Thermodynamics of a Peltier cell

Physics – 397

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Introduction:

Thermoelectric devices are solid state devices that convert thermal energy from a temperature gradient into electrical energy (Seebeck effect) or convert electrical energy into a temperature gradient (Peltier effect). Seebeck first found that an electromotive force is generated by heating a junction between two dissimilar metals. The converse effect discovered by Peltier in 1834 and demonstrated beyond doubt by Lenz in 1838 when he successfully froze water at a bismuth-antimony junction. With the development of semiconductor compounds such as alloys of bismuth telluride or antimony telluride the pumping of substantial quantities of heat from one junction to another simply by passing an electric current is now possible and industrial and commercial applications are in process of development.

In this experiment students will be able to learn, how a commercial Peltier cell is used as a heat pump and as a heat engine. They can estimate the efficiency of the device. The laws of thermodynamics, particularly the second law, provide the students with a powerful perspective for evaluating the performance one can expect from thermoelectric devices. The commercial Peltier coolers are used in small refrigerators, CPU coolers, electronic component cooler, etc. These are yet to be used for large scale air cooling or fridges due to less efficiency than the mechanical heat pump.

Theory:

The thermoelectric effect is particularly interesting at metal-semiconductor junction, because it is much larger than in the case of a junction between two metals. Let us consider an *n*-type crystal with two Ohmic contacts (Fig.1.1)

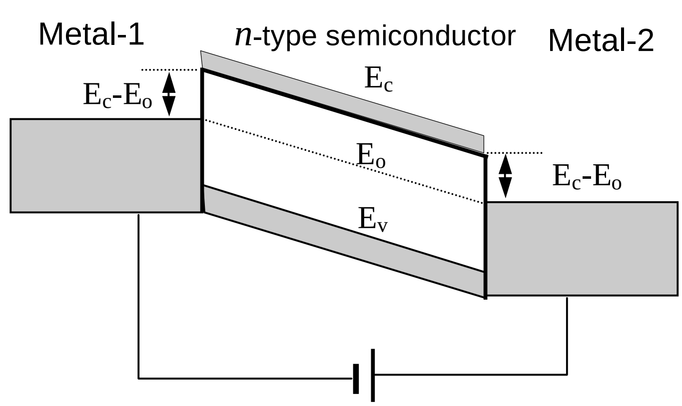


Fig. 1.1

E_c is the energy of the conduction band electrons of the semiconductor, E_o is the Fermi level. Shaded area represents electron-filled energy bands. As the contact is formed and upon reaching the equilibrium the Fermi levels of the metal and semiconductor merges. With a potential applied across the contacts, electrons with energies greater than E_c-E_o

can get into the semiconductor. Consequently, metal-1 at the left-hand contact, loses the electrons occupying its highest energy states because electrons flow from left to right in the diagram in response to the applied potential. At the right hand contact, these electrons are deposited into metal-2, so that the hottest electrons are moved from metal-1 to metal-2 by virtue of the contact effects and the current flow. As a result, metal-1 is cooled and metal-2 is heated by the amount of energy transferred per electron, which clearly equals E_c-E_o plus the kinetic energy of the electrons moving from a hot to a cold region. This is expressed in terms of the thermoelectric power Q_n for a *n*-type semiconductor, which is defined as:

$$-Q_n T = (E_c - E_o) + 2K_B T \quad \text{.........} \; (1)$$

Where, $\boldsymbol{K_B}$ is the Boltzmann Constant. Similarly the thermoelectric power for a *p*-type semiconductor is:

$$Q_p T = (E_o - E_v) + 2K_B T \quad \text{...........} \; (2)$$

Equations (1) and (2) show that the large values of thermoelectric power found in semiconductors basically result from the fact that the average potential energy for conduction electrons (or holes) is larger than the Fermi energy, in contrast to the situation in metals. It is advantageous to use a *p*-type and an *n*-type element together, because the thermoelectric effects of the two are additive. If two contacts of a semiconductor are maintained at a different temperatures (T_h-T_c=ΔT) , a potential difference can be observed between them (V_S). This is called Seebeck voltage and arises from the more rapid diffusion of carriers at the hot junction. These carriers diffuse to the cold junction, so that such a contact acquires a potential having the same sign as the diffusing majority carriers. The seebeck coefficient, S is defined as

