The University of Hong Kong
Department of Physics

Physics Laboratory
PHYS3760 Physics Laboratory

Experiment No. 3760-6:
Thermoelectric phenomena: heat pump and heat engine

Student number:

University number:

Objective:

To learn about the operation principle of the heat pump and heat engine

Introduction

Section A – Coefficient of performance, Thermal efficiency and Carnot efficiency

1. Peltier effect is the cooling and heating at the junctions of two dissimilar metals when an electrical current is passed through the metals.
2. Seebeck effect occurs when a temperature gradient generates an electrical current in the loop of two dissimilar metals,
3. Heat Pump

   In Heat Pump mode the peltier does work to pump heat out of the cold reservoir and into the hot reservoir.
   W = work done by the peltier (equal to the area under the Input Power curve),
   Q_{hot} = heat pumped into the hot reservoir,
   Q_{cold} = heat pumped out of the cold reservoir.

   By the first law of thermodynamics,
   $$Q_{hot} = Q_{cold} + W$$

A graph of heat pump

4. Heat Engine

   In a heat engine, heat flows out of the hot reservoir, some of the heat is converted to work, and the rest of the heat flows into the cold reservoir.
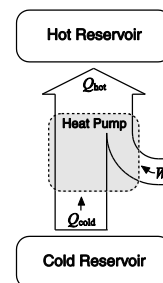 W = work done by the heat engine,
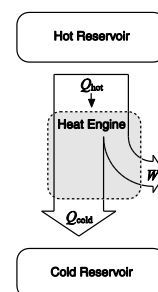 Q_{hot} = heat flow out of the hot reservoir,
   Q_{cold} = heat flow into the cold reservoir.

   By the first law of thermodynamics,
   $$W = Q_{hot} - Q_{cold}$$

A graph of heat engine

5. Coefficient of Performance and Thermal efficiency
   ▪ In the real case, the efficiency of a *heat pump* is called **Coefficient of Performance** defined by the Q_{cold}, the heat absorbed from the cold reservoir divided by the W, work done

   Equation of coefficient of performance   i.e. $k_{pump} = \dfrac{Q_{cold}}{W}$ (1)

   ▪ In the real case, the efficiency of a *heat engine* is called **thermal efficiency** defined by the W, work done divided by the Q_{Hot}, the heat released from the hot reservoir

   Equation of thermal efficiency   i.e. $k_{engine} = \dfrac{W}{Q_{Hot}}$ (2)

   In this experiment, the heat input is supplied by an electric current and the work output is in form of electric power.

6. Ideal Coefficient of Performance
   ▪ In the ideal case, the coefficient of performance or COP, of a heat pump is the ratio of the change in heat at the "output" (the heat reservoir of interest) to the supplied work

   Equation of Ideal coefficient of performance   .i.e. $COP = \dfrac{T_{Cold}}{T_{Hot} - T_{Cold}}$ (3)

   Where T_{Hot} and T_{Cold} are the temperatures of the hot reservoir and the cold reservoir in absolute temperature scale.

7. Carnot efficiency
   ▪ In the ideal case, Nicolas Léonard Sadi Carnot showed that the maximum efficiency of a *heat engine* is called Carnot Efficiency which depends only on the temperatures between the heat and cold reservoir.

   Equation of Carnot efficiency   i.e. $\eta_{Carnot} = \dfrac{T_{Hot} - T_{Cold}}{T_{Hot}}$ (4)

   Where T_{Hot} and T_{Cold} are the temperatures of the hot reservoir and the cold reservoir in absolute temperature scale.

   The only engines which can be 100% efficient are ones which operate with a cold reservoir at absolute zero degree. The Carnot efficiency is the best a heat engine can do for a given pair of temperatures when there is no energy loss.

