Instruction Manual and Experiment Guide for the PASCO scientific Model TD-8564

THERMAL EFFICIENCY APPARATUS

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**Model TD-8564
THERMAL EFFICIENCY
APPARATUS**

WATER
PUMP
7.5 - 12 VDC
@500mA

THERMISTOR
SELECT

PELTIER
DEVICE

COOLING
WATER

HEATER

5
12 V

0.5Ω   1.0Ω   2.0Ω

Cold
Reservoir

Q_c

T_c

Hot
Reservoir

Q_h

T_h

W

Heat
Engine

THERMISTOR TABLE

KΩ	°C	KΩ	°C	KΩ	°C	KΩ	°C	KΩ	°C	KΩ	°C	KΩ	°C	KΩ	°C	KΩ	°C
461	-5	269	5	161	15	100	25	63.4	35	41.2	45	27.4	55	18.6	65	12.9	75
436	-4	255	6	153	16	95.4	26	60.7	36	39.6	46	26.4	56	17.9	66	12.4	76
413	-3	242	7	146	17	91.1	27	58.1	37	37.9	47	25.3	57	17.3	67	12.0	77
391	-2	230	8	139	18	87.0	28	55.6	38	36.4	48	24.6	58	16.6	68	11.6	78
370	-1	218	9	133	19	83.1	29	53.2	39	34.9	49	23.4	59	16.0	69	11.2	79
351	0	207	10	126	20	79.4	30	51.0	40	33.5	50	22.5	60	15.5	70	10.8	80
332	1	197	11	120	21	75.9	31	48.9	41	32.2	51	21.7	61	14.9	71	10.4	81

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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 (SF-9584)
- 3 kg (7 lbs) ice and a bucket for the ice-water bath
- Ohmmeter (SB-9624)
- 1 Ammeter (up to 3A) (SB-9624A)
- 2 Voltmeters (SB-9624A)
- Patch Cords (SE-9750-51)

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 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]
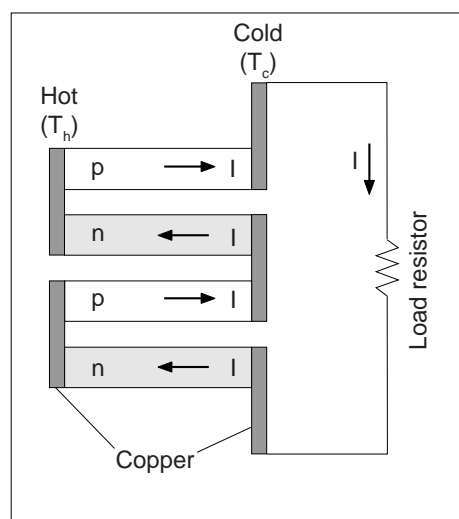
Figure 1: Arrangement of Thermocouples

[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.

Quick Start

The following sections of this manual are essential to operate the Thermal Efficiency Apparatus and will give the user the minimum amount of information necessary to get started quickly:

Theory

Heat Engine

- Introduction

- Actual Efficiency

- Carnot Efficiency

Measurements Using the Thermal Efficiency Apparatus

Direct Measurements

- Temperatures

- Power to the Hot Reservoir

- Power Used by the Load Resistor

Experiment — 1: Heat Engine Efficiency and Temperature Difference

The other portions of the manual provide a more detailed explanation of the operation of the Thermal Efficiency Apparatus in other modes as well as the heat engine mode.

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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 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.
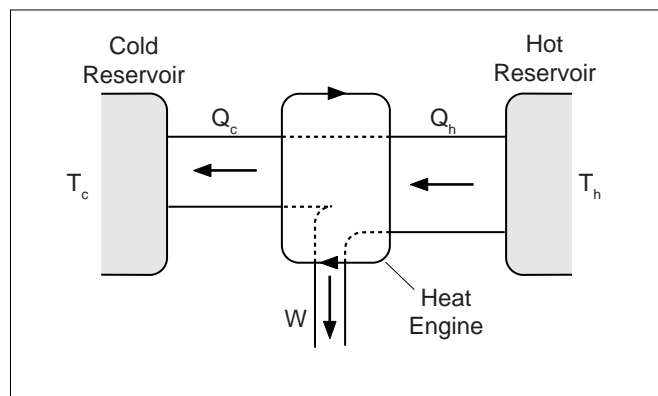
Figure 2: Heat Engine

Actual Efficiency

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

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

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 3.

