# EXPERIMENT 21

## Thermal Efficiency Apparatus

## Introduction

The Thermal Efficiency Apparatus can be used as a heat engine or a heat pump. When used as a heat engine, heat from the hot reservoir is used to do work by running a current through a load resistor. The actual efficiency of this real heat engine can be obtained and compared to the theoretical maximum efficiency. When used as a heat pump to transfer heat from the cold reservoir to the hot reservoir, the actual coefficient of performance and the theoretical maximum coefficient of performance can be obtained. The apparatus is built around a thermoelectric converter called a Peltier device. To simulate the theoretical heat engines found in textbooks which have infinite hot and cold reservoirs, one side of the Peltier device is maintained at a constant cold temperature by pumping ice water through the block and the other side of the Peltier device is maintained at a constant hot temperature using a heater resistor imbedded in the block. The temperatures are measured with thermistors which are imbedded in the hot and cold blocks.

### Additional Equipment Needed

To perform the experiments in this manual, you will need the following equipment in addition to the Thermal Efficiency Apparatus.

- 1 DC power supply capable of 2.5A at 12V
- 3 kg (7 lbs) ice and a bucket for the ice-water bath
- Ohmmeter
- 1 Ammeter (up to 3A)
- 2 Voltmeters
- Patch Cords

## History

The principle upon which the Thermal Efficiency Apparatus operates has been known since the 1800's but has only become practical since the recent development of semiconductors. In 1821 the Russian-German physicist Thomas Johann Seebeck discovered that when a junction of dissimilar metals is heated, a current is produced[1]. This phenomenon is now known as the Seebeck Effect and is the basis of the thermocouple. Then, in 1834, Jean-Charles-Athanase Peltier discovered the opposite of the Seebeck Effect, that a current flowing through a junction of dissimilar metals causes heat to be absorbed or freed, depending on the direction in which the current is flowing[2]. Since the Thermal Efficiency Apparatus is operated in this manner the thermoelectric converter is called a Peltier device. However, the Thermal Efficiency Apparatus also exhibits the Seebeck Effect because the two sides of the device are maintained at different temperatures. Today the Seebeck Effect is achieved using pn junctions. The arrangement of the dissimilar semiconductors is as seen in Figure 21.1. If the left side of the device is maintained at a higher temperature than the right side, then holes generated near the junction drift across the junction into the p region and electrons drift into the n region. At the cold junction on the right side, the same process occurs but at a slower rate so the net effect is a flow of electrons in the n region from the hot side to the cold side. Thus there is a current from the cold side to hot side in the n region[3].

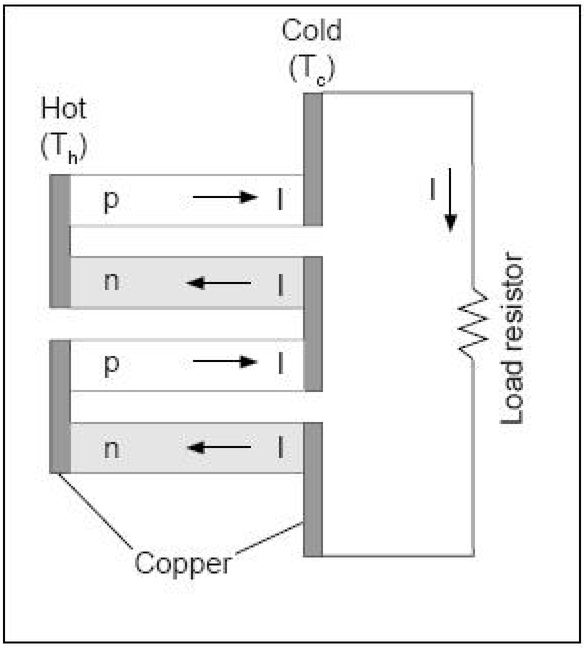


Figure 21.1: *Arrangement of Thermocouples*

[1] Timetables of Science, by Alexander Hellemans and Bryan Bunch, Simon & Schuster, NY, 1988, p.281.

[2] IBID, p.301.

[3] Circuits, Devices, and Systems, 3rd ed., by Ralph J. Smith, Wiley, 1976, p.543.

## Theory

### *Heat Engine*

Introduction

A heat engine uses the temperature difference between a hot reservoir and a cold reservoir to do work. Usually the reservoirs are assumed to be very large in size so the temperature of the reservoir remains constant regardless of the amount of heat extracted or delivered to the reservoir. This is accomplished in the Thermal Efficiency Apparatus by supplying heat to the hot side using a heating resistor and by extracting heat from the cold side using ice water.

In the case of the Thermal Efficiency Apparatus, the heat engine does work by running a current through a load resistor. The work is ultimately converted into heat which is dissipated by the load resistor (Joule heating).

A heat engine can be represented by a diagram (Figure 21.2). The law of Conservation of Energy (First Law of Thermodynamics) leads to the conclusion that $Q_H = W + Q_C$, the heat input to the engine equals the work done by the heat engine on its surroundings plus the heat exhausted to the cold reservoir.