Section B – Load resistance and Efficiency

8. All real electrical power supplies (including the peltier heat engine) have an internal resistance, R_i. They can be modeled as an ideal voltage source in series with a resistor, as shown below (with an output load connected).
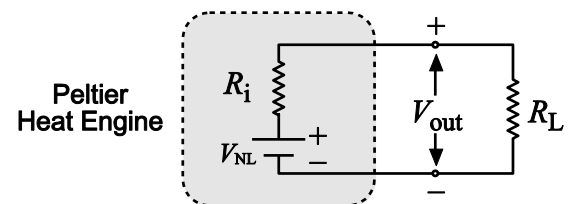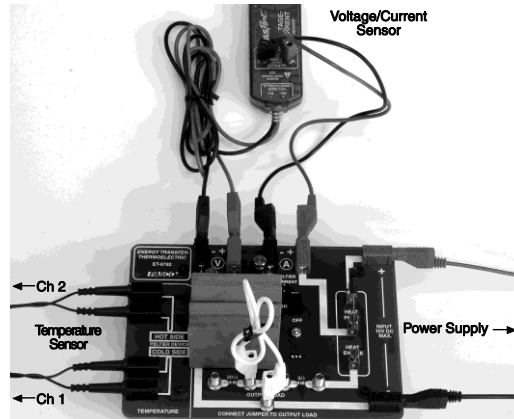
The voltage of the ideal voltage source, V_{NL}, is called the no-load voltage. For a peltier heat

engine V_{NL} depends only on ΔT.

$$\text{Equation of output power} \qquad P = \frac{V_{NL}^2 R_L}{(R_i + R_L)^2} \qquad (5)$$

Setup

Procedure

Section A – Coefficient of performance, Thermal efficiency and Carnot efficiency

Data Collecting:

Part 1 - Heat Pump Performance

1. Turn on the power supply.
2. Connect a jumper from the terminal at the bottom of the board to Terminal B. This makes the load resistance 3 Ω + 7 Ω = 10 Ω.
3. Start the DataStudio program and open the file "Conservation of Energy.ds"
4. Before you start, the aluminum blocks should both be at room temperature.
5. The knife switch should be in neutral position (straight up)
6. **The fan should be <u>switched off</u>**
7. Set the input DC Voltage to 4 volts. **[Never set the input DC Voltage above 10V.]**
8. Start data recording, then set the knife switch to Heat Pump.
9. **<u>Record the input Power data appear in the top section of graph for the discussion</u>**. Observe how the temperatures of the aluminum blocks change for about a minute (or until the cold side appears to reach a minimum temperature) . **[Thermoelectric circuit board should not be run with hot side above 80°C for longer than 5 min.]**

Part 2 - Heat Engine Performance

10. When the Heat Pump mode runs for about **<u>a minute</u>** (or until the cold side appears to reach a minimum temperature), switch to Heat Engine mode **<u>immediately</u>**.
11. **<u>Record the Power Generated data now appears in the bottom section of the graph display.</u>** Observe how the temperatures of the aluminum blocks change.
12. Continue to record until the aluminum blocks are close to the same temperature.

Data Exporting:

1. Click on the File >> Export Data

2. In the window of Export Data, Click on the item that you would like to export.
3. Save as the exported file as text file.

Data Collecting:
1. Unplug the jumper which connecting the resistors.

2. Open the file "Load of efficiency.ds"

3. Click the Start button. DataStudio will show live temperature readings in the Digits display, but it won't start recording yet.

4. Observe the temperature of both sides of the peltier; both should be close to room temperature. During the experiment, you will take the peltier through several cycles of heating and cooling. You must ensure that both sides of the peltier are close to room temperature before each cycle starts. Note the room temperature for future reference.

5. Set the voltage on power supply to about **7 volts**. Set the switch to Heat Pump mode for about **2 seconds**, then return it to the neutral position. If the voltage/current sensor beeps, then the current is too high (over 1 amp) and you should decrease the voltage (then close the switch again to test it).

6. Set the switch to the Heat Engine position and allow the blocks to cool. Wait until both sides are within a few degrees of room temperature. (To cool faster, install the heat sink on the hot block and turn on the cooling fan. It also helps to put a metal object in contact with both blocks.)

7. Connect the output load jumper to terminal D. This bypasses all of the resistors and reduces the load resistance to almost zero. Note that the resistance is not exactly zero because the wires and traces on the board have some resistance.