> ➤**NOTE:** The arrows are reversed compared to the heat in Figure 2. By conservation of energy,
> $$Q_C + W = Q_H,$$
> or in terms of power
> $$P_C + P_W = P_H.$$

Figure 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

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

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.

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

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 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 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 1. Notice that as the temperature increases, the thermistor resistance decreases (100 kΩ is a higher temperature than 200 kΩ).

> ➤ **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 kΩ above 21°C which is
>
> $$1.3k\Omega \times \left(\frac{1°C}{120 - 115k\Omega} \right) = 0.26°C$$
>
> Therefore 118.7 kΩ is 21.26°C.

Table 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

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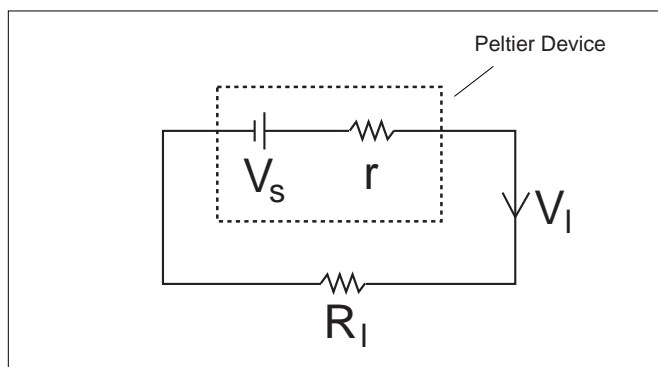

Figure 5: Procedure for Finding Internal Resistance

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.

First run the Thermal Efficiency Apparatus with a load resistor (R) as in figure 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 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 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 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 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 7).
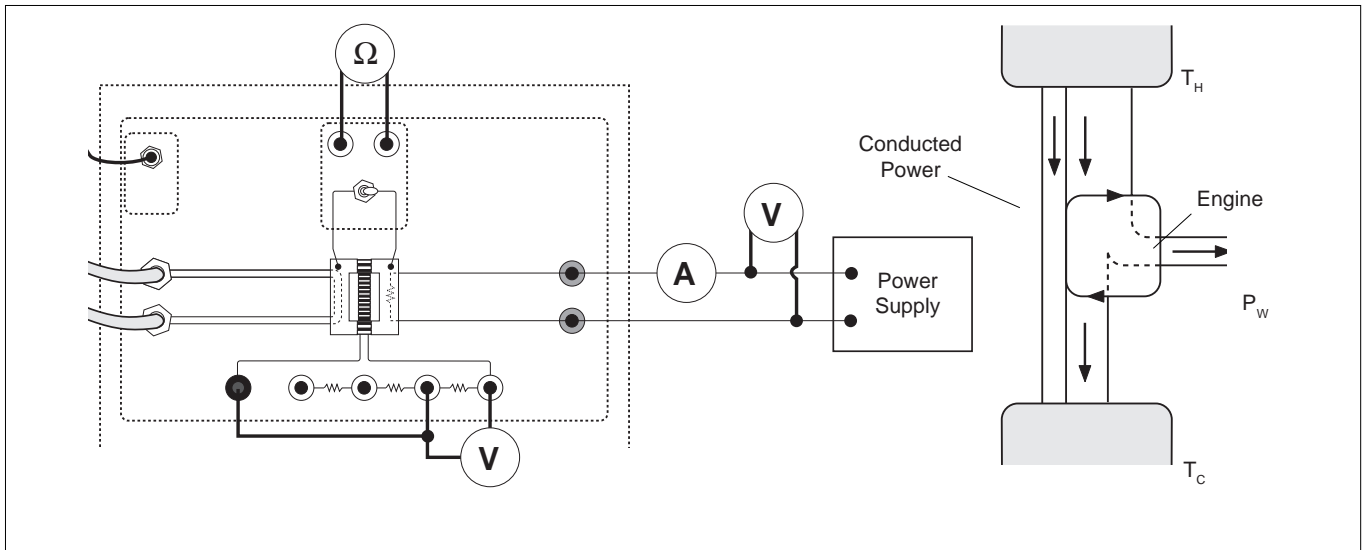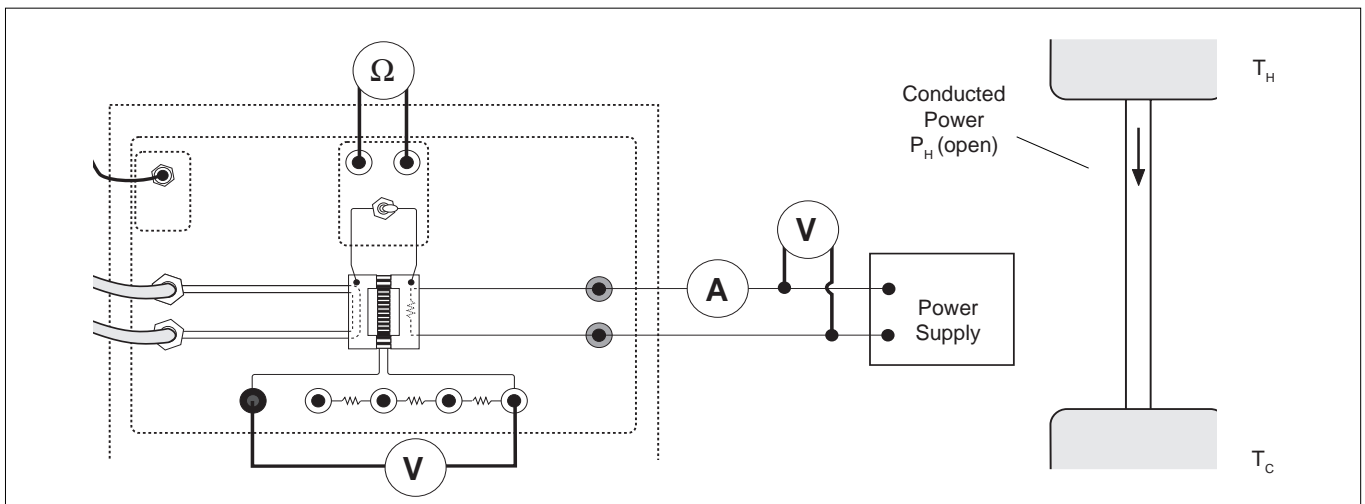