$$S = \frac{V_S}{\Delta T} \quad \text{........} \; (3)$$

Thermoelectric cooling: Current (I_P) flowing in a circuit containing a semiconductor-metal contact tends to pump heat from one electrode to the other because of the Peltier effect. The Thermoelectric power of semiconductor is large enough to make such electronic cooling of practical interest, particularly where small size and absence of mechanical movements are desired. A single cooling unit consisting of a *p*-type element and an *n*-type element joined with Ohmic contacts is sketched in Fig.1.2

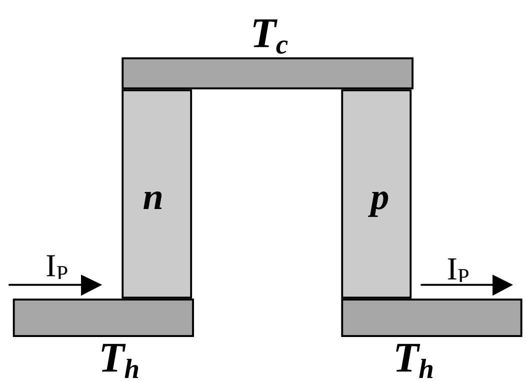


Fig. 1.2

The current I_P pumps heat from the common junction, cooling it an amount ΔT below the hot junction ($\Delta T = T_h - T_c$). The Peltier cooling effect is reduced by heat conducted down the elements normal thermal conductance, together with Joule heating in the elements due to the electric current. The heat removal rate at the cold junction is expressed as:

$$Q_c = S I_P T_c - \frac{1}{2} I_P^2 R_P - k \Delta T \qquad \text{……….. (4)}$$

or

$$Q_c = \Pi I_P - \frac{1}{2} I_P^2 R_P - k \Delta T \qquad \text{……….. (5)}$$

Where, Q_c is the heat removal rate from the cold junction
- k is the thermal conductance
- R_P is the electrical resistance of the semiconductor elements
- S is the Seebeck coefficient
- Π is the Peltier coefficient ($\Pi = ST$)

The factor ½ comes from an exact solution of the heat-transport equation for the problem. The power balance flow chart as expressed by equations (4) and (5) is illustrated in Fig.1.3. There is an optimum current for maximum ΔT for a Peltier cell (Fig.1.4). At low current the Peltier effect is small. At large currents, the cooling effect (Π I) is large, but the Joule heating is even larger because it increases as the square of the current. The cooling performance of a Peltier cell is best described by the figure of merit, defined as:

$$Z = \frac{S^2 \sigma}{K} \qquad \text{………. (6)}$$

Where, σ is the electrical conductivity and K is the thermal conductivity. It can be seen that a useful material has a large Seebeck coefficient and electrical conductivity but a small thermal conductivity.

