Instruction Manual and Experiment Guide for the PASCO scientific Model TD-8557

012-03060C
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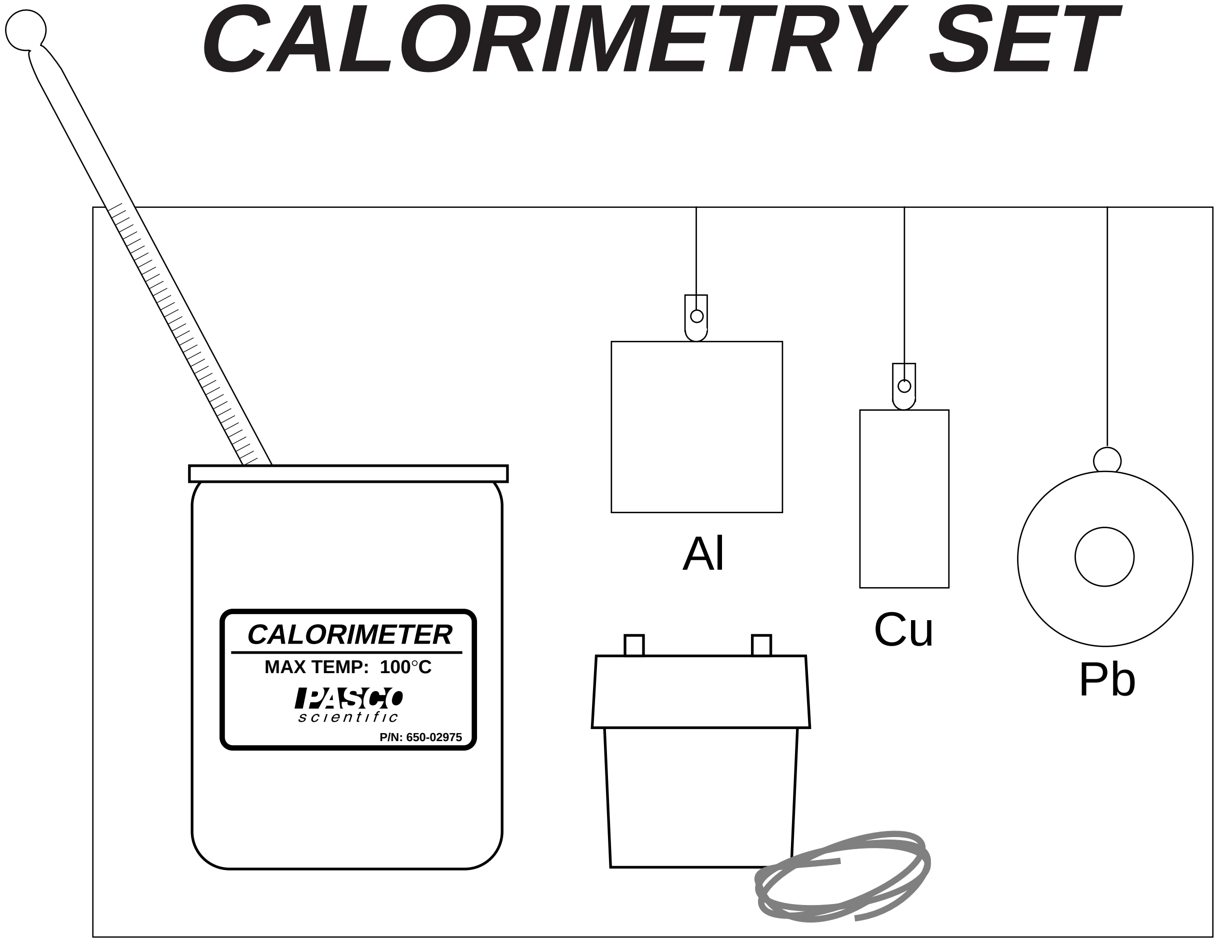
BASIC CALORIMETRY SET



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When returning equipment for repair, the units must be packed properly. Carriers will not accept responsibility for damage caused by improper packing. To be certain the unit will not be damaged in shipment, observe the following rules:

① The packing carton must be strong enough for the item shipped.

② Make certain there are at least two inches of packing material between any point on the apparatus and the inside walls of the carton.

③ Make certain that the packing material cannot shift in the box or become compressed, allowing the instrument come in contact with the packing carton.

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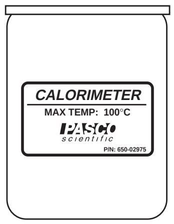
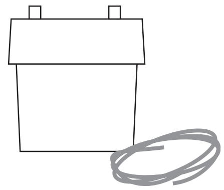
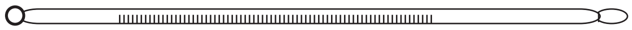
Introduction



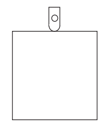
Calorimeters (6)



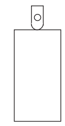
Water Trap with Plastic Tubing



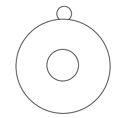
Thermometer



Aluminum



Copper



Lead

Introduction

Understanding calorimetry is the first step into the field of thermodynamics, the study of the role of heat in physical processes. With the addition of a balance, ice, and a heat source, such as PASCO's Model TD-8556 Steam Generator, this Basic Calorimetry Set provides the equipment necessary to perform a variety of calorimetry experiments. Four important, introductory experiments are described in this manual, including:

① **What is a Calorie?**

An introduction to the ideas of temperature and heat, and a demonstration of the conservation of energy.

② **Thermal Capacity and Specific Heat**

The specific heats of Aluminum, Copper, and Lead are measured.

③ **Latent Heat of Vaporization**

The role of heat transfer in the conversion of steam into water is investigated.

④ **Latent Heat of Fusion**

The role of heat transfer in the conversion of ice into water is investigated.

Equipment

The PASCO Model TD-8557 Basic Calorimetry Set includes the equipment shown at the top of the page:

- six styrofoam Calorimeters
- a water trap with plastic tubing
- a thermometer measuring from -20°C to 110°C in one degree increments
- samples of Aluminum, Copper, and Lead, approximately 200 grams each, for investigating the specific heats of metals.

Notes on Calorimetry

A calorimeter is a vessel or device that thermally isolates an experiment from its surroundings. Ideally, this means that the results of an experiment performed in a calorimeter are independent of the temperature of the surroundings, because no heat flows into or out of the calorimeter.

However, no calorimeter is perfect, and there is always some unwanted and unaccountable heat flow affecting the results of any calorimetric experiment. To minimize unwanted heat flow, always plan the experiment so that:

① *the time between the taking of initial and final temperatures is minimal.*

In other words, do the critical portion of the experiment quickly, so there is minimal time for unwanted heat flow between measurements. (Don't rush; just plan carefully.)

② *whenever possible, room temperature is approximately midway between the beginning and ending temperatures of the experiment.*

When the experimental temperature is colder than room temperature, heat flows from the surroundings into the calorimeter. When the experimental temperature is hotter than room temperature, heat flows from the calorimeter into the surroundings. If the experimental temperature varies above and below room temperature by equal amounts, the heat gained and lost to the environment will be approximately equal, minimizing the net affect on the experiment.

③ *mass measurements of liquids are made as near the critical temperature measurements as possible.*

This reduces the effects of mass loss by evaporation. Measuring liquid masses by taking appropriate differences is a useful technique (see the instructions in the individual experiments).

> ➤ **NOTE:** In applying the above rules, it is often helpful to perform a quick preliminary experiment to determine the best choice for initial masses and temperatures.

Notes

Experiment 1: What is a Calorie?

EQUIPMENT NEEDED:

— Calorimeter
— Balance
— Thermometer
— Hot and cold water

Introduction

When two systems or objects of different temperature come into contact, energy in the form of heat is transferred from the warmer system into the cooler. This transfer of heat raises the temperature of the cooler system and lowers the temperature of the warmer system. Eventually the two systems reach some common, intermediate temperature, and the heat transfer stops.

The standard unit for measuring heat transfer is the calorie. A calorie is defined as the amount of energy required to raise the temperature of one gram of water from 14.5°C to 15.5°C. However, for our purposes, we can generalize this definition by simply saying that a calorie is the amount of energy required to raise the temperature of one gram of water one degree Celsius (the variation with temperature is slight).

In this experiment, you will combine hot and cold water of known temperature and mass. Using the definition of the calorie, you will be able to determine the amount of heat energy that is transferred in bringing the hot and cold water to their final common temperature, and thereby determine if heat energy is conserved in this process.

Procedure

① Determine the mass of the empty calorimeter, M_{cal}. Record your result in Table 1.1 on the following page.