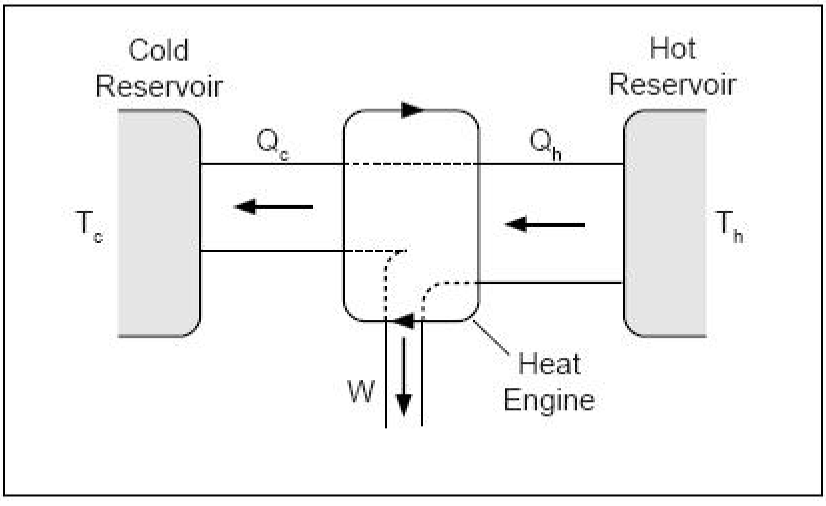


Figure 21.2: *Heat Engine*

### Actual Efficiency

The efficiency of the heat engine is defined to be the work done divided by the heat input

$$e = \frac{W}{Q_H}$$

21-4

So if all the heat input was converted to useful work, the engine would have an efficiency of one (100% efficient). Thus, the efficiency is always less than one.

> **NOTE:** Since you will be measuring the rates at which energy is transferred or used by the Thermal Efficiency Apparatus all measurements will be power rather than energy. So
>
> $P_H = dQ_H/dt$ and then the equation
>
> $Q_H = W + Q_C$ becomes $P_H = P_W + P_C$ and the efficiency becomes
>
> $$e = \frac{P_W}{P_H}$$

### Carnot Efficiency

Carnot showed that the maximum efficiency of a heat engine depends only on the temperatures between which the engine operates, not on the type of engine.

$$e_{Carnot} = \frac{T_H - T_C}{T_H}$$

where the temperatures must be in Kelvin. The only engines which can be 100% efficient are ones which operate between $T_H$ and absolute zero. The Carnot efficiency is the best a heat engine can do for a given pair of temperatures, assuming there are no energy losses due to friction, heat conduction, heat radiation, and Joule heating of the internal resistance of the device.

### Adjusted Efficiency

Using the Thermal Efficiency Apparatus, you can account for the energy losses and add them back into the powers $P_W$ and $P_H$ . This shows that, as all losses are accounted for, the resulting adjusted efficiency approaches the Carnot efficiency, showing that the maximum efficiency possible is not 100%.

## *Heat Pump (Refrigerator)*

### Introduction

A heat pump is a heat engine run in reverse. Normally, when left alone, heat will flow from hot to cold. But a heat pump does work to pump heat from the cold reservoir to the hot reservoir, just as a refrigerator pumps heat out of its cold interior into the warmer room or a heat pump in a house in winter pumps heat from the cold outdoors into the warmer house.

In the case of the Thermal Efficiency Apparatus, heat is pumped from the cold reservoir to the hot reservoir by running a current into the Peltier device in the direction opposite to the direction in which the Peltier device will produce a current.

A heat pump is represented in a diagram such as Figure 21.3.

→**NOTE:** The arrows are reversed compared to the heat in Figure 21.2. By conservation of energy,

$$Q_C + W = Q_H,$$

or in terms of power

$$P_C + P_W = P_H.$$

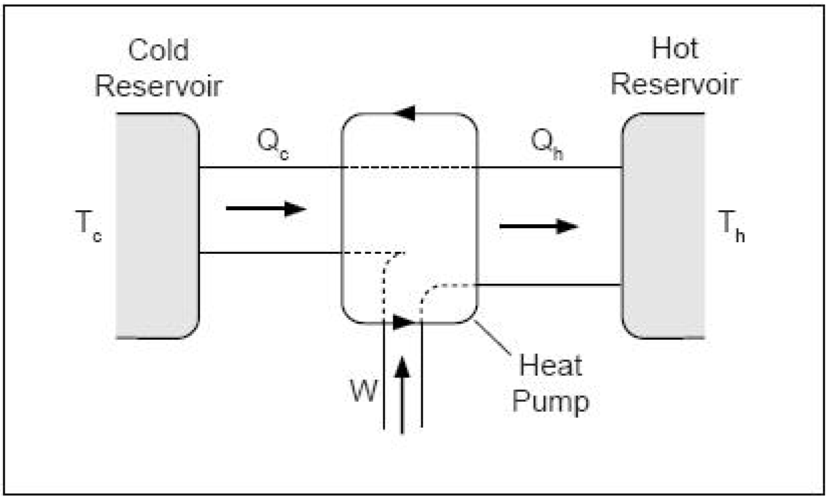


Figure 21.3: *Heat Pump*

### Actual Coefficient of Performance

Instead of defining an efficiency as is done for a heat engine, a coefficient of performance (COP) is defined for a heat pump. The COP is the heat pumped from the cold reservoir divided by the work required to pump it

$$k = COP = \frac{P_C}{P_W}.$$

This is similar to efficiency because it is the ratio of what is accomplished to how much energy was expended to do it. Notice that although the efficiency is always less than one, the COP is always greater than one.

**Maximum Coefficient of Performance**

As with the maximum efficiency of a heat engine, the maximum COP of a heat pump is only dependent on the temperatures.

$$k_{\max} = \frac{T_C}{T_H - T_C}$$

where the temperatures are in Kelvin. Adjusted Coefficient of Performance If all losses due to friction, heat conduction, radiation, and Joule heating are accounted for, the actual COP can be adjusted so it approaches the maximum COP.