Figure 6: Heat Engine With A Load

Figure 7: No Load

Copy-Ready Experiments

The following experiments are written in worksheet form.
Feel free to photocopy them for use in your lab.

> ➤ **NOTE:** The first paragraph in each experiment lists all the equipment needed
> to perform the experiment. Be sure to read this equipment list first, as the require-
> ments vary with each experiment.

Experiment 1: Heat Engine and Temperature Difference

EQUIPMENT NEEDED:

— Thermal Efficiency Apparatus
— ohmmeter
— patch cords
— 3 kg (7 lbs) ice and a bucket for the ice-
   water 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 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.

➤ 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.
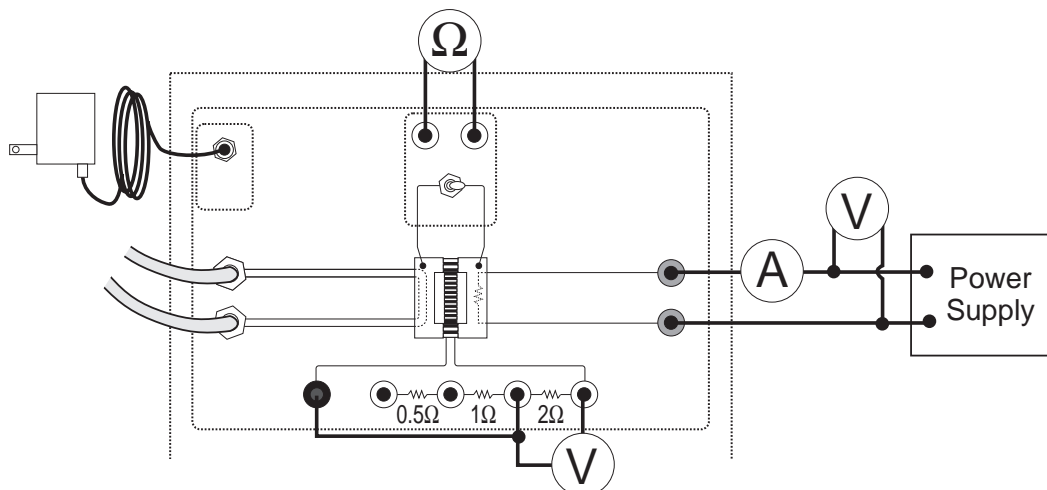

Figure 1.1

⑤ Connect the 2Ω load resistor with a short patch cord as shown in Figure 1.1. Connect a voltmeter across the load resistor. The choice of the 2Ω load resistor is arbitrary. Any of the load resistances may be used.

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 1.1. Convert the resistances to temperatures using the chart on the front of the device or Table 1 as explained in the Measurements section and record these temperatures in Table 1.2.

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 1.1.

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 1.1 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 1.2.

② Calculate the temperature difference for each trial and record it in Table 1.2.