② Fill the calorimeter about 1/3 full with cold water. Weigh the calorimeter and water together to determine $M_{cal + H_2O}$, cold. Record your result.

③ Fill a second calorimeter approximately 1/3 full of hot water. The water should be at least 20°C above room temperature. Weigh the calorimeter and water together to determine $M_{cal + H_2O}$, hot. Record your result

④ Measure T_{hot} and T_{cold}, the temperatures in degrees Celsius of the hot and cold water, and record your results.

⑤ Immediately after measuring the temperatures, add the hot water to the cold and stir with the thermometer until the temperature stabilizes. Record the final temperature of the mixture, T_{final}.

⑥ Repeat the experiment twice with different masses of water at different temperatures. (You might try adding cold water to hot instead of hot to cold.)

Data

Table 1.1 Data

	Trial 1	Trial 2	Trial 3
M_{cal}			
$M_{cal + H_2O}$, cold			
$M_{cal + H_2O}$, hot			
T_{hot}			
T_{cold}			
T_{final}			
M_{final}			

Calculations

From your data, make the calculations necessary to determine the mass of the hot and cold water that were combined, and also the temperature changes (ΔT) undergone by each. Enter your results in Table 1.2.

Using the equations shown below, calculate ΔH_{cold} and ΔH_{hot}, the heat gained by the cold and hot water, respectively. Enter your results in the table.

$$\Delta H_{cold} = (M_{H_2O,\ cold})\,(\Delta T_{cold})\,(1\ cal/gm°C);\quad \Delta H_{hot} = (M_{H_2O,\ hot})\,(\Delta T_{hot})\,(1\ cal/gm°C$$

Table 1.2 Calculations

	Trial 1	Trial 2	Trial 3
$M_{H_2O,\ cold}$			
$M_{H_2O,\ hot}$			
ΔT_{hot}			
ΔT_{cold}			
ΔH_{cold}			
ΔH_{hot}			

Questions

① Which had more thermal energy, the two cups of water before they were mixed together or after they were mixed? Was energy conserved?

② Discuss any unwanted sources of heat loss or gain that might have had an effect on the experiment.

③ If 200 grams of water at 85°C were added to 150 grams of water at 15°C, what would be the final equilibrium temperature of the mixture?

Experiment 2: Specific Heat

EQUIPMENT NEEDED:

— Calorimeter
— Samples of aluminum, copper, and lead
— Boiling water
— Thread
— Thermometer
— Balance
— Cool water
— Antifreeze.*

* Part 2 of this experiment requires approximately 100 grams of antifreeze.

Introduction

The Specific Heat of a substance, usually indicated by the symbol c, is the amount of heat required to raise the temperature of one gram of the substance by one degree Centigrade. From the definition of the calorie given in Experiment 1, it can be seen that the specific heat of water is 1.0 cal/g°C. If an object is made of a substance with specific heat equal to c_{sub}, then the heat, ΔH, required to raise the temperature of that object by an amount ΔT is:

$$\Delta H = (\text{mass of object})\ (c_{sub})\ (\Delta T).$$

In Part 1 of this experiment you will measure the specific heats of several metals, including aluminum, copper, and lead. In Part 2 you will measure the specific heat of antifreeze.

Procedure

➤ **CAUTION:** This experiment involves the use of boiling water and the handling of **HOT** metal objects. Work carefully.

PART 1: The Specific Heats of Aluminum, Copper, and Lead

① Measure M_{cal}, the mass of the calorimeter you will use (it should be empty and dry). Record your result in Table 2.1.

② Measure the masses of the aluminum, copper, and lead samples. Record these masses in Table 2.1 in the row labeled M_{sample}.

③ Attach a thread to each of the metal samples and suspend each of the samples in boiling water. Allow a few minutes for the samples to heat thoroughly.
Perform steps ① through ① for each metal sample.

④ Fill the calorimeter approximately 1/2 full of cool water—use enough water to easily cover any one of the metal samples.

⑤ Measure T_{cool}, the temperature of the cool water, and record your measurement in the table.

⑥ Immediately following your temperature measurement, remove the metal sample from the boiling water, quickly wipe it dry, then suspend it in the cool water in the calorimeter (the sample should be completely covered but should not touch the bottom of the calorimeter).

⑦ Stir the water with your thermometer and record T_{final}, the highest temperature attained by the water as it comes into thermal equilibrium with the metal sample.

⑧ Immediately after taking the temperature, measure and record M_{total}, the total mass of the calorimeter, water, and metal sample.

PART 2: The Specific Heat of Antifreeze

Repeat Part 1 of this experiment, but instead of using the metal samples, heat approximately 100 grams of antifreeze to approximately 60°C. Measure and record the temperature, then quickly pour the antifreeze into the calorimeter of cool water and stir until the highest stable temperature is reached (about 1 minute). Record your data and calculations on a separate sheet of paper. You will need the following data: M_{cal}, the mass of the calorimeter, M_{H_2O}, the mass of the calorimeter plus water, T_{cool} (the temperature of the cool water), M_{final} and T_{final}, the mass and temperature of the calorimeter plus water plus antifreeze.

DATA AND CALCULATIONS

Table 2.1 Data and Calculations (Part 1)

	Trial 1 Aluminum	Trial 2 Copper	Trial 3 Lead
M_{cal} (g) M_{sample} (g) $T_{cool\ (°C)}$ $T_{final\ (°C)}$ M_{total} (g)			
M_{H_2O} ΔT_{H_2O} c (cal/gm°C)			

Part 1

For each metal tested, use the equations shown below to determine M_{H_2O}, the mass of the water used, ΔT_{H_2O}, the temperature change of the water when it came into contact with each metal sample, and ΔT_{sample}, the temperature change of the metal sample when it came into contact with the water. Record your results in Table 2.1.

$$\mathbf{M}_{H_2O} = \mathbf{M}_{final} - (\mathbf{M}_{cal} + \mathbf{M}_{sample});\ \Delta\mathbf{T}_{H_2O} = \mathbf{T}_{final} - \mathbf{T}_{cool};\ \Delta\mathbf{T}_{sample} = \mathbf{100\ °C} - \mathbf{T}_{final}$$

From the law of energy conservation, the heat lost by the metal sample must equal the heat gained by the water:

$$\text{Heat lost by sample} = (\mathbf{M}_{sample})(\mathbf{c}_{sample})(\Delta\mathbf{T}_{sample}) = (\mathbf{M}_{H_2O})(\mathbf{c}_{H_2O})(\Delta\mathbf{T}_{H_2O}) = \text{Heat gained by water}$$

($\mathbf{c}_{H_2O}$ is the specific heat of water, which is **1.0 cal/g°C**.)

Use the above equation, and your collected data, to solve for the specific heats of aluminum, copper, and lead. Record your results in the bottom row of Table 2.1.

Part 2

M_{cal} = ____________

M_{H_2O} = ____________

T_{cool} = ____________

M_{final} = ____________

T_{final} = ____________

Perform calculations similar to those performed in part 1 to determine c_{anti}, the specific heat of antifreeze.

c_{anti} = ____________

Questions

① How do the specific heats of the samples compare with the specific heat of water?

② Discuss any unwanted heat loss or gain that might have effected your results?

③ From your measured specific heat for antifreeze, which should be the better coolant for an automobile engine, antifreeze or water? Why is antifreeze used as an engine coolant?

Notes

Experiment 3: Latent Heat of Vaporization

EQUIPMENT NEEDED:

— Calorimeter
— Steam Generator *
— Tubing
— Thermometer
— Water Trap
— Balance

* If a steam generator is not available, a distillation flask and Bunsen burner is adequate. A second flask can be used as a water trap.

Introduction

When a substance changes phase, the arrangement of its molecules changes. If the new arrangement has a higher internal energy, the substance must absorb heat in order to make the phase transition. Conversely, if the new arrangement has a lower internal energy, heat will be released as the transition occurs.

In this experiment you will determine how much more energy is contained in one gram of steam at 100°C, than in one gram of water at the same temperature. This value is called the Latent Heat of Vaporization of water.

Procedure

➤ **CAUTION:** This experiment requires the use of live steam. Work carefully.

① Measure T_{rm}, the room temperature.

② Set up a steam generator with a water trap as shown in Figure 3.1. The tube lengths should be approximately as shown in the figure.

③ Weigh a calorimeter to determine M_{cal}, the mass of the empty, dry calorimeter.

④ Fill the calorimeter approximately 1/2 full of cool water (about 10°C below room temperature).

⑤ Turn on the steam generator and wait for the steam to flow freely for at least a minute.