8. Ensure the fan is turned off.

9. Set the switch to Heat Pump mode. Watch the difference in temperature between the two blocks (ΔT). You are waiting for ΔT to reach 35 $^\circ$C, which will take about one minute.

10. When ΔT reaches 35 $^\circ$C, change the switch to Heat Engine Mode **immediately**. The temperature difference will start to decrease. When ΔT drops below 35 $^\circ$C, DataStudio will automatically start recording. You will see data appear on the graph of Power Generated vs. ΔT.

11. When ΔT drops below 5 $^\circ$C, data recording will stop automatically.

12. Change the name of the data run to indicate the load resistance.
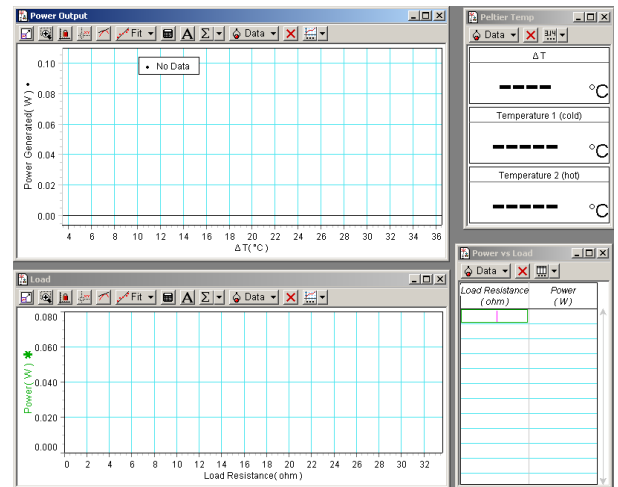
13. Click Start. DataStudio will display temperature data, but it won't start recording yet.

14. Use the fan to cool the blocks to within a few degrees of room temperature.

15. Change the output load to 3 Ω (connect the jumper to terminal C).
16. Repeat the cycle of heating and cooling. (Go back to step 8.)
17. Repeat the cycle again for the following values of output load:
- 7 Ω (Connect the jumper to B, but also connect a shorting jumper from C to D.)
- 10 Ω (Connect the jumper to B.)
- 20 Ω (Connect the jumper to A, but also connect a shorting jumper from B to D.)
- 30 Ω (Connect the jumper to A.)

When you are finished, you will have acquired power and temperature data for six different values of output load resistance.

From the data that has been recorded you will extract the data needed to plot a graph of Power Generated (P) versus Load Resistance (R_L) at $\Delta T = 30$ °C.

On the graph of P vs. ΔT use the smart cursor to read the power generated at $\Delta T = 30$ °C for each value of load resistance. (Use the zoom select tool to change the scale of the graph and enlarge the area around the data at 30 °C in order to read the data precisely.)

Enter the values in the Power vs. Load table. As you enter data into the table, they will be plotted on the Power vs. Load Resistance graph.

Data Exporting:
1. Click on the File >> Export Data
2. In the window of Export Data, Click on the item that you would like to export.
3. Save as the exported file as text file.

Data:

Section A – Coefficient of performance, Thermal efficiency and Carnot efficiency

Step 9: Input Power = _____

Step 11: Power Generated =_____

Discussion:

Section A – Coefficient of performance, Thermal efficiency and Carnot efficiency

1. According to equation (1), use your values for the heat pumped out of the cold block (Q_{cold}) and the area under the Power versus time curve (W) to calculate the Coefficient of Performance, k_{pump},
2. According to equation (3), use your values for the maximum temperature of the hot block and the minimum temperature of the cold block calculate the ideal Coefficient of Performance, *COP*,
3. According to equation (2), use your values for the heat output from the hot block (Q_{hot}) and the area under the Power Generated versus time curve (W) to calculate the thermal efficiency, k_{engine},
4. According to equation (4), use your values for the maximum temperature of the hot block and the minimum temperature of the cold block calculate the Carnot efficiency, η_{Carnot}
5. Comment on the differences and discuss the obtained results.