③ Calculate the actual efficiencies from the powers and record in Table 1.2.

④ Calculate the Carnot (maximum) efficiencies from the temperatures and record in Table 1.2.

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Table 1.2 Calculated Values

Trial	P_H	P_w	T_H (k)	T_c (k)	ΔT (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. ΔT and also plot the actual efficiency vs. ΔT. This may be done on the same graph.

> ➤ NOTE: We are assuming by doing this that T_c 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:

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Experiment 2: 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 ice-water 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 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.

➤ 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.
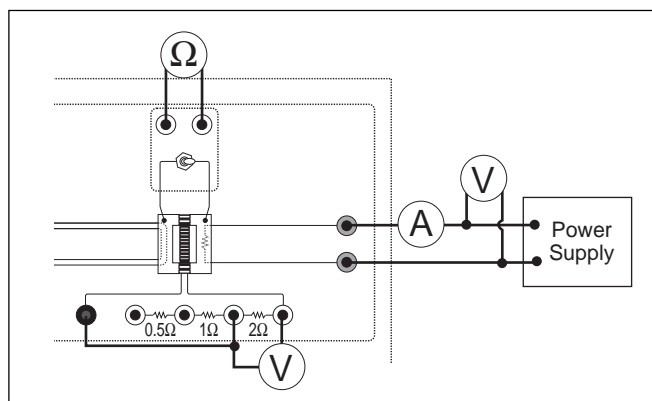

Figure 2.1

B. Connect the 2Ω load resistor with a short patch cord as shown in Figure 2.1. Connect a voltmeter across the load resistor.

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 3. Convert the resistances to temperatures using the chart on the front of the device or Table 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_W) in Table 2.1.

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 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 2.1 and convert them to degrees. Also record V_H, I_H and V_p.

Calculations for the Heat Engine

① Actual Efficiency: Calculate the actual efficiency using

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

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

Record the powers in Table 2.2 and the efficiency in Table 2.3.

Table 2.1 Data

Mode	T_H (kΩ)	T_c (kΩ)	T_H (°C)	T_c (°C)	V_H	I_H	V_w	V_S
Engine								
Open								

Table 2.2 Calculated Values

Internal Resistance = r = _____

Mode	T_h (K)	T_c (K)	P_h	P_w	I_w
Engine (2Ω load)					
Open					

Table 2.3 Results

	Actual	Adjusted	Maximum (Carnot)	% Difference
Efficiency				

② Maximum Efficiency: Convert the temperatures to Kelvin and record in Table 2.2. Calculate the Carnot efficiency using the temperatures and record in Table 2.3.

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 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 P_H (Figure 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 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 2.2. Then calculate the adjusted efficiency and record the result in Table 2.3.

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

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

and record in Table 2.3.

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?

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Experiment 3: Heat Pump Coefficient of Performance

EQUIPMENT NEEDED:

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

➤ **NOTE:** Before doing this experiment, it is necessary to perform the HEAT ENGINE
EFFICIENCY experiment to get the data necessary to determine the internal resistance of
the Peltier device.

To complete the measurements for this experiment, use the following instructions to run the
apparatus as a heat pump (pumping heat from the cold side to the hot side):