⑥ Measure Tinitial and $M_{cal + H_2O}$, the temperature of the cool water and the mass of the water plus calorimeter.

⑦ Immediately immerse the free end of the short tube into the cool water in the calorimeter. Stir the water continuously with the thermometer.

➤ **IMPORTANT:** The bottom of the water trap should be kept HIGHER than the water level in the calorimeter to avoid water being pulled from the calorimeter back into the water trap.

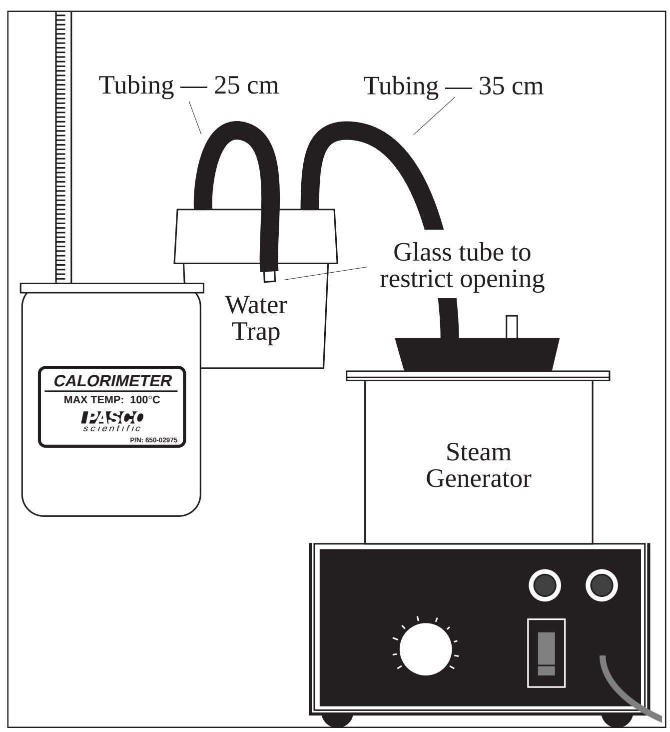


Figure 3.1 Equipment Setup

⑧ When the water temperature, T, gets as far above room temperature as it was initially below room temperature (i.e. $T_{rm} - T_{initial} = T - T_{initial}$), remove the steam tube. Continue stirring the water and record the highest stable temperature attained by the water (T_{final}).

➤ **IMPORTANT:** Always remove the steam tube from the water before turning off the steam generator heat. (Can you explain why?)

⑨ Immediately weigh the water to determine M_{final}, the total mass of calorimeter plus water plus (condensed) steam.

Data

T_{rm} = ____________

M_{cal} = ____________

$T_{initial}$ = ____________

$M_{cal + H_2O}$ = ____________

T_{final} = ____________

M_{final} = ____________

Calculations

When steam condenses in cool water, heat energy is released into the water in two ways. One, the latent heat of vaporization is released. With this release of heat, the steam is converted into water, but the newly converted water is still at boiling temperature, 100 °C. Second, the newly converted water releases heat as it comes into thermal equilibrium with the cooler water, at a final equilibrium temperature, T_{final}.

According to the principle of the conservation of energy, the total heat released by the steam equals the total heat absorbed by the cooler water. Stated mathematically:

$$(\mathbf{M}_{steam})(\mathbf{H}_v) + (\mathbf{M}_{steam})(\mathbf{1\ cal/gm^\circ C})(\mathbf{T}_{steam} - \mathbf{T}_{final}) = (\mathbf{M}_{H_2O})(\mathbf{1\ cal/gm^\circ C})(\mathbf{T}_{final} - \mathbf{T}_{initial});$$

where,

$M_{steam} = M_{final} - M_{cal + H_2O}$ = ________________

$M_{H_2O} = M_{cal + H_2O} - M_{cal}$ = ________________

T_{steam} = 100 °C

H_v = the Latent Heat of Vaporization per gram of water

Use your data and the above information to determine H_v, the latent heat of vaporization per gram of water.

➤ **NOTE:** The thermometer also absorbs a certain amount of heat during the experiment. As a good approximation, assume that the heat capacity of the thermometer is equivalent to that of approximately 1 gram of water (i.e., add one gram to M_{H_2O} in the above equation).

H_v = ____________

Questions

① Why would a burn produced by 1 gram of steam at 100°C do more damage than a burn caused by 1 gram of water at 100°C?

② Speculate on how the heat of vaporization might influence climate and weather systems.

③ In what way does water used to cook food serve as a refrigerant?
(Hint: What happens when the water all boils away?)

Notes

Experiment 4: Latent Heat of Fusion

EQUIPMENT NEEDED:

— Calorimeter
— Ice in water (at melting point)
— Thermometer
— Warm water

Just as steam has a higher internal energy content than water, so water has a higher internal energy content than ice. It takes a certain amount of energy for the water molecules to break free of the forces that hold them together in the crystalline formation of ice. This same amount of energy is released when the water molecules come together and bond to form the ice crystal.

In this experiment, you will measure the difference in internal energy between one gram of ice at 0°C and one gram of water at 0°C. This difference in energy is called the Latent Heat of Fusion of water.

Procedure

① Measure T_{rm}, the room temperature.

② Weigh a calorimeter to determine M_{cal}, the mass of the empty, dry calorimeter.

③ Fill the calorimeter approximately 1/2 full of warm water (about 15°C above room temperature.)

④ Measure $M_{cal + H_2O}$, the mass of the calorimeter and water.

⑤ Measure $T_{initial}$, the initial temperature of the warm water.

⑥ Add small chunks of ice to the warm water, wiping the excess water from each piece of ice immediately before adding. Add the ice slowly, stirring continuously with the thermometer until each chunk melts.

⑦ When the temperature of the mixture is as much below room temperature as the warm water was initially above room temperature (i.e., $T_{rm} – T = T_{initial} - T_{rm}$), and all the ice is melted, measure the final temperature of the water (T_{final}).

⑧ Immediately after measuring T_{final}, weigh the calorimeter and water to determine M_{final}.

Suggested Additional Experiment

Repeat the above experiment, but, instead of ordinary ice, use the material which is packaged in metal or plastic containers to be frozen and used in picnic coolers.

Data

T_{rm} = ________________

M_{cal} = ________________

$M_{cal + H_2O}$ = ________________

$T_{initial}$ = ________________

T_{final} = ________________

M_{final} = ________________

Calculations

According to the principle of the conservation of energy, the quantity of heat absorbed by the ice as it melts and then heats up to the final equilibrium temperature must equal the quantity of heat released by the warm water as it cools down to the final equilibrium temperature. Mathematically:

$$(\mathbf{M}_{ice})\ (\mathbf{H}_f) + (\mathbf{M}_{ice})\ (\mathbf{1\ cal/g^\circ C})\ (\mathbf{T}_{final} - \mathbf{0^\circ C}) = (\mathbf{M}_{H_2O})\ (\mathbf{1\ cal/g^\circ C})\ (\mathbf{T}_{initial} - \mathbf{T}_{final});$$

where,

$M_{ice} = M_{final} - M_{cal + H_2O}$ = ____________________

$M_{H_2O} = M_{cal + H_2O} - M_{cal}$ = ____________________

H_f = the Latent Heat of Fusion for one gram of water

Use your data and the above information to determine H_f, the latent heat of fusion per gram of water.

H_f = ________________

Questions

① What advantage might the commercially packaged coolant material have over ice other than that it produces less mess? (If you didn't perform the optional part of the experiment, what properties would a material need in order to be a better coolant than ice?)

② Design an experiment to determine which of two substances (e.g. ice and packaged coolant) will keep a cooler:

a. cool for the longest time, and

b. at a lower temperature.

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.

Contacting Technical Support

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

- If your problem is computer/software related, note:

  Title and Revision Date of software.

  Type of Computer (Make, Model, Speed).

  Type of external Cables/Peripherals.