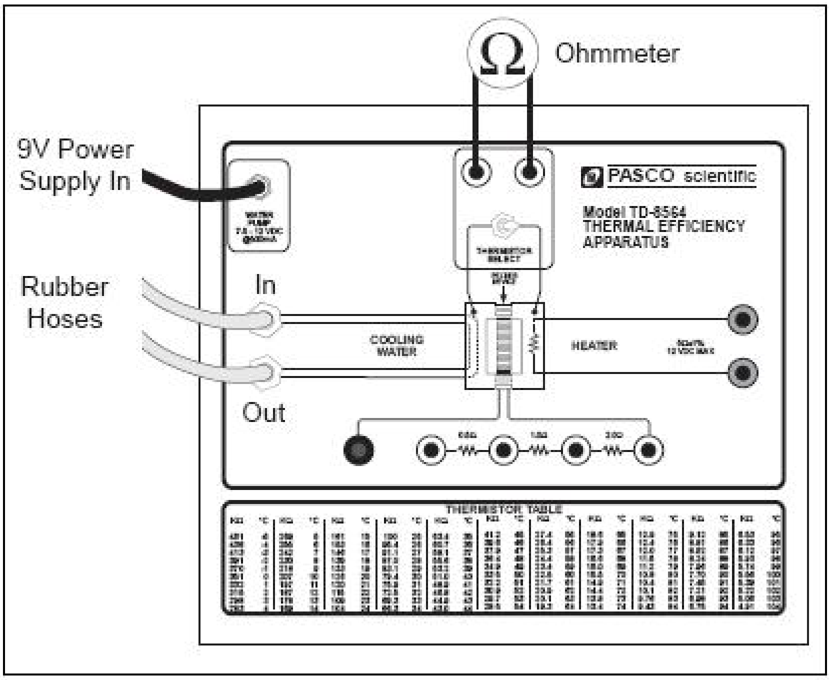


Figure 21.4: *Thermal Efficiency Apparatus*

## Measurements Using the Thermal Efficiency Apparatus

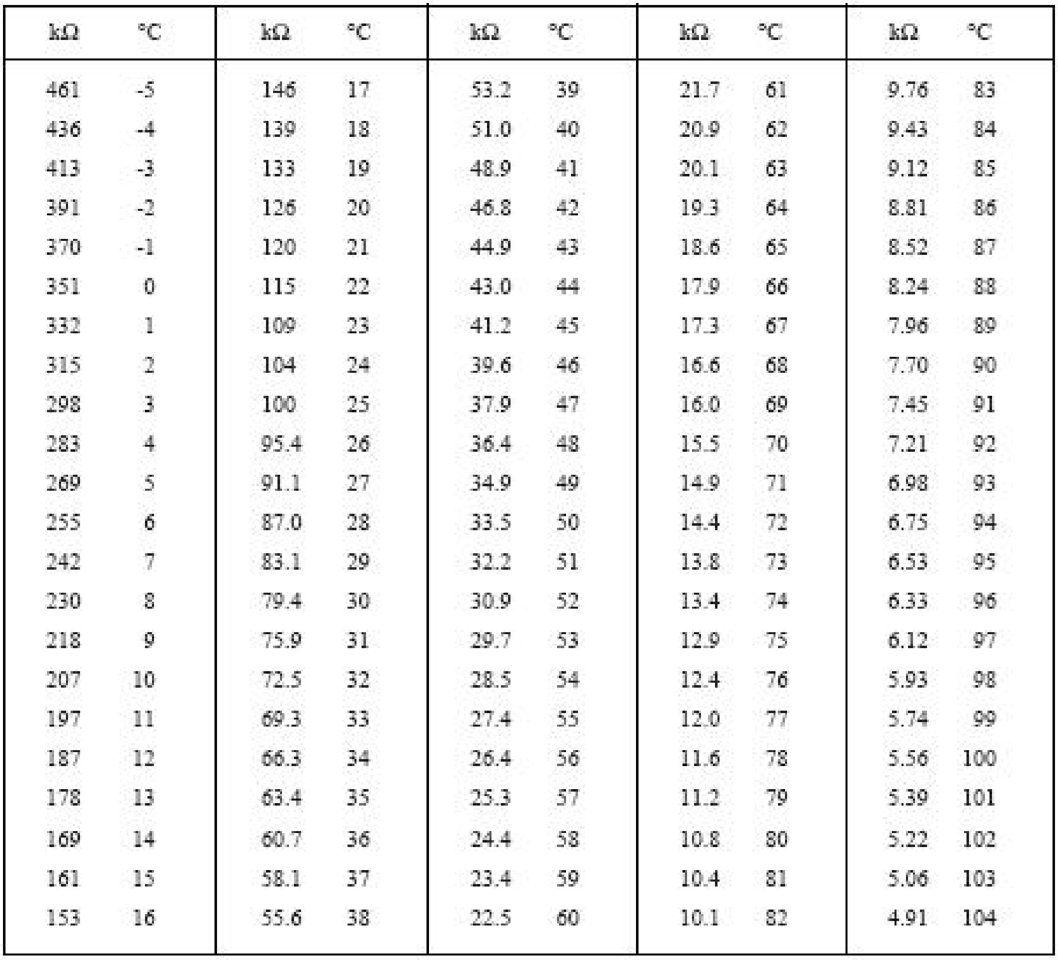
### *Direct Measurements*

Three quantities may be directly measured with the Thermal Efficiency Apparatus: temperatures, the power delivered to the hot reservoir, and the power dissipated by the load resistors. The details of how these measurements are made follow.

### Temperatures

The temperatures of the hot and cold reservoirs are determined by measuring the resistance of the thermistor imbedded in the hot or cold block. To do this, connect an ohmmeter to the terminals located as shown in Figure 21.4. The switch toggles between the hot side and the cold side. The thermistor reading can be converted to a temperature by using the chart located on the front of the Thermal Efficiency Apparatus and in Table 21.1. Notice that as the temperature increases, the thermistor resistance decreases (100 kΩ is a higher temperature than 200 kΩ).