Setup

① Prepare the ice-water bath and immerse both rubber tubes from the Thermal Efficiency
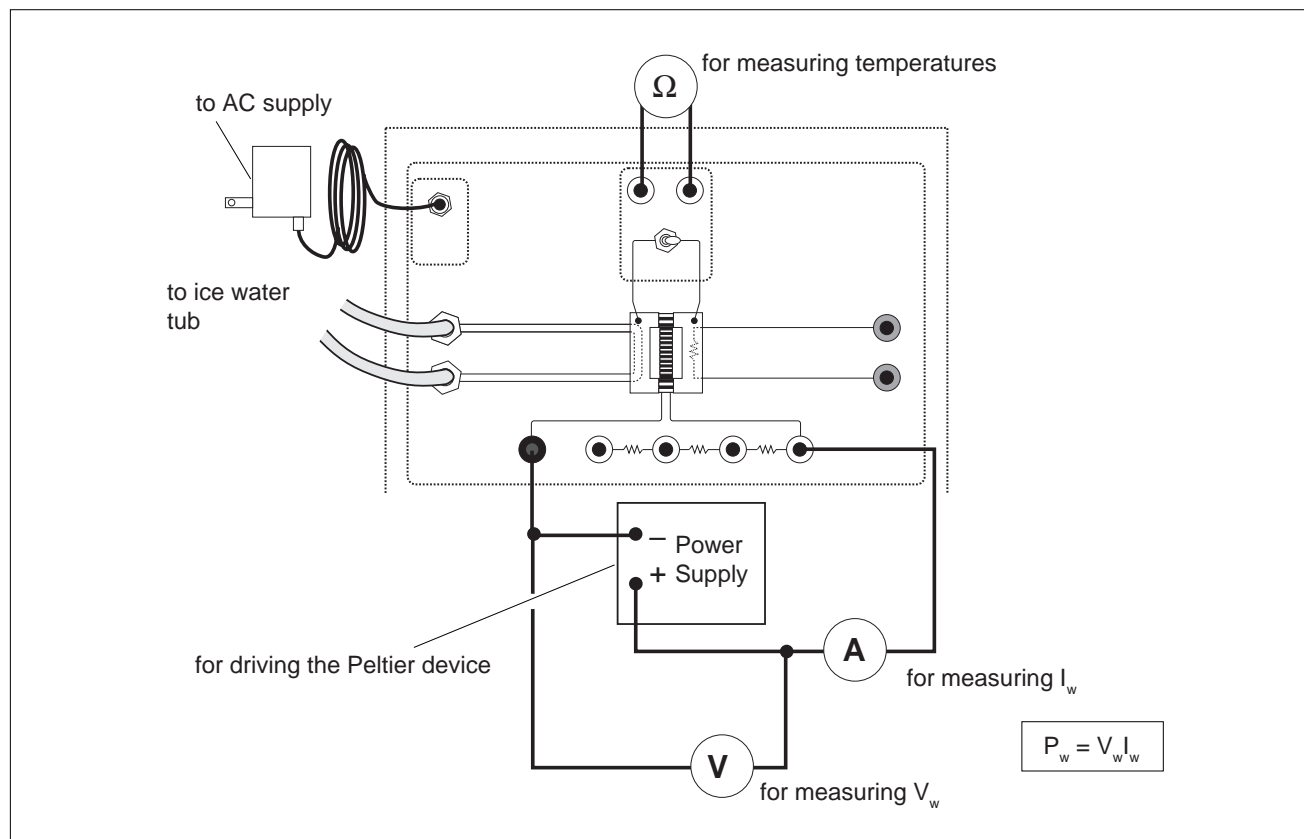Apparatus into the bath (Figure 4).

Figure 3.1 Heat Pump Mode

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 Disconnect the power supply to the hot side. Connect the power supply directly across the Peltier device with no load resistance. See Figure 3.1

④ Connect an ammeter and a voltmeter to the power supply.

Procedure

① Increase the voltage until equilibrium is reached at the same hot temperature as in the previous experiment. The hot side is now being heated by heat pumped from the cold side rather than the heater resistor.

② Record the resistances and convert them to degrees. Also record the voltage (V_W) and the current (I_W) in Table 3.1.

Analysis

① Actual Coefficient of Performance: Calculate the actual COP using the data taken in the Heat Engine experiment.

$$\kappa = \frac{P_C}{P_W} = \frac{P_{H(OPEN)} - P_W}{P_W}$$

Record this result in Table 3.1.

② Maximum Coefficient of Performance: Calculate the maximum COP using

$$\kappa_{MAX} = \frac{T_C}{T_H - T_C}$$

and record this result in Table 3.1.

③ Adjusted Coefficient of Performance: Part of the power being applied to the Peltier device is being dissipated in the Joule heating of the internal resistance of the device rather than being used to pump the heat from the cold reservoir. Therefore, to adjust for this, I^2r must be subtracted from the power input to the Peltier device. Then the COP becomes the heat pumped from the cold reservoir divided by work done to pump the heat, rather than dividing by the work done to pump the heat and heat the internal resistance. In terms of the power,

$$\kappa_{ADJUSTED} = \frac{P_{H(OPEN)} - P_W}{P_W - I_W^2 r}$$

Record this result in Table 3.1. Calculate the percent difference between the adjusted COP and maximum COP:

$$\% \ Difference = \frac{\kappa_{MAX} - \kappa_{ADJUSTED}}{\kappa_{MAX}} \times 100\%$$

and record in Table 3.1.

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Table 3.1 Heat Pump Data and Results

T_H (kΩ)	T_C (kΩ)	T_H (K)	T_C (K)	V_W	I_W	P_W	COP actual	COP max	COP adj	% diff

Questions

① If the difference between the temperature of the hot side and the cold side was decreased, would the maximum COP increase or decrease?

② 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?