- 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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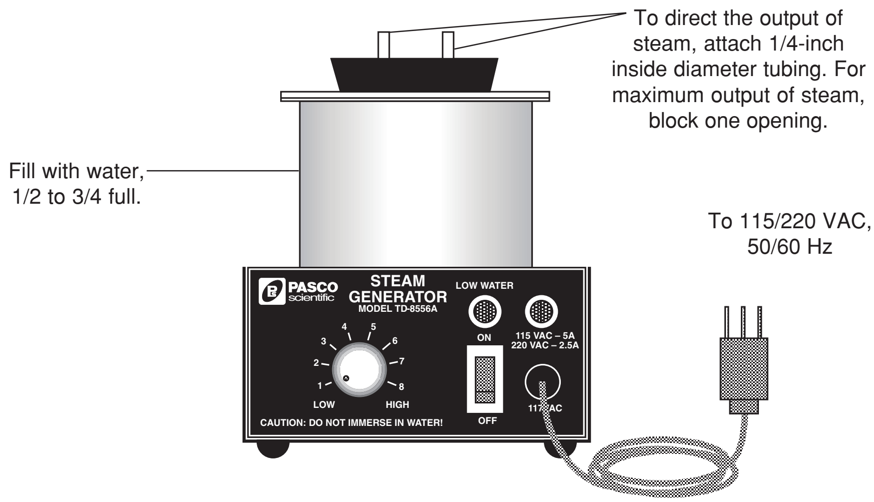
Instruction Sheet for the PASCO Model TD-8556A

STEAM GENERATOR



Introduction

The PASCO scientific Model TD-8556A Steam Generator is an efficient source of steam and hot water for the student lab. The one liter stainless steel tank is electrically heated with a variable output of up to 400 Watts. The dangers of overheating are eliminated by the thermal circuit breaker that disconnects the power if the water boils dry.

Operation

> ➤**CAUTION:**
> ① The stainless steel tank gets **HOT** when the unit is on.
> ② **DO NOT** immerse the unit in water.
> ③ **ALWAYS** plug into a grounded receptacle. Do not use a three-to-two-prong adaptor.

Operation is simple. Plug the unit into a standard 115/220 VAC, 50/60 Hz outlet. Fill the one liter tank approximately 1/2 to 3/4 full of water and place the rubber stopper over the top. Flip the ON/OFF switch to ON. The switch will light to show that power is entering the unit. Turn the power dial clockwise, and the heater will click on. Set the dial to 8 if you want steam or boiling water, to a lower setting if you want hot but not boiling water. At full power, it will take 10-15 minutes to bring 3/4 of a liter of water from room temperature to boiling.

A baster is provided for removing hot water from the tank for use in experiments. If you need steam, attach plastic tubing (1/4-inch inside diameter) to the tubes on the rubber stopper—two experiments can be performed simultaneously. For the full steam output of approximately 10 grams/minute, block the tubing on one side with a tubing clamp.

If the water in the tank runs low, the thermal circuit breaker will cut off the power to the heater and the LOW WATER light will come on. In this case, just add more water to the tank. When the tank cools sufficiently, the heater will restart automatically.

If the ON/OFF switch ever fails to illuminate when switched to ON, check the fuse on the front panel of the unit.

> ➤**IMPORTANT:** If the fuse is blown, replace only with a similarly rated fuse. For 115 V use 5 Amp, 250 V, for 220 V use 2.5 Amp, 250 V.

This instruction sheet written/edited by: Bruce Lee

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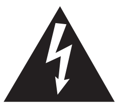
CAUTION
RISK OF ELECTRIC SHOCK. DO NOT OPEN

CAUTION:
TO PREVENT THE RISK OF ELECTRIC SHOCK, DO NOT REMOVE COVER ON UNIT. NO USER SERVICEABLE PARTS INSIDE. REFER SERVICING TO QUALIFIED SERVICE PERSONNEL.



The lightning flash with arrowhead, within an equilateral triangle, is intended to alert the user of the presence of uninsulated "dangerous voltage" within the product's enclosure that may be of sufficient magnitude to constitute a risk of electric shock to persons.

The exclamation point within an equilateral triangle is intended to alert the user of the presence of important operating and maintenance (servicing) instructions in the literature accompanying the appliance.

The TD-8556A is suitable for indoor use only and is subject to the following environmental conditions:

Maximum elevation: 2000 meters or 6500 feet

Temperature range: 5°C to 40°C.

Maximum relative humidity: 80% for temperatures up to 31°C decreased linearly to 50% at 40°C.

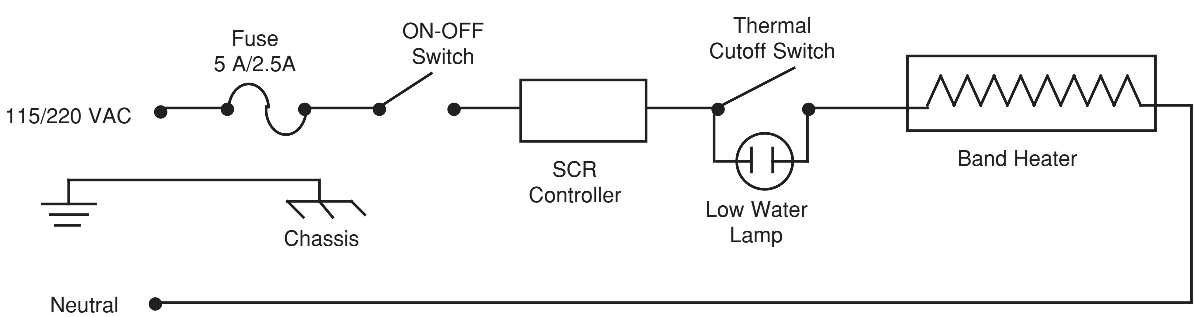
Power input maximum fluctuation: less than ±10% of the nominal voltage.

Transit overvoltage rating: Category II per IEC 10101(1990) clause 5.4.2.

Pollution degree: Degree 2 per IEC 664.

Limited Warranty

PASCO scientific warrants this product to be free from defects in materials and workmanship for a period of one year from the date of shipment to the customer. PASCO will repair or replace, at its option, any part of the product which is deemed to be defective in material or workmanship. This warranty does not cover damage to the product



Schematic - TD-8556A

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PASCO offers a variety of equipment that will help you take full advantage of your Steam Generator. In particular, the PASCO Model TD-8558A Thermal Expansion Apparatus allows accurate measurements of the thermal expansion of steel, copper, and aluminum. The Model TD-8557 Basic Calorimetry Set provides an excellent and very affordable introduction to the basic principles of thermodynamics: define the calorie, measure the heat of vaporization and fusion of water, and investigate the specific heats of metals.

The PASCO Model TD-8561 Thermal Conductivity Apparatus and Model TD-8550A Thermoelectric Converter also utilize the Steam Generator.

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- If possible, have the apparatus within reach when calling to facilitate description of individual parts.

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

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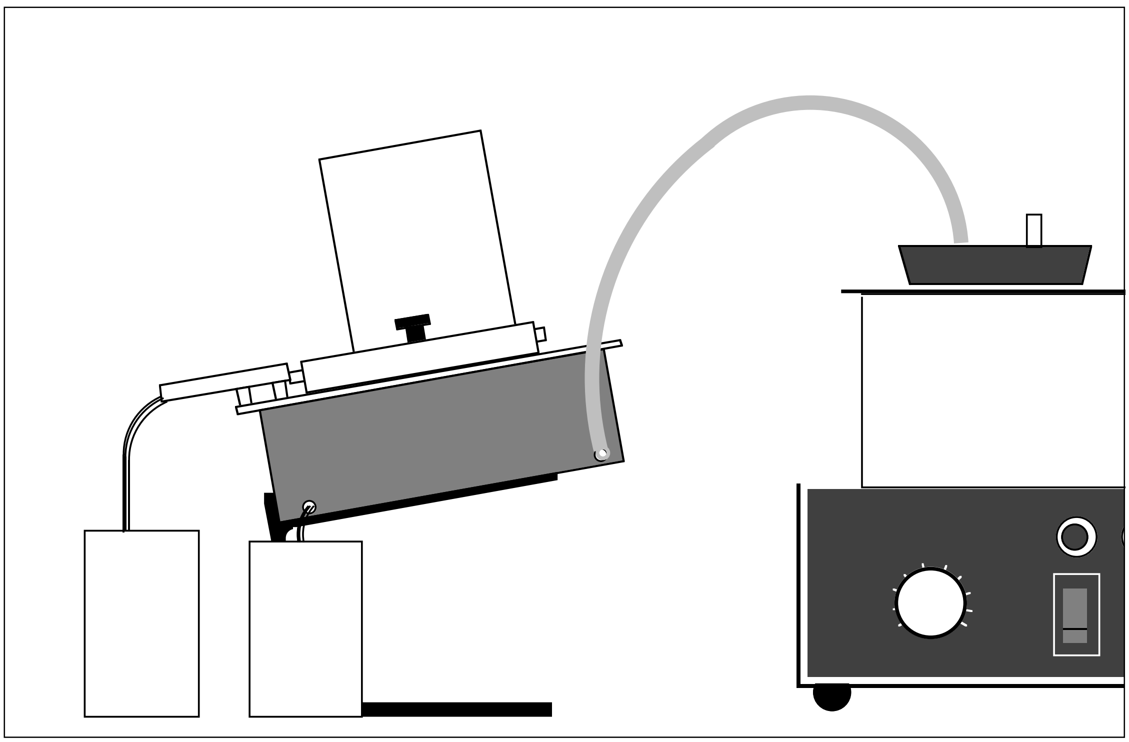
- Have the manual at hand to discuss your questions.