Table 21.1: *Resistance to Temperature Conversion Chart*



| kΩ | °C | kΩ | °C | kΩ | °C | kΩ | °C | kΩ | °C |
|---|---|---|---|---|---|---|---|---|---|
| 461 | -5 | 146 | 17 | 53.2 | 39 | 21.7 | 61 | 9.76 | 83 |
| 436 | -4 | 139 | 18 | 51.0 | 40 | 20.9 | 62 | 9.43 | 84 |
| 413 | -3 | 133 | 19 | 48.9 | 41 | 20.1 | 63 | 9.12 | 85 |
| 391 | -2 | 126 | 20 | 46.8 | 42 | 19.3 | 64 | 8.81 | 86 |
| 370 | -1 | 120 | 21 | 44.9 | 43 | 18.6 | 65 | 8.52 | 87 |
| 351 | 0 | 115 | 22 | 43.0 | 44 | 17.9 | 66 | 8.24 | 88 |
| 332 | 1 | 109 | 23 | 41.2 | 45 | 17.3 | 67 | 7.96 | 89 |
| 315 | 2 | 104 | 24 | 39.6 | 46 | 16.6 | 68 | 7.70 | 90 |
| 298 | 3 | 100 | 25 | 37.9 | 47 | 16.0 | 69 | 7.45 | 91 |
| 283 | 4 | 95.4 | 26 | 36.4 | 48 | 15.5 | 70 | 7.21 | 92 |
| 269 | 5 | 91.1 | 27 | 34.9 | 49 | 14.9 | 71 | 6.98 | 93 |
| 255 | 6 | 87.0 | 28 | 33.5 | 50 | 14.4 | 72 | 6.75 | 94 |
| 242 | 7 | 83.1 | 29 | 32.2 | 51 | 13.8 | 73 | 6.53 | 95 |
| 230 | 8 | 79.4 | 30 | 30.9 | 52 | 13.4 | 74 | 6.33 | 96 |
| 218 | 9 | 75.9 | 31 | 29.7 | 53 | 12.9 | 75 | 6.12 | 97 |
| 207 | 10 | 72.5 | 32 | 28.5 | 54 | 12.4 | 76 | 5.93 | 98 |
| 197 | 11 | 69.3 | 33 | 27.4 | 55 | 12.0 | 77 | 5.74 | 99 |
| 187 | 12 | 66.3 | 34 | 26.4 | 56 | 11.6 | 78 | 5.56 | 100 |
| 178 | 13 | 63.4 | 35 | 25.3 | 57 | 11.2 | 79 | 5.39 | 101 |
| 169 | 14 | 60.7 | 36 | 24.4 | 58 | 10.8 | 80 | 5.22 | 102 |
| 161 | 15 | 58.1 | 37 | 23.4 | 59 | 10.4 | 81 | 5.06 | 103 |
| 153 | 16 | 55.6 | 38 | 22.5 | 60 | 10.1 | 82 | 4.91 | 104 |

→ **NOTE:** To get the exact temperature reading the user must interpolate between numbers on the chart. For example, suppose the ohmmeter reads

118.7 kΩ. This reading lies between

120 kΩ = 21°C and 115 kΩ = 22°C. The reading is

120-118.7 = 1.3 kW above 21°C which is

$$1.3\text{k}\Omega\left(\frac{1^0 C}{120-115k\Omega}\right)=0.26^0 C$$

Therefore 118.7 kΩ is $21.26^0$C.

**Power Delivered to the Hot Reservoir ($P_H$)**

The hot reservoir is maintained at a constant temperature by running a current through a resistor. Since the resistance changes with temperature, it is necessary to measure the current and the voltage to obtain the power input.

Then $P_H = I_H V_H$.

**Power Dissipated by the Load Resistor ($P_W$)**

The power dissipated by the load resistor is determined by measuring the voltage drop across the known load resistance and using the formula

$$P_W = \frac{V^2}{R}.$$

The load resistors have a tolerance of 1%.

→**NOTE:** We may use the equation $P_W = \frac{V^2}{R}$ measuring the power in the load resistor because the temperature (and therefore resistance) of this resistor does not change significantly. We may not use this equation to measure power in the heating resistor, since its temperature (and resistance) changes.

When the Thermal Efficiency Apparatus is operated as a heat pump rather than as a heat engine, the load resistors are not used so it is necessary to measure both the current and the voltage. So the current into the Peltier device is measured with an ammeter, and the voltage across the Peltier device is measured with a voltmeter and the power input is calculated with the formula $P_W = I_W V_W$.

## Indirect Measurements

It will be necessary to know three additional quantities in the experiments: [1] The internal resistance of the Peltier device; [2] The amount of heat conducted through the device and the amount radiated away; [3] The amount of heat pumped from the cold reservoir. These quantities may be determined indirectly with the Thermal Efficiency Apparatus in the following ways.

## Internal Resistance

Before the adjusted efficiency can be calculated, it is necessary to calculate the internal resistance. This is accomplished by measuring the voltage drop across the Peltier device when an external load is applied.

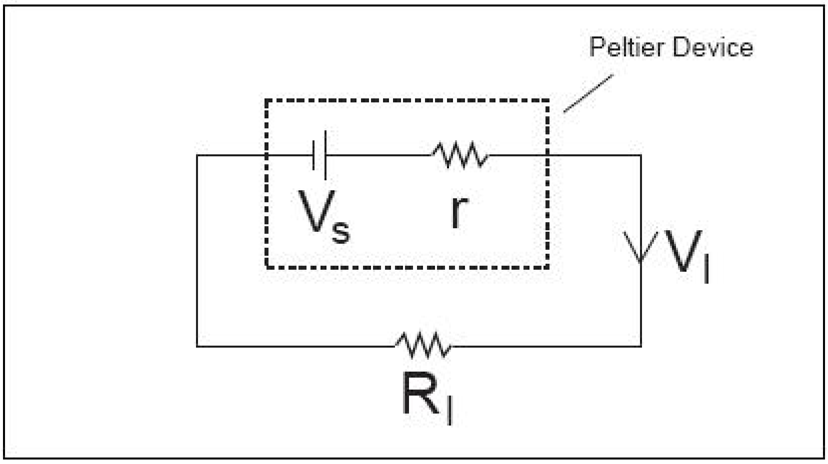


Figure 21.5: *Procedure for Finding Internal Resistance*

## Internal Resistance

Before the adjusted efficiency can be calculated, it is necessary to calculate the internal resistance. This is accomplished by measuring the voltage drop across the Peltier device when an external load is applied.