Experiment 4: Thermal Conductivity

Introduction

The rate at which heat is conducted through a material of thickness x and cross-sectional area A depends on the difference in temperature between the sides (ΔT) and the thermal conductivity (k) of the material.

$$Power = \frac{Heat}{Time} = \frac{kA\,(\Delta T)}{x}$$

For the Thermal Efficiency Apparatus, the Peltier device has 71 couples and each couple consists of 2 elements, so there is a total of 142 elements which conduct heat (Figure 9).

Each element has a length to area ratio of 8.460 cm^{-1}. So $\dfrac{x}{A} = \dfrac{8.460cm^{-1}}{142}$. Use the data taken in Experiment 2 for the Open Mode to calculate the thermal conductivity of the Peltier device:

$$k = \frac{P_{H\,(OPEN)}\,(x/A)}{\Delta T}$$

Question

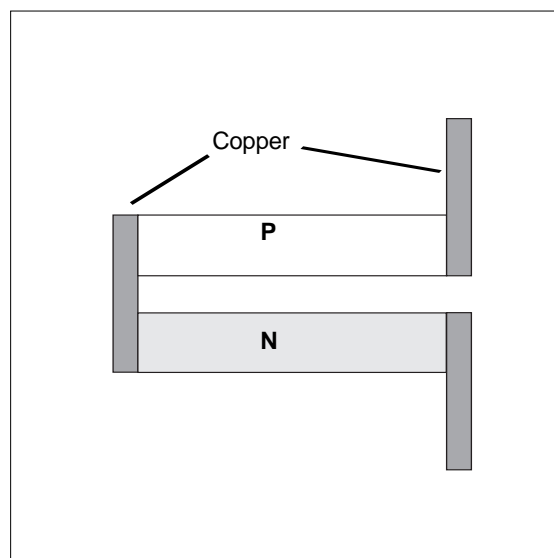① How does the thermal conductivity of the Peltier device compare with the thermal conductivity of copper?

Figure 4.1 One Couple Equals Two Elements

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Experiment 5: Load for Optimum Performance

EQUIPMENT NEEDED:

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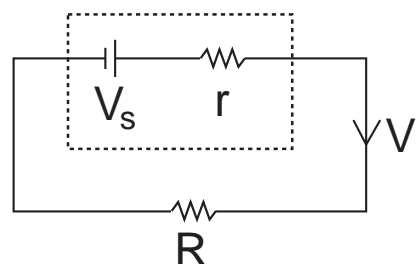— 2 voltmeters
— patch cords

Figure 5.1 Peltier device connected to a load resistor

Theory

This experiment finds the load resistor which maximizes the power output of the heat engine. The power delivered to the load resistor, *R, is P = I²R*. The amount of current that flows through the load resistor varies as the load is varied. From Figure *10, $V_S = I(r+R)$* where V_S is the Seebeck voltage and r is the internal resistance of the Peltier device.

So the power can be expressed in terms of the Seebeck voltage, the internal resistance, and the load resistance:

$$P = \left(\frac{V_s}{r+R}\right)^2 R$$

Assuming the Seebeck voltage remains constant if the temperatures of the hot and cold reservoirs are constant, the power can be maximized with respect to the load resistance by taking the derivative and setting it equal to zero:

$$\frac{dP}{dR} = \frac{V_S^2(r-R)}{(r+R)^3} = 0$$

This shows that when the load resistance is equal to the internal resistance of the Peltier device, the power delivered to the load will be a maximum.
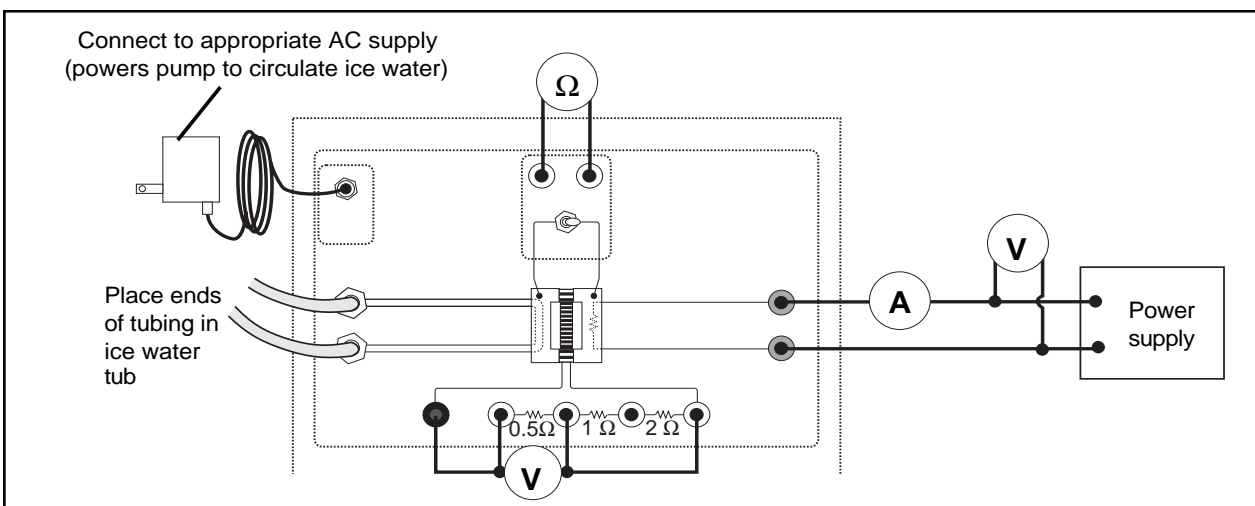