Includes Teacher's Notes and Typical Experiment Results

Instruction Manual and Experiment Guide for the PASCO scientific Model TD-8561

012-03349D
5/94

THERMAL CONDUCTIVITY APPARATUS



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Introduction

Thermal Conductivity Apparatus

Heat can be transferred from one point to another by three common methods: conduction, convection and radiation. Each method can be analyzed and each yields its own specific mathematical relationship. The TD-8561 Thermal Conductivity Apparatus allows one to investigate the rate of thermal conduction through five common materials used in building construction.

The equation giving the amount of heat conducted through a material is:

$$\Delta \mathbf{Q} = \mathbf{k\, A}\, \Delta \mathbf{T}\, \Delta \mathbf{t} / \mathbf{h}.$$

In this equation, **ΔQ** is the total heat energy conducted, **A** is the area through which conduction takes place, **ΔT** is the temperature difference between the sides of the material, Δt is the time during which the conduction occurred and h is the thickness of the material. The remaining term, **k**, is the thermal conductivity of a given material.

The units for **k** depend upon the units used to measure the other quantities involved. Some sample conversions between different possible sets of units are shown in Table 1.

	$\frac{\text{Btu in.}}{\text{in.}^2 \text{ sec °R}}$	$\frac{\text{Btu in.}}{\text{in.}^2 \text{ hr °R}}$	$\frac{\text{Btu ft}}{\text{ft}^2 \text{ hr °R}}$	$\frac{\text{Btu in.}}{\text{ft}^2 \text{ hr °R}}$
$\frac{\text{Watt cm}}{\text{cm}^2 \text{ °K}}$	1.338×10^{-2}	4.818	57.82	693.8
$\frac{\text{Watt m}}{\text{m}^2 \text{ °K}}$	1.338×10^{-5}	4.818×10^{-2}	0.5782	6.938
$\frac{\text{Watt in.}}{\text{in.}^2 \text{ °R}}$	9.485×10^{-4}	3.414	40.97	491.7
$\frac{\text{Cal cm}}{\text{cm}^2 \text{ sec °K}}$	5.600×10^{-3}	20.16	241.9	2.903×10^{3}

Table 1

The importance of **k** lies in whether one wishes to conduct heat well (good conductor) or poorly (good insulator). Therefore, the relative size of **k** is of importance to designers and builders, and should be of importance to home owners.

Note further that choosing a material with a small value for **k** does not guarantee a well-insulated structure. The amount of heat conducted out in winter (and therefore needing to be replaced) depends also upon three other factors: area, thickness and temperature difference. The same holds true for heat conducted in during the summer.

The equation for determining k is:

$$\mathbf{k} = \Delta \mathbf{Q\, h} / \mathbf{A}\, \Delta \mathbf{T}\, \Delta \mathbf{t} = \underline{\qquad}$$

The technique for measuring thermal conductivity is straightforward. A slab of the material to be tested is clamped between a steam chamber, which maintains a constant temperature of 100 °C, and a block of ice, which maintains a constant temperature of 0°C. A fixed temperature differential of 100 °C is thereby established between the surfaces of the material. The heat transferred is measured by collecting the water from the melting ice. The ice melts at a rate of 1 gram per 80 calories of heat flow (the latent heat of melting for ice).

The thermal conductivity, k, is therefore measured using the following equation:

$$k = (\text{cal cm/cm}^2 \text{ sec}) = \frac{(\text{mass of melted ice})\,(80 \text{ cal/gm})\,(\text{thickness of material})}{(\text{area of ice})\,(\text{time during which ice melted})\,(\text{temp. differential})}$$

where distances are measured in centimeters, masses in grams, and time in seconds.

The Thermal Conductivity Apparatus includes the following equipment (see Figure 1):

- Base
- Steam chamber with hardware for mounting sample
- Ice mold with cover (Part # 648-03427)
- Materials to test: Glass, wood, lexan, masonite, and sheet rock (The wood, masonite, and sheet rock are covered with aluminum foil for waterproofing.)

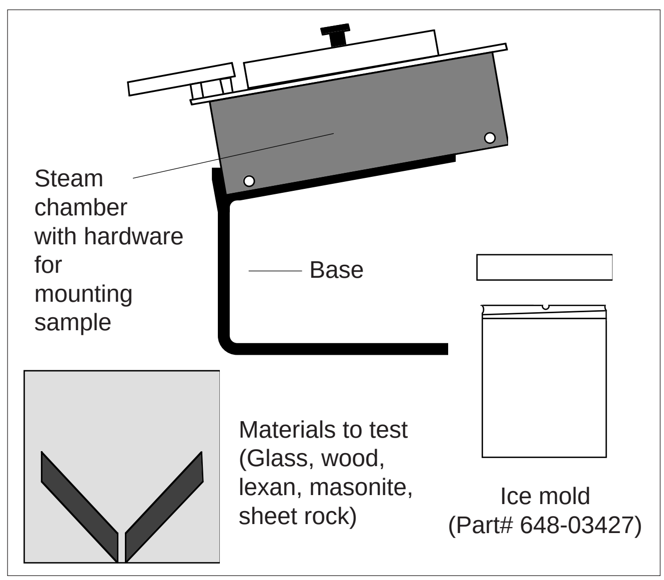

Figure 1 Equipment Included with the Thermal Conductivity Apparatus

Notes

Experiment: Measuring Thermal Conductivity

EQUIPMENT NEEDED:

- — Steam generator that will deliver approximately 10 grams/minute (e.g., PASCO's Model TD-8556 Steam Generator)
- — Freezer
- — Container to collect melted ice (a paper cup is fine)
- — Gram balance to weigh collected water (you could collect the water in a graduated flask, but your results will be less accurate)
- — Container to collect condensed steam
- — Grease such as petroleum jelly ("Vaseline")

Measuring Thermal Conductivity

① Fill the ice mold with water and freeze it. Do not freeze water with lid on jar. (A few drops of a non-sudsing detergent in the water before freezing will help the water to flow more freely as it melts and will not significantly effect the results.)

② Run jar under warm water to loosen the ice in the mold.

➤ **NOTE:** Do not attempt to "pry" the ice out of the mold.

③ Measure and record **h**, the thickness of the sample material.

④ Mount the sample material onto the steam chamber as shown in Figure 2.

➤ **NOTE:** Take care that the sample material is flush against the water channel, so water will not leak, then tighten the thumbscrews. A bit of grease between the channel and the sample will help create a good seal.

⑤ Measure the diameter of the ice block. Record this value as $\mathbf{d_1}$. Place the ice on top of the sample as shown in Figure 2. Do not remove the ice but make sure that the ice can move freely in the mold. Just place the open end of the mold against the sample, and let the ice slide out as the experiment proceeds.