First run the Thermal Efficiency Apparatus with a load resistor (R) as in figure 21.6. The electrical equivalent of this setup is shown in figure 5. Kirchoff's Loop Rule gives

$$V_S - Ir - IR = 0$$

Next, run the Thermal Efficiency Apparatus with no load, as in Figure 21.7. Since there is no current flowing through the internal resistance of the Peltier Device, the voltage drop across the internal resistance is zero and the voltage measured will just be $V_S$.

Since we have measured $V_w$ rather than I in the heat engine mode, the equation above becomes

$$V_s - \left(\frac{V_w}{R}\right) r - V_w = 0$$

Solving this for the internal resistance gives us

$$r = \left(\frac{V_s - V_w}{V_w}\right) R.$$

You may also find the resistance by measuring the currents for two different load resistors and then solving the resulting loop rule equations simultaneously.

**Heat Conduction and Radiation**

The heat that leaves the hot reservoir goes two places: part of it is actually available to be used by the heat engine to do work while the other part bypasses the engine either by being radiated away from the hot reservoir or by being conducted through the Peltier device to the cold side. The portion of the heat which bypasses the engine by radiation and conduction would be transferred in this same manner whether or not the device is connected to a load and the heat engine is doing work.

The Thermal Efficiency Apparatus is run with a load connected to measure $P_H$ (Figure 21.6) and then the load is disconnected and the power input into the hot reservoir is adjusted to maintain the temperatures (less power is needed when there is no load since less heat is being drawn from the hot reservoir). See Figure 21.7. $P_{H(open)}$ is the power input to the hot reservoir when no load is present. Since, while there is no load, the hot reservoir is maintained at an equilibrium temperature, the heat put into the hot reservoir by the heating resistor must equal the heat radiated and conducted away from the hot reservoir. So measuring the heat input when there is no load determines the heat loss due to radiation and conduction. It is assumed this loss is the same when there is a load and the heat engine is operating.

**Heat Pumped from the Cold Reservoir**

When the Thermal Efficiency Apparatus is operated as a heat pump, conservation of energy yields that the rate at which heat is pumped from the cold reservoir, $P_C$, is equal to the rate at which heat is delivered to the hot reservoir, $P_H$, minus the rate at which work is being done, $P_W$ (Figure 21.3).

The work can be measured directly but the heat delivered to the hot reservoir has to be measured indirectly. Notice that when the heat pump is operating, the temperature of the hot reservoir remains constant. Therefore, the hot reservoir must be in equilibrium and the heat delivered to it must equal the heat being conducted and radiated away. So a measurement of the heat conducted and radiated away at a given temperature difference will also be a measurement of the heat delivered to the hot reservoir. The heat conducted and radiated is measured by running the device with no load and measuring the heat input needed to maintain the temperature of the hot side (Figure 21.7).