Figure 5.2 Connecting the 0.5Ω load resistor

Procedure

① Connect a DC power supply and a voltmeter and ammeter to the heater block terminals. Turn on the voltage to about 11 V.

➤ 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.

② Connect the 0.5W load resistor with a short patch cord as shown in Figure 11. Connect a voltmeter across the load resistor.

➤ NOTE: Alternatively, a variable power resistor (rheostat) may be used in place of the load resistors supplied with the Thermal Efficiency Apparatus. This has the advantage of being able to continuously vary the load resistance. However, it will be necessary to measure the resistance of the load.

③ 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.

④ 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 5.1. Convert the resistances to temperatures using the chart on the front of the device or Table 1 as explained in the Measurements section.

⑤ Record the voltage (V_H) across the heating resistor, the current (I_H), and the voltage across the load resistor (V_W) in Table 5.1.

Table 5.1: Heat Engine Data and Results

R(Ω)	T_H (kΩ)	T_C (kΩ)	T_H (°K)	T° (°K)	V_H	I_H	V_W	P_H	P_L	e
0.5										
1.0										
1.5										
2.0										
2.5										
3.0										
3.5										

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⑥ Calculate the power input to the hot side, $P_H = I_H V_H$, and the power dissipated by the load resistor, $P_L = \dfrac{V_w^2}{R}$. Calculate the efficiency, $e = \dfrac{P_L}{P_H}$. Record all these values in Table 5.1.

⑦ Adjust the power input to the hot side to keep the temperature of the hot reservoir at the same temperature as it was for the 0.5 Ω resistor while Steps 1 through 6 are repeated for the other possible load resistances: 1, 1.5, 2, 2.5, 3, and 3.5 ohms.

Questions

① For which load resistor is the efficiency a maximum?

② If you have done experiment 2: How does the load resistance for optimum efficiency compare with the internal resistance measured in that experiment?

Notes:

Teacher's Guide

Experiment 1: Heat Engine and Temperature Difference

Notes on Setup

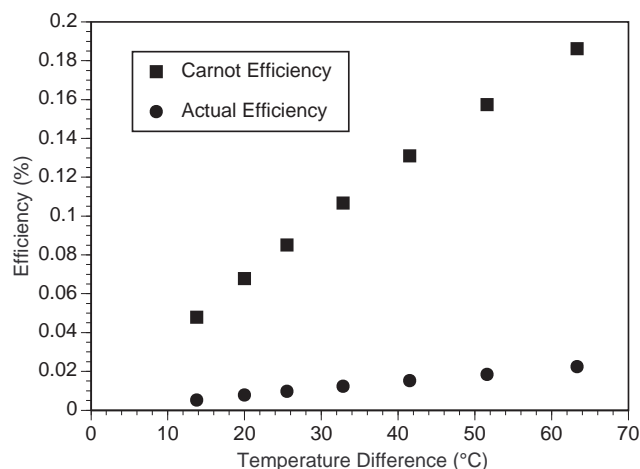② It may be necessary to prime the pump by sucking on the output line briefly.

Notes on Calculations

① Use the equations $P_H = V_H I_H$ and $P_W = \dfrac{V_W^2}{R}$

③ $efficiency = \dfrac{P_W}{P_H}$

④ $e_{Carnot} = \dfrac{T_H - T_C}{T_H}$

Notes on Analysis and Questions

① Yes.

②,③ Both Carnot and actual efficiency increase with increasing temperature difference. (for a constant cold temperature)

④ In these trials, 11-12% of the available energy was used.