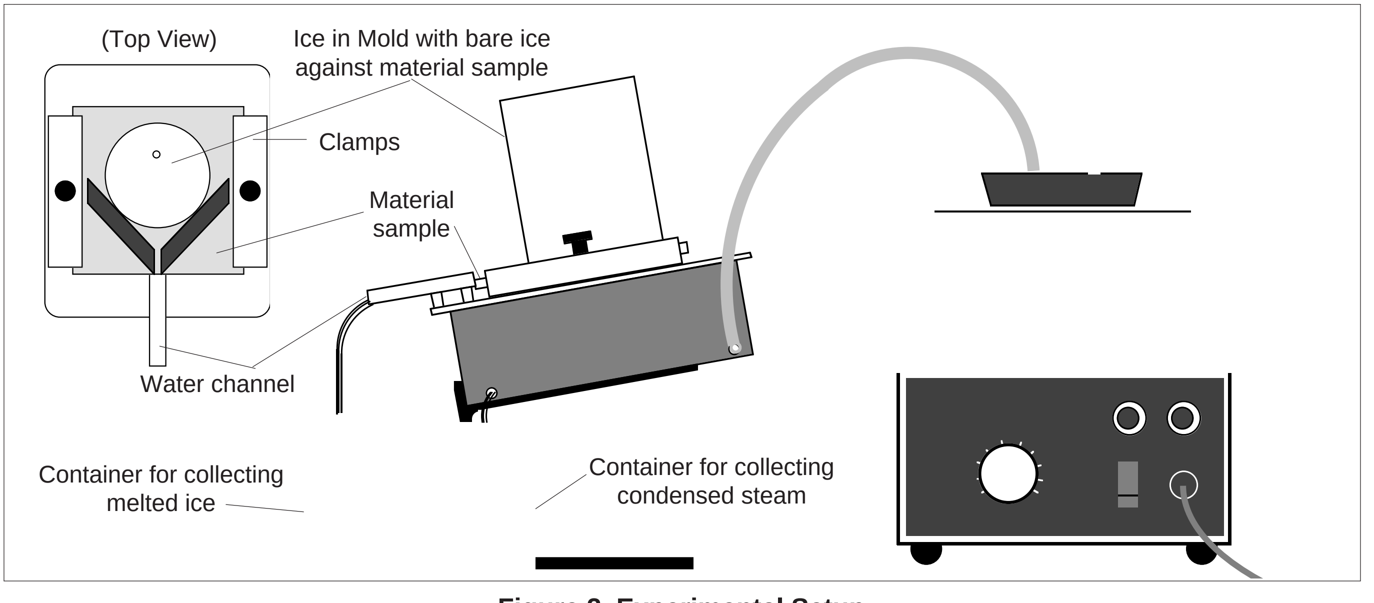

Figure 2 Experimental Setup

⑥ Let the ice sit for several minutes so it begins to melt and comes in full contact with the sample. (Don't begin taking data before the ice begins to melt, because it may be at a lower temperature than 0 °C.)

⑦ Obtain data for determining the ambient melting rate of the ice, as follows:

a. Determine the mass of a small container used for collecting the melted ice and record it.

b. Collect the melting ice in the container for a measured time $\mathbf{t_a}$ (approximately 10 minutes).

c. Determine the mass of the container plus water and record it.

d. Subtract your first measured mass from your second to determine $\mathbf{m_{wa}}$, the mass of the melted ice.

⑧ Run steam into the steam chamber. Let the steam run for several minutes until temperatures stablize so that the heat flow is steady. (Place a container under the drain spout of the steam chamber to collect the water that escapes from the chamber.)

⑨ Empty the cup used for collecting the melted ice. Repeat step 7, but this time with the steam running into the steam chamber. As before, measure and record $\mathbf{m_w}$, the mass of the melted ice, and **t**, the time during which the ice melted (5-10 minutes).

⑩ Remeasure the diameter of the ice block and record the value as $\mathbf{d_2}$.

DATA AND CALCULATIONS

① Take the average of $\mathbf{d_1}$ and $\mathbf{d_2}$ to determine $\mathbf{d_{avg}}$, the average diameter of the ice during the experiment.

② Use your value of $\mathbf{d_{avg}}$ to determine **A**, the area over which the heat flow between the ice and the steam chamber took place. (Assume that **A** is just the area of the ice in contact with the sample material.)

③ Divide $\mathbf{m_{wa}}$ by $\mathbf{t_a}$ and $\mathbf{m_w}$ by **t** to determine $\mathbf{R_a}$ and **R**, the rates at which the ice melted before and after the steam was turned on.

④ Subtract $\mathbf{R_a}$ from **R** to determine $\mathbf{R_0}$, the rate at which the ice melted due to the temperature differential only.

⑤ Calculate **k**, the conductivity of the sample:

k (cal cm/cm^2 sec) = __________

ΔT = Boiling point of water (100 °C at sea level) - 0°C.

Data and Calculations Table

h	d_1	d_2	t_a	m_{wa}	t	m_w	d_{avg}	A	R_a	R	R_0

$$\frac{(R_0)\ (80\ \text{cal/gm})\ (h)}{(A)\ (\Delta T);}$$ __________

PASCO scientific

Teacher's Guide

Experiment: Thermal Conductivity Apparatus

Notes on Procedure

① Expect 10-15% error under normal (student laboratory) operating conditions.

② Keep the ice as isolated from the surroundings as possible. Our best results were obtained using a PASCO styrofoam calorimeter cup as an ice mold; however, this has the disadvantage of splitting the cup when the water freezes. (Medium-sized styrofoam cups also work very nicely.) Whatever mold you use, leave it on the ice during the experiment.

③ Apply a dab of grease to the joint between the plate and the water trough to prevent leakage. Vaseline® works well; it melts, but still seals the gap.

④ A note about the aluminum covers on some samples: This was found experimentally to have no measurable effect on the conductivity of the samples. We tested this using a glass plate which we measured both with and without an aluminum cover, and there was no statistically significant difference between multiple readings in both states.

Accepted Values

Substance	**cal•cm/cm^2•sec•°C**	**watt•m/m^2•K**
Masonite	1.13 x 10^{-4}	0.047
Wood (Pine)	206 - 3.3 x 10^{-4}	0.11 - 0.14
Lexan	4.6 x 10^{-4}	0.19
Sheet Rock	10.3 x 10^{-4}	0.43
Glass	17.2 - 20.6 x 10^{-4}	0.72 - 0.86

Note

Values (with the exception of Lexan) from the *Handbook of Chemistry and Physics, 46th Edition,* published by The Chemical Rubber Company. Value for Lexan is from a specifications sheet provided by the manufacturer. Values for Masonite and for Sheet Rock will vary considerably.

Notes

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  Type of Computer (Make, Model, Speed).

  Type of external Cables/Peripherals.

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  Have the manual at hand to discuss your questions.

Instruction Manual and Experiment Guide for the PASCO scientific Model TD-8572

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HEAT ENGINE/ GAS LAW APPARATUS

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Introduction

The PASCO TD-8572 Heat Engine/Gas Law Apparatus is used for quantitative experiments involving the Ideal Gas Law (as described below) and for investigations of a working heat engine. The equipment allows the amount of work done by thermal energy to be measured.

The heart of this apparatus is a nearly friction-free piston/cylinder system. The graphite piston fits snugly into a precision-ground Pyrex cylinder so that the system produces almost friction-free motion and negligible leakage.

Equipment

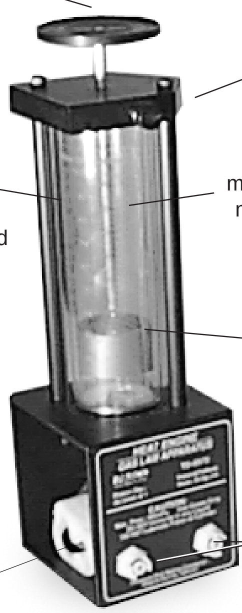


Figure 1. Base apparatus

The Heat Engine/Gas Law Apparatus is designed with two pressure ports with quick-connect fittings for connecting to the air chamber tubing.

The apparatus can be connected to a Low Pressure Sensor for use with PASCO computer interfaces.

> ⚠ Do not apply lubricant to the piston or cylinder.

> ⚠ Do not immerse the base apparatus in liquid.

> ⚠ Note: Use only non-caustic/non-toxic gases such as air or helium.

The apparatus includes the following equipment

- base apparatus (Figure 1)
  - piston diameter: 32.5 mm ± 0.1
  - mass of piston and platform: 35.0 g ± .06
- air chamber (Figure 2)
- 3 hose configurations: one with one-way check valves and one with a clamp (Figure 2), and one plain piece of tubing (not shown)
- 1 each, one-holed and two-holed rubber stopper

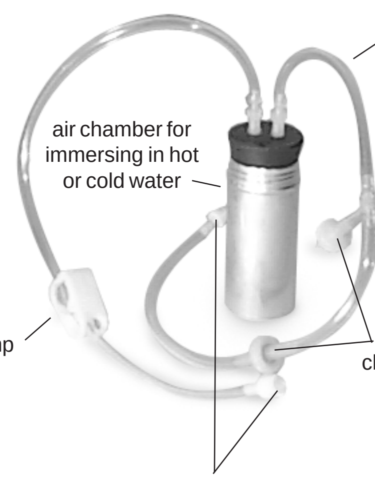


Figure 2. Air chamber and tubing

> ⚠ Always release the tubing clamps prior to storage to avoid permanently deforming the tubing.

> ⚠ Maximum Pressure: 345 kPa.

Notes:

Experiment 1: Operation of a Heat Engine

Equipment Required:	
• Heat Engine/Gas Law Apparatus	• container of hot water
• 100 – 200 g mass	• container of ice water

Equipment Setup

① Using the one-holed stopper, connect the tubing with the one-way valves to the air chamber and to a connecting port on the base assembly.

② Close the shut-off valve on the tubing from the unused port.