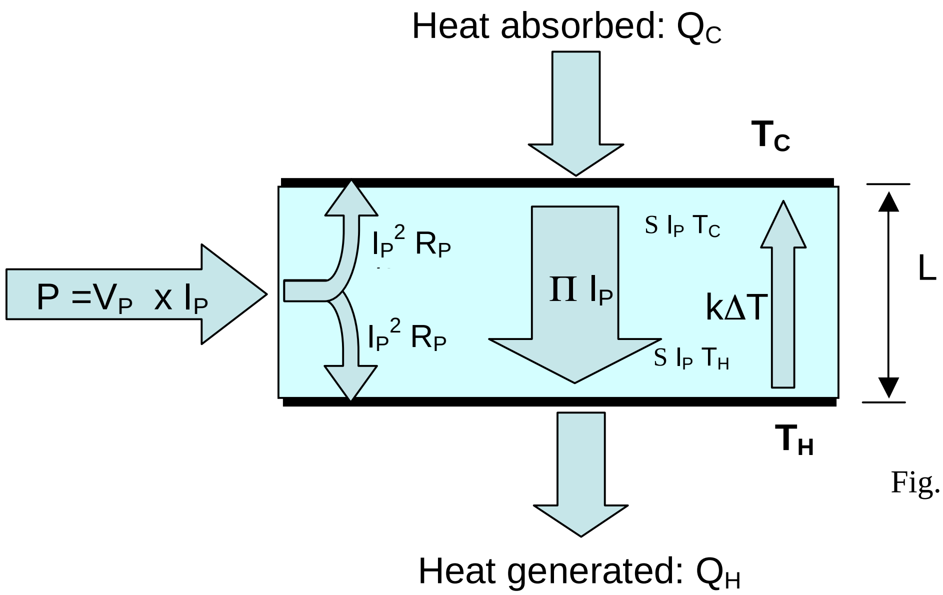

Heat absorbed: Q_C
T_C
$I_P^2\ R_P$
$P = V_P\ \ x\ I_P$
$\Pi\ I_P$
$S\ I_P\ T_C$
$k\Delta T$
L
$I_P^2\ R_P$
$S\ I_P\ T_H$
T_H
Heat generated: Q_H

Fig. 1.3

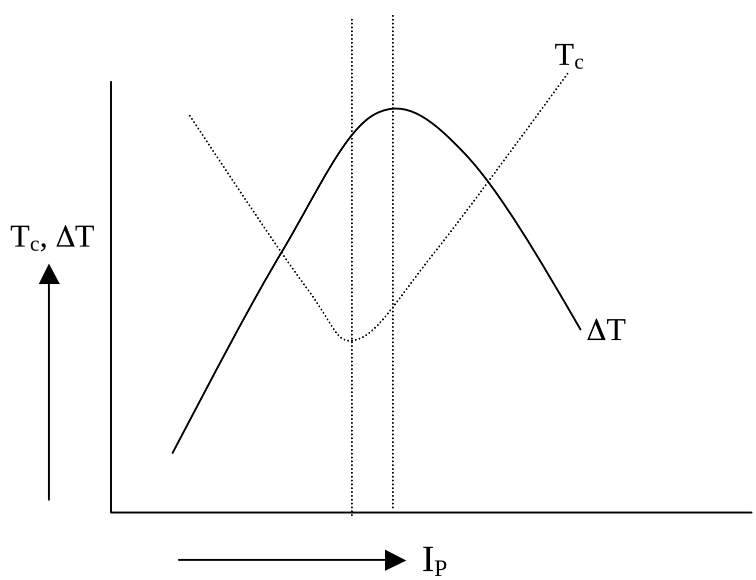

T_c
T_c, ΔT
ΔT
I_P

Fig. 1.4

Experimental Procedure

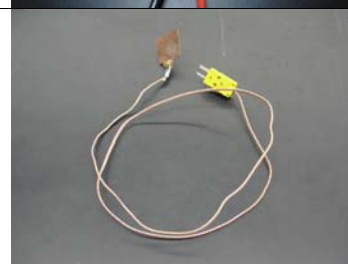
List of equipments:

1. Commercial Peltier cell
2. Aluminum or Copper Heat-sink
3. Small power film resistor heater
4. Two Thermocouples
5. Thermal paste
6. Water (ice) bath
7. Two Multimeters
8. DC Power Supply (0 – 20 V, 0 – 3 A)
9. Thermometer
10. Variable resistance (0 – 10 Ω)
11. Connecting wires

We suggest that the basic experiments are as follows:

1. Determination of Seebeck Coefficient
2. Determination of Thermal Conductivity and Thermal Conductance
3. Peltier cell as a Het Engine: efficiency and Carnot efficiency
4. Determination of internal resistance and resistivity of a Peltier cell
5. Peltier cell as a cooler: Maximum temperature difference, ΔT
6. Peltier cell as a heat pump
7. Determination of Peltier coefficient
8. Determination of cooling efficiency, η_C
9. Determination of figure of merit, Z
10. Determination of coefficient of performance, β

In the following pages, we give you guidance on how to perform the experiments above.

