addition to the Peltier effect) that occurs in the TEC semiconductor materials when current is passed through it;
3. Normal (non-electronic) heat flow from the hot output port of the TEC to the cooler input port, such as occurs when the TEC is disconnected electrically. This is shown schematically in fig. 5, along with the relevant equations.

Remember that the model applies to steady state operation of the TEC. The TEC (and especially the thermal reservoirs attached to it) possess significant heat capacity. When input-output conditions are altered, it will take some minutes for the reservoirs and the TEC parts to heat up or cool down, and for a new steady state to be established.

TEC operation modes

Conceptually, the apparatus allows the TEC to be operated in three ways:

1. With an approximately fixed current ($I_d \approx 10$ A), supplied from the built in power supply;
2. Not operated, with terminals open circuited ($I_d = 0$): this is accomplished by unplugging **one** of the cords connecting the TEC to the ammeter (DC current);
3. Not driven ($I_h = 0$), but with the TEC terminals short circuited. However, this 3rd state is hard to achieve in practice, because a path needs to have very low (milliohm) resistance to be effectively a short circuit (zero resistance). The resistance of plug-in leads is often higher than this. Also, it may preclude insertion of an ammeter, because the meter's resistance may be too large. If you wish to do such an experiment, connections must be made with thick wire firmly clamped into the screw terminals of the apparatus, and current measurement must be obtained by reading (with an electronic micro-voltmeter) the very low voltage produced across a very low value resistor often called a ”current shunt” or ”current sense resistor” (10 mΩ or 1 mΩ).

Heat can be supplied to the input thermal reservoir at any desired rate by adjusting the 60 Hz voltage output from a Variac variable transformer which is applied (via a separate step-down transformer) to the pair of series connected 1.0 Ω resistors. Power inputs in the range of about $0 - 20$ W are feasible.

When the TEC and its thermal reservoirs are in steady operation, the thermal inertia of the system allows turning off the TEC current I_d for a few seconds without much disruption of its temperature state. Thus, one can record the total Seebeck thermocouple voltage being generated in the TEC simply by breaking the current supply circuit for a few seconds and measuring the voltage across the TEC carefully.

Procedure

Main exercises (complete all, including modelling, for 3 weights)

1. Passive heat flow experiment (TEC in mode (2))

   For several values of P_{in} from 0 to about 5 W, measure the steady state temperatures of the input and output reservoirs, and the ambient air. Graph the temperature differences $T_{in} - T_{out}$ and $T_{out} - T_0$ as a function of P_{in}, and try to estimate the thermal conductance K_d of the TEC (between the two reservoirs) and K_{hs} between the output heat sink and the ambient air.

2. Cooling experiments
   (a) After letting the system cool off (i.e. when the temperature of the thermal reservoir and the heat sink are nearly the same) after experiment 1, operate the TEC with no heat input (TEC mode (1) and with the Variac turned off) to the input reservoir for about 15 minutes, while monitoring the voltage across the TEC and the current supplied to it, as well as the input and output temperatures. Draw a graph of the temperature change and the electrical power input P_d versus time. It will be hard to establish a completely steady state, but after a few minutes, changes in state should be slow enough that the temperatures and power input P_d can effectively be measured nearly simultaneously.
   (b) After about 15 minutes of cooling in exercise 2(a), with the temperature difference in the TEC of about 30°C, turn on the Variac and apply different power inputs (P_{in}) to the system. For each value of P_{in} allow the system to reach a semi-steady state (run each trial for roughly 2 minutes). In steps lasting a few minutes each (so a steady state is approximated) apply increasing amounts of power to the resistors on the input reservoir (0 to 10W). Monitor the reservoir temperatures, P_{in} and P_d (with I_d on) and also V_s, the Seebeck voltage (with $I_d = 0$), and plot graphs of the reservoir temperature differences, P_d and V_d versus P_{in}. To measure the Seebeck voltage, turn off the TEC at the end of each trial for a second or two, and study the DC voltage. When you turn off the TEC the voltmeter will first show the voltage changing abruptly, then changing in a continuous manner; The value you are looking for is the start of this continuous run-off of voltage. This value corresponds to the Seebeck voltage and will be used to calculate the Seebeck coefficient.

3. After examining the modelling equations given in fig. 5, select results from experiments 1, 2(b) which allow you to calculate K_d (thermal conductance of the system), S_d (Seebeck coefficient) and R_d.[1]

4. Use the TEC model to predict the results of 2(a) (i.e. calculate te lowest achievable temperature at the thermal reservoir with no heat input).

5. Decide what would be the optimum drive current (derivative of P_{in} for the device if it is to be operated (say) with an output temperature of 35°C and an input temperature not exceeding 5°C. Recall that $P_{out} = P_{in} + P_d$. We desire a situation

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[1] Note that the R_d is the resistance across the TEC and not the resistance of the resistors used in conjunction with the Variac power source.

in which P_{out} is largest: it corresponds to the point at which the heat is rapidly leaving the TEC's thermal reservoir. Hence we want to maximize P_{out}. When operated at this current, what is the maximum rate (P_{in} at which heat can be supplied the input reservoir (without it warming above 5 C)?

6. What is the lowest input temperature that can be achieved with this device (using the optimum input current), if absolutely no heat is admitted to the input reservoir?

Additional Exercises

The model described above does not take into account thermal conductances / resistances between the heat sink and the environment, or the input reservoir and the environment, or in the TEC between the semiconductor elements and the surface of the TEC. Can you estimate these from observational data you can obtain or by looking up properties of materials in handbooks and create a more complete model of the TEC? How would you make a dynamic model (one that would predict warm-up /cool-down rates)?

References

[1] `http://en.wikipedia.org/wiki/Thermoelectric_effect#Peltier_effect`

[2] `http://www.ferrotec.com/usa/thermoelectric/ref/3ref2.htm`

[3] `http://www.peltier-info.com/info.html`
`and links at bottom of Introduction page`

[4] `http://www.tf.uni-kiel.de/matwis/amat/elmat_en/kap_2/backbone/r2_3_3.html`
`(Theory of Seebeck and Peltier effects)`

The lab manual was revised in 2014 by P. Albanelli and S. Fomichev.