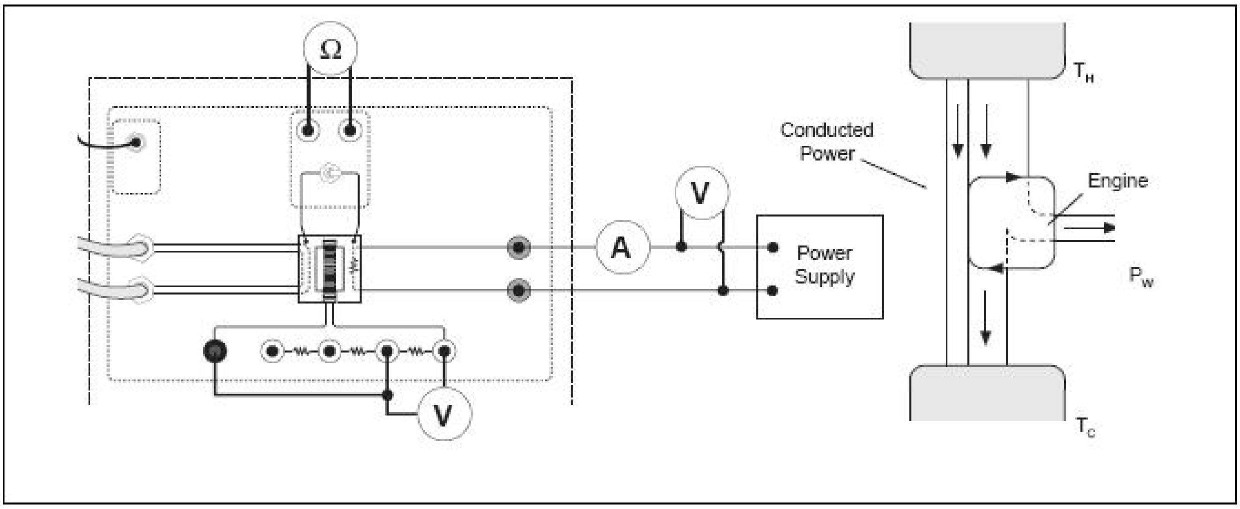


Figure 21.6: *Heat Engine with a Load*

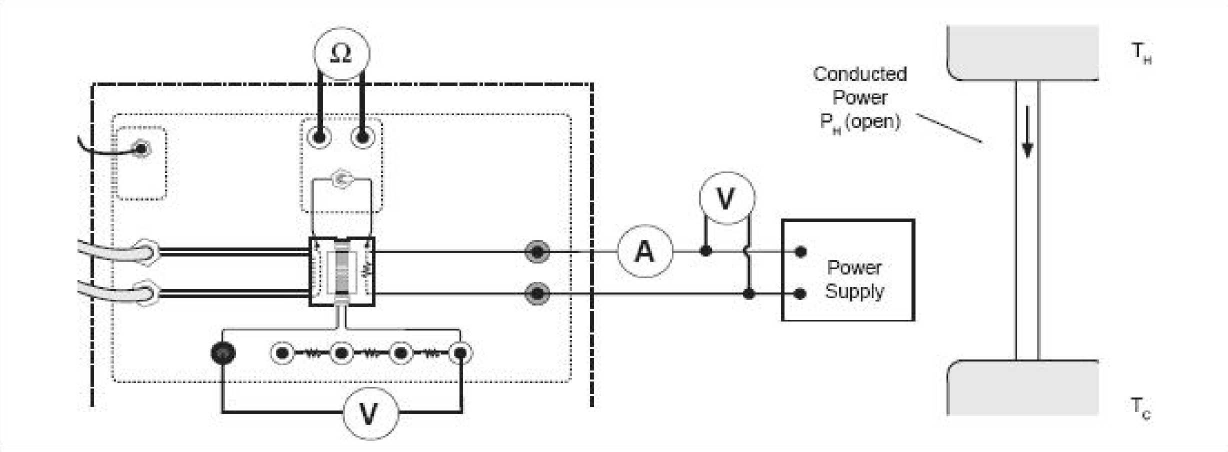


Figure 21.7: *No Load*

# *Experiment 21A: Heat Engine and Temperature Difference*

**EQUIPMENT NEEDED:**

— Thermal Efficiency Apparatus

— ohmmeter

— patch cords

— 3 kg (7 lbs) ice and a bucket for the icewater bath

— DC power supply capable of 2.5 A at 12 V

— ammeter (up to 3 A)

— 2 voltmeters

## Introduction

In this experiment the user will determine the actual efficiency and the Carnot efficiency of the heat engine as a function of the operating temperatures.

## Setup

1. Prepare the ice-water bath and immerse both rubber tubes from the Thermal Efficiency Apparatus into the bath (Figure 21-4).
2. Plug the 9V transformer into the wall socket and into the pump on the Thermal Efficiency Apparatus. You should now hear the pump running and water should be coming out of the rubber hose marked “out”.
3. Plug the ohmmeter into the thermistor terminals.
4. Connect a DC power supply and a voltmeter and ammeter to the heater block terminals. Adjust the voltage to about 11 V.
5. Connect the 2Ω load resistor with a short patch cord as shown in Figure 21A.1. Connect a voltmeter across the load resistor. The choice of the 2Ω load resistor is arbitrary. Any of the load resistances may be used.

**NOTE:** This is just a suggested value chosen to make the hot temperature nearly at the maximum allowed. Any voltage less than 12 V is suitable. The Thermal Efficiency Apparatus should not be run for more than 5 minutes with the hot side above 80°C. A thermal switch will automatically shut off the current to the heater block if it exceeds 93°C to prevent damage to the device.

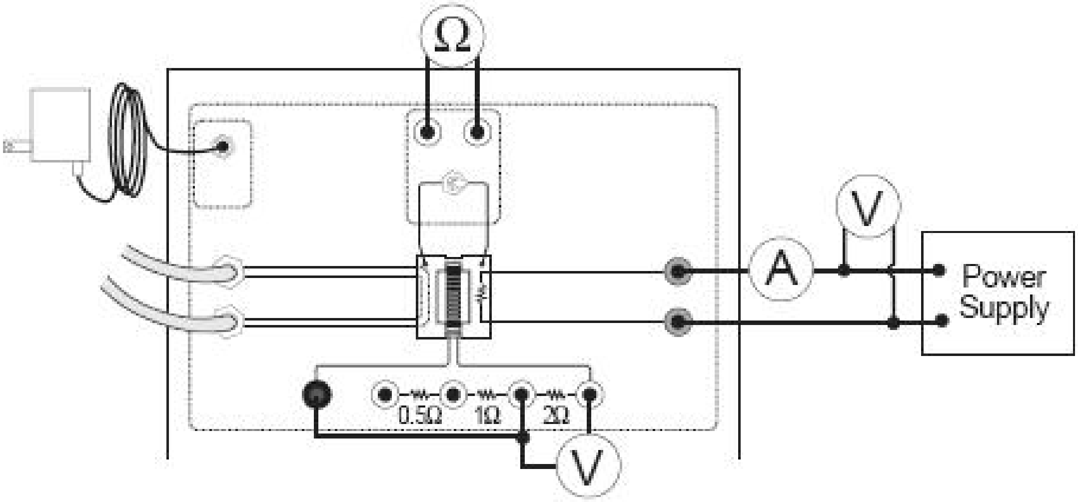


Figure 21A.1

**Procedure**

1. Allow the system to come to equilibrium so that the hot and cold temperatures are constant. This may take 5 to 10 minutes, depending on the starting temperatures. To speed up the process, increase the voltage across the heating resistor momentarily and then return it to the original setting. If it is desired to cool the hot side, the voltage can be momentarily decreased. Remember that the thermistor resistance goes down as the temperature increases.
2. Measure the temperature resistances of the hot side and the cold side by using the toggle switch to switch the ohmmeter to each side. Record the readings in Table 21A.1. Convert the resistances to temperatures using the chart on the front of the device or Table 21A.1 as explained in the Measurements section and record these temperatures in Table 21A.2.
3. Record the voltage ($V_H$) across the heating resistor, the current ($I_H$), and the voltage across the load resistor ($V_W$) in Table 21A.1.
4. Lower the voltage across the heating resistor by about 2 V.
5. Repeat Steps 1 through 4 until data for five different hot temperatures have been taken.