③ Set a mass of 100 to 200 g on the mass platform.

➤ Note: Use a maximum mass of 200 grams in the experiment. A larger mass will cause the valve seals to leak.

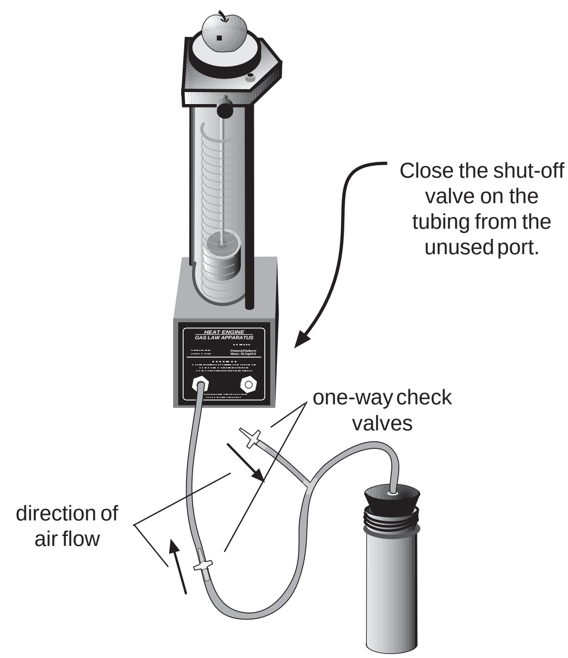


Figure 1.1. Setup for the Heat Engine

Procedure

① Move the air chamber from an ice water bath to a hot water bath. You will note that the air in the chamber quickly expands through the tubing and moves the piston up. Note also that the one-way check valve in the tubing connecting the base apparatus and the air chamber permits air to enter the cylinder, while the other one-way check valve prevents air from leaving through the branched tube.

② Move the air chamber back to the cold bath and note that external air is sucked into the air chamber through the one-way valve located at the end of the branched tube. Note also that the one-way valve in the connecting tube prevents the air from escaping from the piston, so the height of the piston remains the same.

③ Repeat steps 3 and 4 until the mass has been completely lifted.

➤ Note: The greater the temperature differential between the hot and cold water baths, the greater the lift achieved through each cycle through them.

➤ Note: For a more detailed, quantitative investigation of the operation of a heat engine, see Experiment 5 (page 11).

Experiment 2: Charles' Law

Equipment Required:	
• Heat Engine/Gas Law Apparatus	• container of hot water
• thermometer	• ice

Theory

Charles' law states that at a constant pressure, the volume of a fixed mass or quantity of gas varies directly with the absolute temperature:

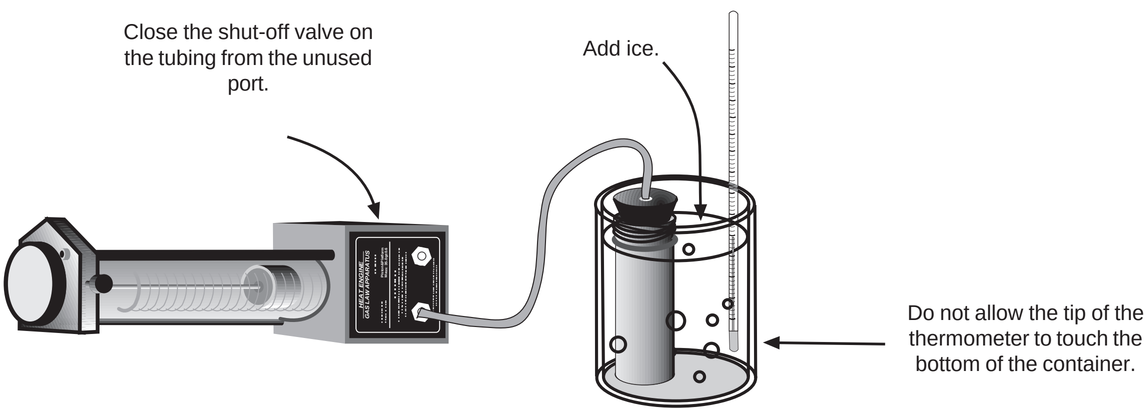
$$V = cT \qquad \text{(at constant } P \text{ and where } T \text{ is expressed in degrees Kelvin)}$$

Setup

① Using the one-holed stopper and plain tubing, connect the base apparatus and the air chamber.

② Close the shut-off valve on the tubing from the unused port.

③ Turn the base apparatus on its side. (In this position, the force acting on the apparatus is the atmospheric pressure and is equal throughout the range of operation of the piston.)



Procedure

① Place the air chamber in a container of hot water. After the chamber equilibrates to the temperature, record the temperature and the height of the piston.

② Add ice to the container and record the temperature and pressure at regular time intervals.

③ Calculate the gas volumes at the various piston positions you measured and make a graph of plots of temperature versus volume. (Hint: The diameter of the piston is 32.5 mm.)

Notes:

Experiment 3: Boyle's Law

Equipment Required:	
• Heat Engine/Gas Law Apparatus	• *Science Workshop* computer interface*
• Pressure Sensor (CI-6532)	

*For details on setting up and operating the Pressure Sensor with *Science Workshop*, please consult the instruction sheet for the Pressure Sensor and the User's Guide for *Science Workshop.*

Theory

Boyle's law states that the product of the volume of a gas times its pressure is a constant at a fixed temperature:

$$PV = a$$

Therefore, at a fixed temperature, the pressure will be inversely related to the volume, and the relationship will be linear:

$$P = \frac{a}{V}$$

Setup

① With the platform raised to its uppermost position, connect the Pressure Sensor to a port on the base apparatus with a short piece of tubing (Figure 3.1).

② Close the shut-off valve on the tubing from the unused port.

③ Connect the Pressure Sensor to the computer interface and set up Science Workshop to record pressure. Be sure that you set up the keyboard sampling option so you can enter height data by hand. (Consult the *Science Workshop User's Guide*, "Keyboard Sampling," for details.)

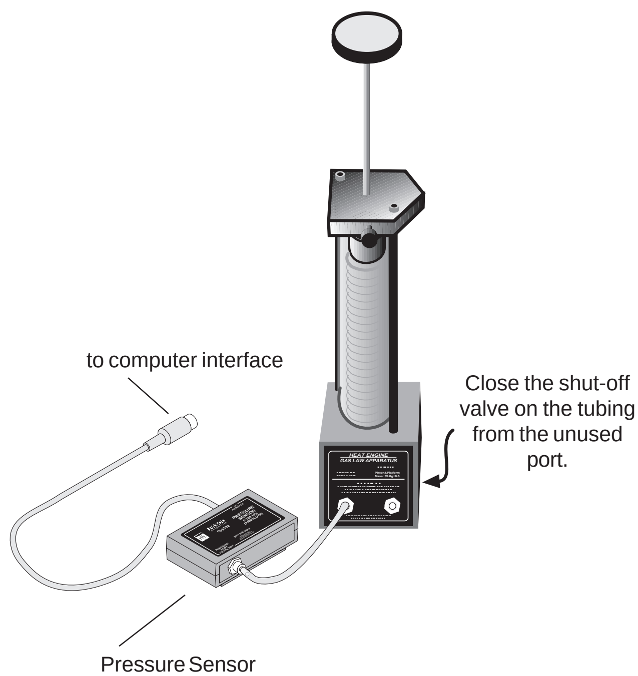


Figure 3.1. Experimental setup

Procedure

① Record the height of the piston and the pressure when the platform is raised to its highest position.

② Press the platform down to a series of levels and record the height and pressure at each level.

③ Convert the height measurements to gas volume measurements. (Hint:
The diameter of the piston is 32.5 mm.)

④ Prepare a graph of pressure versus volume.

➤ Note: The relationship between pressure and volume may not be linear at pressures greater than 120 kPa because of air leakage from the valves and ports at higher pressures.

Experiment 4: Combined Gas Law (Gay-Lussac's)

Equipment Required:	
• Heat Engine/Gas Law Apparatus	• hot plate
• Pressure Sensor (CI-6532)	• Pyrex beaker with water
• *Science Workshop* computer interface*	• ice
• Temperature Sensor (CI-6505)	

*For details on setting up and operating the Pressure Sensor and the Temperature Sensor with *Science Workshop*, please consult the instruction sheets for the Pressure Sensor and the Temperature Sensor and the User's Guide for *Science Workshop*.

Theory

Charles' law states that V is proportional to T, and Boyle's law states that V is proportional to $1/P$. Combining these, we have:

$$V = \frac{aT}{P}$$

The combined gas law predicts that for a given mass of gas, if V is held constant, P is proportional to T.