Section B – Load resistance and Efficiency

6. Based on equation (5) and graphs, under what condition is *P* at its maximum?
7. Plot the Power vs. ΔT graphs for different resistances. Discuss the obtained results.

Appendix A- *details of the DataStudio configuration file of Conservation of energy.ds"*

DataStudio has been configured to measure and record the temperature of both aluminum blocks, the voltage and current applied to the peltier during Heat Pump mode, and the voltage and current generated by the peltier during Heat Engine mode. From these measured quantities, DataStudio will calculate and display heat flow, power and work. The following sections explain how DataStudio makes those calculations.

1. Heat vs. Temperature

Each digits display shows the heat (Q_{hot} or Q_{cold}) that flows into or out of the aluminum block on either the hot or cold side of the peltier. The relationship between heat flow and temperature change is given by

$$Q = mc\Delta T$$

where: Q = heat transferred,
   m = mass of the aluminum block,
   c = specific heat of aluminum = 0.90 J/(g·°C),
   ΔT = change in temperature.

A positive value of Q may represent heat transferred into *or* out of the aluminum block, depending on whether the block is on the hot side or the cold side of the peltier, and whether the peltier is operating as a heat pump or a heat engine.

The temperature of each block is measured by the embedded thermistor. DataStudio calculates the heat flow from the measured temperature change, and pre-entered values of m and c. Click on the calculator icon in the tool bar and look at the equations used; note the constants, m and c, in the bottom section of the calculator window. (The mass of each block is about 19 g. If you would like to enter your own value for the mass, measure the blocks with calipers and use the density of aluminum, 2.7 g/cc, to calculate the mass, then enter it in the calculator.)

2. *Input Power and Work Done by the Peltier Heat Pump*
   In Heat Pump mode, Input Power from the power supply equals the rate at which the peltier does work to pump heat out of the cold reservoir and into the hot reservoir. The Voltage/Current Sensor measures the voltage applied to the peltier, and the current that flows through it. DataStudio calculates the Input Power using the equation: Power = Voltage × Current.
   The area under the plot of Input Power versus time equals the energy supplied to the peltier, which equals the work done by the peltier.

3. *Power Generated and Work Done by the Peltier Heat Engine*
   In Heat Engine mode, Power Generated is the rate at which the peltier does work on the load resistor. The Voltage/Current sensor measures the voltage across the resistor and the current through it. From these measurements, DataStudio calculates the power supplied to the load resistor. The area under the plot of Power Generated versus time equals the work that the peltier has done on the resistor.

Appendix B- *details of the DataStudio configuration file of Load of efficiency.ds"*

1. *Calculations:* DataStudio will measure the temperature of both blocks (T_{hot} and T_{cold}), the voltage across the load resistor, and the current through the load resistor. From these measurements it will make two calculations, temperature difference (ΔT) and output power (P), using the following equations:

$$\Delta T = T_{hot} - T_{cold}$$

$$P = \text{current} \cdot \text{voltage}$$

2. *Start and Stop Conditions:* DataStudio has been configured with start and stop conditions, which control when it records data. The start condition is that ΔT must drop below 35 °C. Before the beginning of each cycle (when $\Delta T < 35\,°C$) you will click the Start button; DataStudio will display live data, but it will not start recording. Data recording will not start until the ΔT has increased above 35 °C and then dropped back below that level. The start condition will enable you to view the temperature measurements without recording them. The stop condition will cause data recording to stop when ΔT drops below 5 °C.

3. *Changing the Name of a Data Run:* DataStudio will record a separate data run for each load resistance. In order to keep track of them, you will rename each data run. By default, the runs are named Run #1, Run #2, etc. In order to rename a run, find it in the Summary window (on the left side of the screen), click on it once to select it, then click on it again to edit it (be careful to single- click twice, and not to double-click). Enter the new name (for instance, "7 ohms"). When DataStudio asks if you would like to rename all the data from this run, select Yes.

References:

1. Pasco Scientific Instruction Manual for Energy Transfer–Thermoelectric ET-8782.
2. Thermoelectric : basics principles and new materials developments / G.S. Nolas, J. Sharp, H.J. Goldsmid, Springer, 2001.