Table 21A.1*: Data for Heat Engine*

| Trial | $T_H$ (kΩ) | $T_c$ (kΩ) | $T_H$ (°C) | $T_H$ (°C) | $V_H$ | $I_H$ | $V_w$ |
|---|---|---|---|---|---|---|---|
| 1 | | | | | | | |
| 2 | | | | | | | |
| 3 | | | | | | | |
| 4 | | | | | | | |
| 5 | | | | | | | |

## Calculations

1. For each of the data runs, calculate the power supplied to the hot reservoir, $P_H$, and the power used by the load resistor, $P_W$, and record these in Table 21A.2.
2. Calculate the temperature difference for each trial and record it in Table 21A.2.
3. Calculate the actual efficiencies from the powers and record in Table 21A.2.
4. Calculate the Carnot (maximum) efficiencies from the temperatures and record in Table 21A.2.

Table 21A.2: *Calculated Values*

| Trial | $P_H$ | $P_w$ | $T_H$ (k) | $T_c$ (k) | $\Delta T$ (k) | $e_{actual}$ | $e_{Carnot}$ |
|---|---|---|---|---|---|---|---|
| 1 | | | | | | | |
| 2 | | | | | | | |
| 3 | | | | | | | |
| 4 | | | | | | | |
| 5 | | | | | | | |

## Analysis and Questions

To compare the actual efficiency to the Carnot efficiency, construct a graph.

Plot the Carnot efficiency vs. DT and also plot the actual efficiency vs. DT. This may be done on the same graph.

→**NOTE:** We are assuming by doing this that Tc was nearly constant.

1. The Carnot efficiency is the maximum efficiency possible for a given temperature difference. According to the graph, is the actual efficiency always less than the Carnot efficiency?
2. Does the Carnot efficiency increase or decrease as the temperature difference increases?
3. Does the actual efficiency increase or decrease as the temperature difference increases?
4. The Carnot efficiency represents the best that a perfect heat engine can do. Since this heat engine is not perfect, the actual efficiency is a percentage of the Carnot efficiency. The overall (actual) efficiency of a real heat engine represents the combination of the engine's ability to use the available energy and the maximum energy available for use. From the data taken, what is the percentage of available energy used by this heat engine?
5. The actual efficiency of this heat engine is very low and yet heat engines of this type are used extensively in remote areas to run things. How can such an inefficient device be of practical use?

***Notes:***

# *Experiment 21B: Heat Engine Efficiency (Detailed Study)*

**EQUIPMENT NEEDED:**

— Thermal Efficiency Apparatus
— ohmmeter
— ammeter (up to 3 A)
— 3 kg — (7 lbs) ice and a bucket for the icewater bath
— 1 DC power supply capable of 2.5 A at 12 V
— patch cords
— 2 voltmeters

## Introduction

In this experiment the user will determine the actual efficiency and the Carnot efficiency of the heat engine and then compensate for the energy losses to show that the compensated actual efficiency approaches the Carnot efficiency.

## Initial Setup

1. Prepare the ice-water bath and immerse both rubber tubes from the Thermal Efficiency Apparatus into the bath (Figure 21.4).
2. Plug the 9V transformer into the wall socket and into the pump on the Thermal Efficiency Apparatus. You should now hear the pump running and water should be coming out of the rubber hose marked “out”.
3. Plug the ohmmeter into the thermistor terminals.

## Modes of Operation:

To obtain all the necessary data for the heat engine it is necessary to run the Thermal Efficiency Apparatus in two different modes. The Heat Engine Mode determines the actual efficiency of the Peltier device. The Open Mode determines the losses due to conduction and radiation. Data from both modes is used to calculate internal resistance and the Carnot Efficiency.

(1) Heat Engine

A. Connect a DC power supply and a voltmeter and ammeter to the heater block terminals. Turn on the voltage to about 11 V.

B. Connect the 2Ω load resistor with a short patch cord as shown in Figure 21B.1. Connect a voltmeter across the load resistor.

→**NOTE:** This is just a suggested value chosen to make the hot temperature nearly at the maximum allowed. Any voltage less than 12 V is suitable. The Thermal Efficiency Apparatus should not be run for more than 5 minutes with the hot side above 80°C. A thermal switch will automatically shut off the current to the heater block if it exceeds 93°C to prevent damage to the device.

C. Allow the system to come to equilibrium so that the hot and cold temperatures are constant. This may take 5 to 10 minutes, depending on the starting temperatures. To speed up the process, increase the voltage across the heating resistor momentarily and then return it to 11 V. If it is desired to cool the hot side, the voltage can be momentarily decreased. Remember that the thermistor resistance goes down as the temperature increases.

D. Measure the temperature resistances of the hot side and the cold side by using the toggle switch to switch the ohmmeter to each side. Record the readings in Table 21B.3. Convert the resistances to temperatures using the chart on the front of the device or Table 21.1 as explained in the Measurements section.

E. Record the voltage ($V_H$) across the heating resistor, the current ($I_H$), and the voltage across the load resistor ($V_H$) in Table 21B.1.

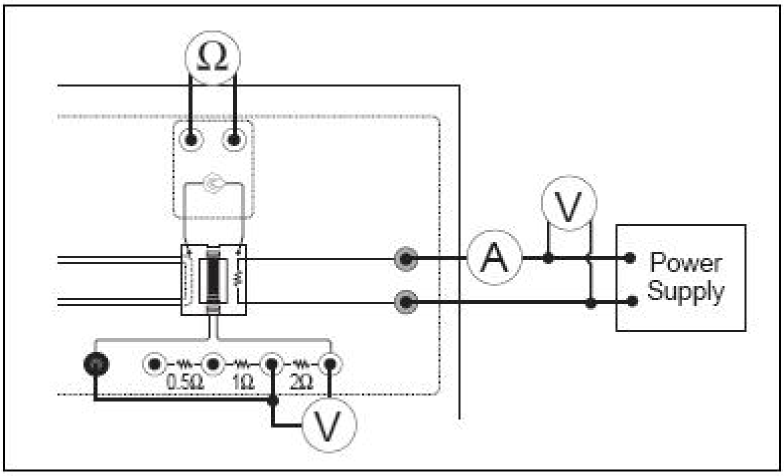


Figure 21B.1

(2) Open

A. Disconnect the patch cord from the load resistor so no current is flowing through the load and thus no work is being done. Now all the power delivered to the heating resistor is either conducted to the cold side or radiated away. Leave the voltmeter attached so that the Seebeck voltage ($V_S$) can be measured. (see figure 21.7).