Component	Manufacturer / Model #	Photo
Peltier Cell	Manufac: TE Technology: TE – 31-1-2.0P TE - 63-1.0-2.0P Manufac: Melcor: CP-1.0-7-08 L CP1.0-17-08 L	
Thermocouple With lead	Thermocouple for OMEGA - i/32	
Thermocouple display unit	OMEGA i/32 Temperature and Process Controller	
Heat sink	Aluminum or Copper Finned Plate	
Thermal paste	OCZ Ultra 5+ Silver Compound	
Power film resistance heater	Manufacturer: CADDOCK MP820	

I. Determination of Seebeck coefficient, thermal conductance, and thermal conductivity:

The experimental setup is shown in Fig.2.1. The Peltier cell is placed on a large aluminum or copper heat sink (finned). Two thin copper plates connected with thermocouples are placed on the top and bottom of the Peltier cell. To achieve good thermal contact, small amount of thermal paste should be applied uniformly on both sides of the peltier cell. The small resistance heater (MP820) is placed on the top. The polystyrene screw is tightened so that the Peltier cell, thermocouple plates and the heater are firmly attached with the heat sink.

After the connections are completed, the temperature of the top and bottom of the cell should be the same as the room temperature.

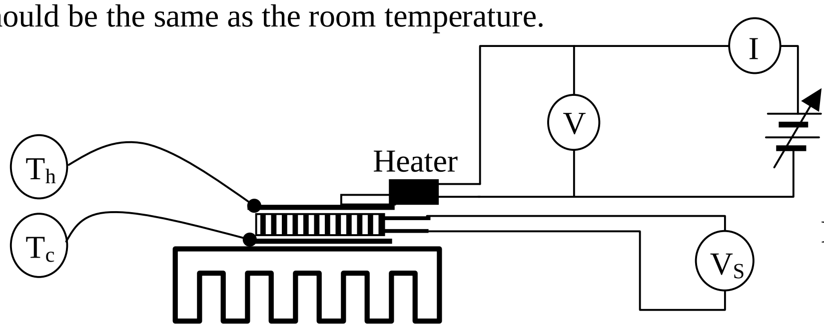


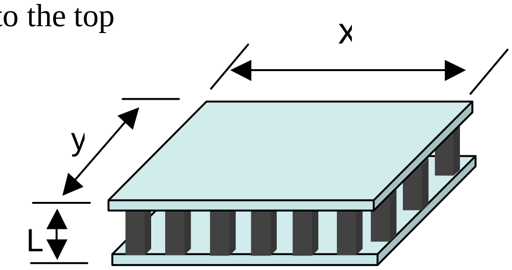
Fig.2.1

If one increases the current through the heater, V, I, V_S, T_h and T_c will change. This will enable you to determine a number of parameters that characterize the Peltier cell. For example, a plot of of ΔT (T_h-T_c) against V_S should allow you to determine the Seeback coefficient S.

Another useful parameter is the thermal conductance of the Peltier Cell, given by
$k = Q/\Delta T$
Assuming that all Q goes from the top to the bottom of the cell. In practice some heat is lost in the ambient.

Since the heat power delivered by the heater to the top junction of the Peltier cell is given by

$Q = V \times I$



Note that the thermal conductivity K of the cell is given by

$$K = \frac{L.Q}{A.\Delta T}$$

where A is the area of the cell and L is the thickness (see Fig. 2.2). Hence, in order to determine this parameter, the physical dimension of the cell must be determined.

II. **Peltier cell as a heat pump:**

The Peltier cell can be used as a cooler. This can be illustrated in the following setup***:*** The Peltier cell should be placed on the heat sink as in ***Expt I***. The heater should be removed and the peltier cell connected to a variable DC power supply (Fig.2.3). If you increase the current I_p through the cell, the temperature of the top junction should decrease. It may be interesting for you to compare the changes in the temperature with those sketched in Fig. 1.4.