⑤ Although the efficiency is low, the reliability is extremely high. (There are no moving parts in the Peltier device.) One practical application of these devices is in satellite power supplies. A small piece of radioactive material is used as a source of heat, and a radiation fin is used as a heat sink. Another similar application is to use the temperature difference between a nuclear isotope and arctic weather to run a remote unmanned weather station. Any application where the thermal mass of the available sources is large, the power requirements are small, and the required reliability is high is good for the Peltier device.

Experiment 2: Heat Engine Efficiency (Detailed Study)

Notes on Setup

② It may be necessary to prime the pump by sucking on the output line briefly.

Sample Data

Mode	T_h (°C)	T_c (°C)	V_h	I_h	V_w	V_s
Engine	57.9	3.5	10.00	2.02	0.890	
Open	57.9	3.3	8.99	1.815		1.495

Calculated Values

Mode	T_h (K)	T_c (K)	P_h	P_w	I_w
Engine	330.9	276.5	20.2	0.40	0.45
Open	330.9	276.3	16.3		

Internal Resistance: $r = 1.36\Omega$

Results

	Actual	Adjusted	Maximum (Carnot)	% Difference
Efficiency	1.96%	17.13%	16.44%	-4.23%

Note that these results were obtained using slightly lower initial voltage than recommended in the lab. In general, mid-range temperatures give better results than extremely large or small temperature differences.

Answers to Questions

① If the temperature difference was decreased, the efficiency would also decrease.

② See experiment 1, question 5.

③ For the hot reservoir, $\Delta S/\Delta t$ was -0.061. For the cold reservoir, it was 0.073. The total change in entropy is positive. In any non-reversible process, the entropy will increase.

Experiment 3: Heat Pump Coefficient of Performance

Typical Results

Note that values of Ph and r were taken from experiment 2.

T_h (K)	T_c (K)	V_w	I_w	P_w	COP	COP_{max}	COP_{adj}	% diff
330.9	275.5	3.64	1.63	5.93	1.75	4.97	4.48	9.9%

Answers to Questions

① The COP increases when the difference in temperature decreases.

② For the hot reservoir, $\Delta S/\Delta t = +0.018$. For the cold reservoir, it is – 0.0215. The net change in entropy is negative. Work is done by the heat pump to decrease the entropy.


Experiment 4: Thermal Conductivity

Answer to Questions

① The thermal conductivity, based on the data taken in experiment 2 of this guide, is 1.79 Watt/mK. By comparison, the thermal conductivity of copper (at 273 K) is 401 Watt/mK.

The Peltier device is made of Bismuth Telluride, which has an accepted thermal conductivity of approximately 1.6 Watt/mK

Experiment 5: Load for Optimum Performance

Notes on Sample Data
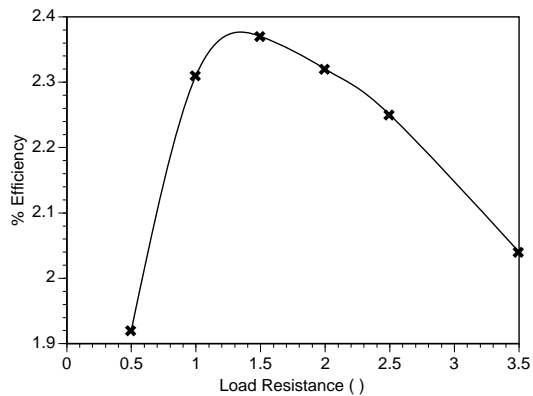
Answer to Question

The efficiency is a maximum when the 1.5Ω resistance is used. This is close to the value of the internal resistance determined in experiment 2, as well.

Technical Support

Feed-Back

If you have any comments about this product or this manual please let us know. If you have any suggestions on alternate experiments or find a problem in the manual please tell us. PASCO appreciates any customer feed-back. Your input helps us evaluate and improve our product.

To Reach PASCO

For Technical Support call us at 1-800-772-8700 (toll-free within the U.S.) or (916) 786-3800.

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Before you call the PASCO Technical Support staff it would be helpful to prepare the following information:

• If your problem is with the PASCO apparatus, note:

  Title and Model number (usually listed on the label).

  Approximate age of apparatus.

  A detailed description of the problem/sequence of events. (In case you can't call PASCO right away, you won't lose valuable data.)

  If possible, have the apparatus within reach when calling. This makes descriptions of individual parts much easier.

• If your problem relates to the instruction manual, note:

  Part number and Revision (listed by month and year on the front cover).

  Have the manual at hand to discuss your questions.

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