B. Decrease the voltage applied to the hot side so that the system comes to equilibrium at the same hot temperature as in the Heat Engine Mode. Since the temperature difference is the same as when the heat engine was doing work, the same amount of heat is now being conducted through the device when there is no load as when there is a load. (It may not be possible to exactly match the previous cold temperature.)

C. Record the resistances in Table 21B.1 and convert them to degrees. Also record $V_H$, $I_H$ and $V_P$.

Table 21B.1: *Data*

| Mode | $T_H$ (kΩ) | $T_c$ (kΩ) | $T_H$ (°C) | $T_c$ (°C) | $V_H$ | $I_H$ | $V_w$ | $V_S$ |
|---|---|---|---|---|---|---|---|---|
| Engine | | | | | | | | ▨ |
| Open | | | | | | | ▨ | |

**Calculations for the Heat Engine**

(1) Actual Efficiency: Calculate the actual efficiency using

$$e = \frac{P_W}{P_H},$$

where $P_W = \frac{V_W^2}{R}$ and $P_H = I_H V_H$.

Record the powers in Table 21B.2 and the efficiency in Table 21B.3.

Table 21B.2: *Calculated Values*

Internal Resistance = r = ________________

| Mode | $T_h$ (K) | $T_c$ (K) | $P_h$ | $P_w$ | $I_w$ |
|---|---|---|---|---|---|
| Engine (2Ω load) | | | | | |
| Open | | | | ▨ | ▨ |

Table 21.3: *Results*

| | Actual | Adjusted | Maximum (Carnot) | % Difference |
|---|---|---|---|---|
| Efficiency | | | | |

(2) Maximum Efficiency: Convert the temperatures to Kelvin and record in Table 21B.2. Calculate the Carnot efficiency using the temperatures and record in Table 21B.3.

(3) Adjusted Efficiency: The purpose of the following calculations is to account for all the energy losses and adjust the actual efficiency so that it matches the Carnot efficiency.

A. First, the work done in the actual efficiency calculation only includes $\frac{V^2}{R}$ for the power dissipated by the load resistor R but, to account for total work done by the device, it should also include $I^2r$ for the power dissipated by the internal resistance, r, of the device. This Joule heating of the Peltier device is not counted in the actual efficiency because it is not useful work. Thus, in the adjusted efficiency, the total work done in terms of power is

$$P_W^{'} = P_W + I_W^2 r = \frac{V_W^2}{R} + I_W^2 r$$

Where $I_W = \frac{V_W}{R}$. Calculate $I_W$ for the 2Ω load and record in Table 21.4.

B. Second, the heat input must be adjusted. The heat that leaves the hot reservoir goes two places. Part of it is actually available to be used by the heat engine to do work while the other part bypasses the engine either by being radiated away from the hot reservoir or by being conducted through the Peltier device to the cold side. The portion of the heat which bypasses the engine by radiation and conduction would be transferred in this same manner whether or not the device is connected to a load and the heat engine is doing work. Therefore this heat can be considered to not be available to do work and should not be included in the heat input in the adjusted efficiency.

$$P_H^{'} = available\ heat = P_H - P_{H(open)}$$

The Thermal Efficiency Apparatus is run with a load connected to measure PH (Figure 21.6) and then the load is disconnected and the power input into the hot reservoir is adjusted to maintain the temperatures (less power is needed when there is no load since less heat is being drawn from the hot reservoir). See Figure 21.7. $P_{H(open)}$ is the power input to the hot reservoir when no load is present. Since, while there is no load, the hot reservoir is maintained at an equilibrium temperature, the heat put into the hot reservoir by the heating resistor must equal the heat radiated and conducted away from the hot reservoir. So measuring the heat input when there is no load determines the heat loss due to radiation and conduction. It is assumed this loss is the same when there is a load and the heat engine is operating.

Having accounted for the obvious energy losses, the adjusted efficiency should match the Carnot efficiency which assumes no energy loss. The adjusted efficiency is

$$e'_{adjusted} = \frac{P'_W}{P'_H} = \frac{P_W + I_W^2 r}{P_H - P_{H(open)}}$$

Calculate the internal resistance, r, using the equation

$$r = \left(\frac{V_P - V_W}{V_W}\right) R$$

which is derived in the Indirect Measurement section. Record this resistance in Table 21B.2. Then calculate the adjusted efficiency and record the result in Table 21B.3.

Calculate the percent difference between the adjusted efficiency and the Carnot (maximum) efficiency

$$\%\,Difference = \frac{e_{\max} - e_{adjusted}}{e_{\max}}\, x\, 100\%$$

and record in Table 21B.3.

## Questions

1. If the difference between the temperature of the hot side and the cold side was decreased, would the maximum efficiency increase or decrease?
2. The actual efficiency of this heat engine is very low and yet heat engines of this type are used extensively in remote areas to run things. How can such an inefficient device be of practical use?
3. Calculate the rate of change in entropy for the system which includes the hot and cold reservoirs. Since the reservoirs are at constant temperature, the rate of change in entropy is

$$\frac{\Delta S}{\Delta t} = \frac{\Delta Q / \Delta t}{T} = \frac{P}{T}$$

for each reservoir. Is the total change in entropy positive or negative? Why?