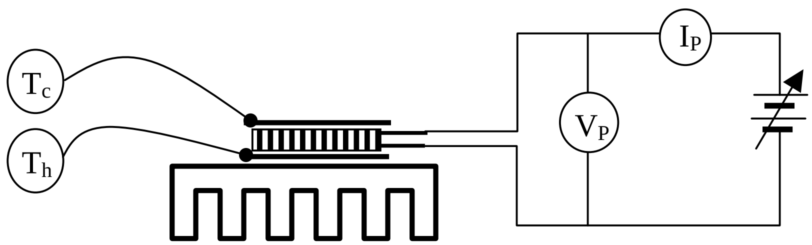


Fig.2.3

As decscribed in the introduction, the performance of a Peltier cooler is often characterized by a figure of merit

$$Z = \frac{S^2 \sigma}{K}$$

Hence, a determination of the electrical conductivity $\boldsymbol{\sigma}$ is needed to find $\boldsymbol{Z}$. Notice that $\boldsymbol{\sigma}$ is related to the internal resistance $\boldsymbol{R_p}$ via:

$$\sigma = \frac{L}{R_P \, . A}$$

To find the internal electrical resistance of the Peltier cell, consider the equivalent circuit (Fig. 2.4). Since the sum of the potential drops around the closed circuit must be zero, the following relationship must be satisfied:

$V_p = I_P.R_P + S.\Delta T$

This allows you to estimate R_p**.**

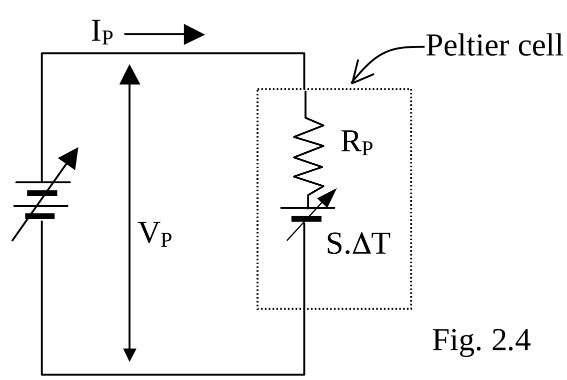


Fig. 2.4

III. **Peltier cell as a heat engine:**

All non-ideal devices operate at efficiencies less than 100%. To determine the practical efficiency of a Peltier cell as a heat engine, we can use the experimental setup in Fig. 2.5. The heat sink is placed in a Ice-water bath, the heater current is gradually increased until the temperature T_h reaches the room temperature. When the top is at room temperature, there is no possibility of losing heat to the ambient. Under this situation, measure the power delivered to the heater (V x I). Measure ΔT (T_h-T_c), and the voltage across the Peltier cell. As you already determined the internal resistance (R_P) of the Peltier cell, connect a resistor which is adjusted to be equal to that of R_P (R_P=R_m) , to ensure maximum power transfer to the external resistor, R_m. Measure the voltage across R_m, which is termed as V_{rm}.

Power delivered to R_m, $P_{rm} = \frac{V_{rm}^2}{R_m}$

Total power delivered to the external and the internal resistance $P_{total} = \frac{2V_{rm}^2}{R_m}$

The efficiency of the peltier cell as a heat engine: $\eta_{HE} = \frac{P_{total}}{V \times I}$

The Carnot efficiency of the heat engine is, $\eta_C = \frac{\Delta T}{T_h}$

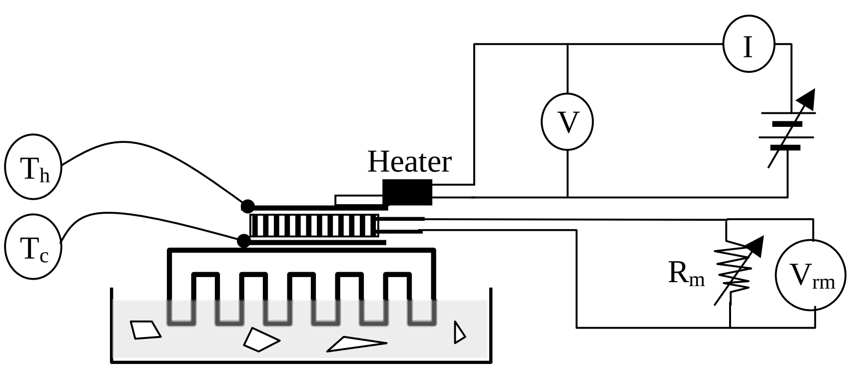


Fig. 2.5

***IV*. Determination of Peltier coefficient:**

The principle behind one method of determining the Peltier coefficient Π is as follows:

If a current I_p is supplied to the cell, the temperature of the upper junction will be lower than $T_{h.}$ If a current is now applied to the heater such that $T_c = T_h$, the term KΔT in Eq. 4 disappears and the heater power (VxI) equals the quantity of heat removed (Q_{remove}) from the top junction.

$$Q_{remove} = V \times I \qquad (heater)$$

$$Q_{remove} = \Pi\, I_P - \frac{1}{2} I_P^2\, R_P - k\Delta T$$

$$= \Pi I_P - \frac{1}{2} I_P^2\, R_P$$

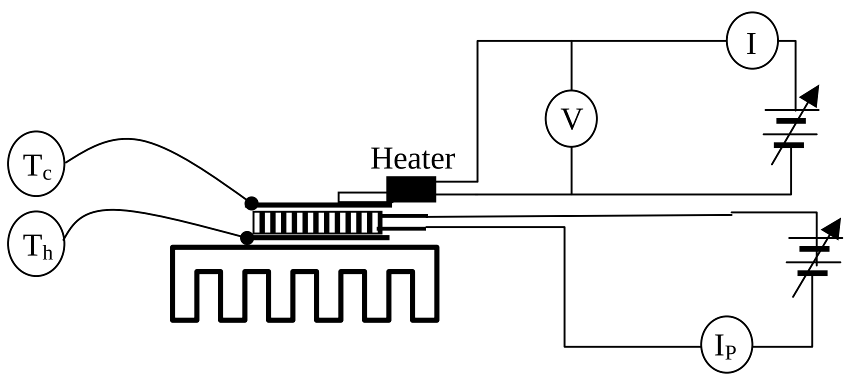


Fig. 6

This should allow you to estimate the Peltier coefficient.

Above equation can be linearized as:

$$\frac{Q_{remove}}{I_P} = \Pi - \frac{1}{2} I_P\, R_P$$

Plot of Q_{remove}/I_P vs I_P gives the value of $\boldsymbol{\Pi}$ as an intercept.

***V*. Determination of coefficient of performance (β):**

Coefficient of performance, β is the ratio of the rate of heat removal (Q_{remove}) to the power consumed (P_P) by the Peltier cell.

$$P_P = I_P^2 R_P + S I_P \Delta T$$

$$Q_{remove} = \Pi I_P - I_P^2 R_P / 2 - k\Delta T$$

The coefficient of performance is:

$$\beta = \frac{\Pi I_P - I_P^2 R_P / 2 - k\Delta T}{S I_P \Delta T + I_P^2 R_P}$$

It may be interesting for you to compare the I_p dependence of β with mechanical heat pumps.

References:

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3. M. Cvathe and J. Strand, "A thermoelectric experiment in support of the second law", Eur. J. Phys. 9, 11-17 (1988).
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Glossary:

A – Surface area (top or bottom) of Peltier cell
L – Thickness of Peltier cell
K - Thermal conductivity
k – Thermal conductance
K_B – Boltzmann Constant
S – Seebeck Coefficient
V_s – Seebeck voltage
Π - Peltier coefficient
R_P – Internal resistance of Peltier cell
I_P – Current through Peltier cell
V_P – Voltage across Peltier cell
I – current flowing in the power resistor
V – Voltage across power resistor
β - Coefficient of performance
η_C – Carnot efficiency
Z – Figure of merit
σ - Electrical conductivity of Peltier cell