Setup

① Secure the piston just above its lowest position by tightening the thumb screw.

② Connect the Pressure Sensor to a port on the base apparatus with a short piece of tubing.

③ Connect the air chamber fitted with the 2-holed stopper to the other port of the base apparatus with a piece of tubing.

④ Insert the Temperature Sensor into the other hole of the rubber stopper.

> ⚠ Use a silicon lubricant on the end of the Temperature Probe to aid insertion and to prevent damage to the probe.

⑤ Connect the Pressure Sensor and the Temperature Sensor to the computer interface, and set up the *Science Workshop* program to graph temperature versus pressure.

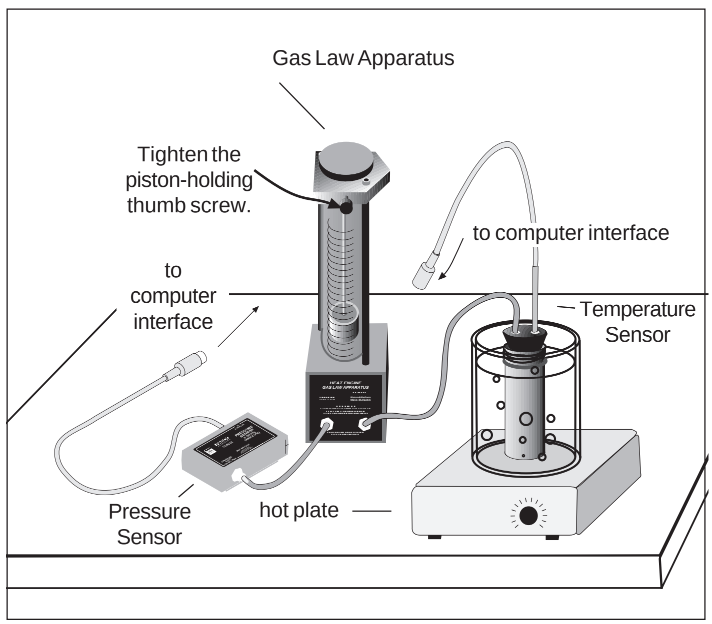


Figure 4.1. Experimental setup

> ➤ Note: You can substitute a thermometer in the water container for the Temperature Sensor. Be sure to keep the tip of the thermometer from touching the bottom of the container.

⑥ Place the air chamber in the Pyrex container and turn on the hot plate.

Procedure

① Record the temperature and pressure as the water heats.

② Display a graph of temperature versus pressure in Science Workshop.

Experiment 5: The Mass Lifter Heat Engine[1]

The Heat Engine/Gas Law Apparatus is ideal for use in the calculus-based experiment 18.10 of the *Workshop Physics Activity Guide*. Following is a slightly modified reprint of the experiment:

Equipment Required:	
• Heat Engine/Gas Law Apparatus	• 1 calipers
• 2 Pyrex beakers, 1000 ml (to use as reservoirs)	• 1 mass set, 20 g, 50 g, 100 g, 200 g
• 1 ruler	• 1 hot plate
• 1 barometer pressure gauge	• 1 vat to catch water spills

Optional:

- a computer-based laboratory system with barometer sensor

Your working group has been approached by the Newton Apple Company about testing a heat engine that lifts apples that vary in mass from 100 g to 200 g from a processing conveyer belt to the packing conveyer belt that is 10 cm higher. The engine you are to experiment with is a "real" thermal engine that can be taken through a four-stage expansion and compression cycle and that can do useful mechanical work by lifting small masses from one height to another. In this experiment we would like you to verify experimentally that the useful mechanical work done in lifting a mass, *m*, through a vertical distance, *y*, is equal to the net thermodynamic work done during a cycle as determined by finding the enclosed area on a *P*-*V* diagram. Essentially you are comparing useful mechanical "ma_gy" work (which we hope you believe in and understand from earlier studies) with the accounting of work in an engine cycle as a function of pressure and volume changes given by the expression:

$$W_{net} = \oint P dV$$

Although you can prove mathematically that this relationship holds, the experimental verification will allow you to become familiar with the operation of a real heat engine.

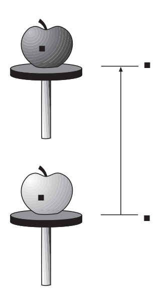


Figure 5.1. Doing useful mechanical work by lifting a mass, *m*, through a height, *y*.

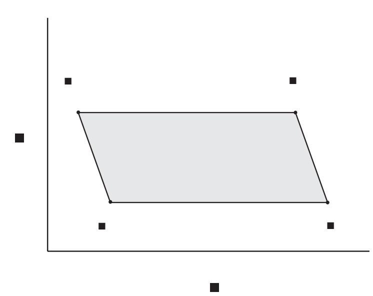


Figure 5.2 Doing thermodynamic work in a heat engine cycle.

[1]Priscilla W. Laws, et al. *Workshop Physics Activity Guide*, 1996 by John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.

The Incredible Mass Lifter Engine

The heat engine consists of a hollow cylinder with a graphite piston that can move along the axis of the cylinder with very little friction. The piston has a platform attached to it for lifting masses. A short length of flexible tubing attaches the cylinder to an air chamber (consisting of a small can sealed with a rubber stopper that can be placed alternately in the cold reservoir and the hot reservoir. A diagram of this mass lifter is shown in Figure 5.2.

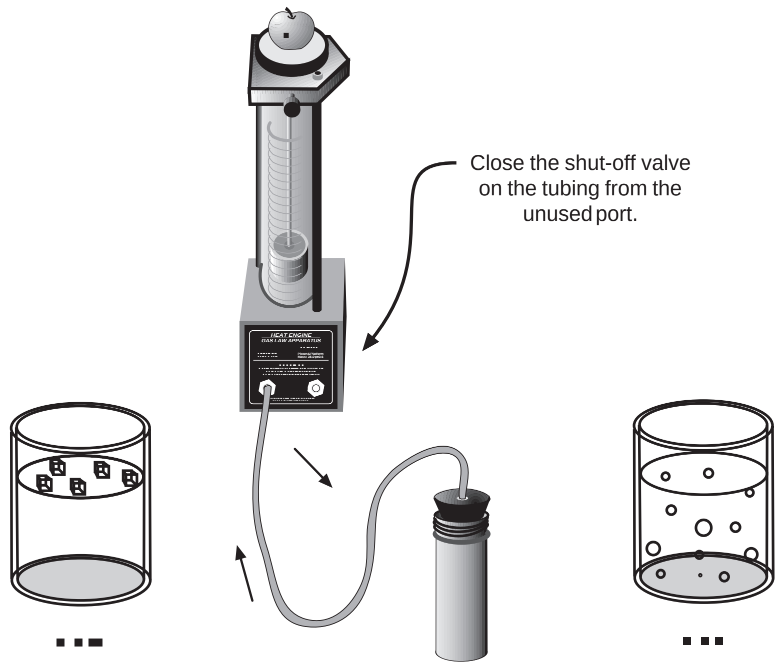


Figure 5.2. A schematic diagram of the incredible mass lifter heat engine.

If the temperature of the air trapped inside the cylinder, hose, and can is increased, then its volume will increase, causing the platform to rise. Thus, you can increase the volume of the trapped air by moving the can from the cold to the hot reservoir. Then, when the apple has been raised through a distance *y*, it can be removed from the platform. The platform should then rise a bit more as the pressure on the cylinder of gas decreases a bit. Finally, the volume of the gas will decrease when the air chamber is returned to the cold reservoir. This causes the piston to descend to its original position once again. The various stages of the mass lifter cycle are shown in Figure 5.3.

Before taking data on the pressure, air volume, and height of lift with the heat engine, you should set it up and run it through a few cycles to get used to its operation. A good way to start is to fill one container with room temperature water and another with hot tap water or preheated water at about 60–70°C. The engine cycle is much easier to describe if you begin with the piston resting above the bottom of the cylinder. Thus, we suggest you raise the piston a few centimeters before inserting the rubber stopper firmly in the can. Also, air does leak out of the cylinder slowly. If a large mass is being lifted, the leakage rate increases, so we suggest that you limit the added mass to something between 100 g and 200 g. After observing a few engine cycles, you should be able to describe each of the points *a*, *b*, *c*, and *d* of a cycle carefully, indicating which of the transitions between points are approximately adiabatic and which are isobaric. You can observe changes in the volume of the gas directly and you can predict how the pressure exerted on the gas by its surroundings ought to change from point to point by using the definition of pressure as force per unit area.

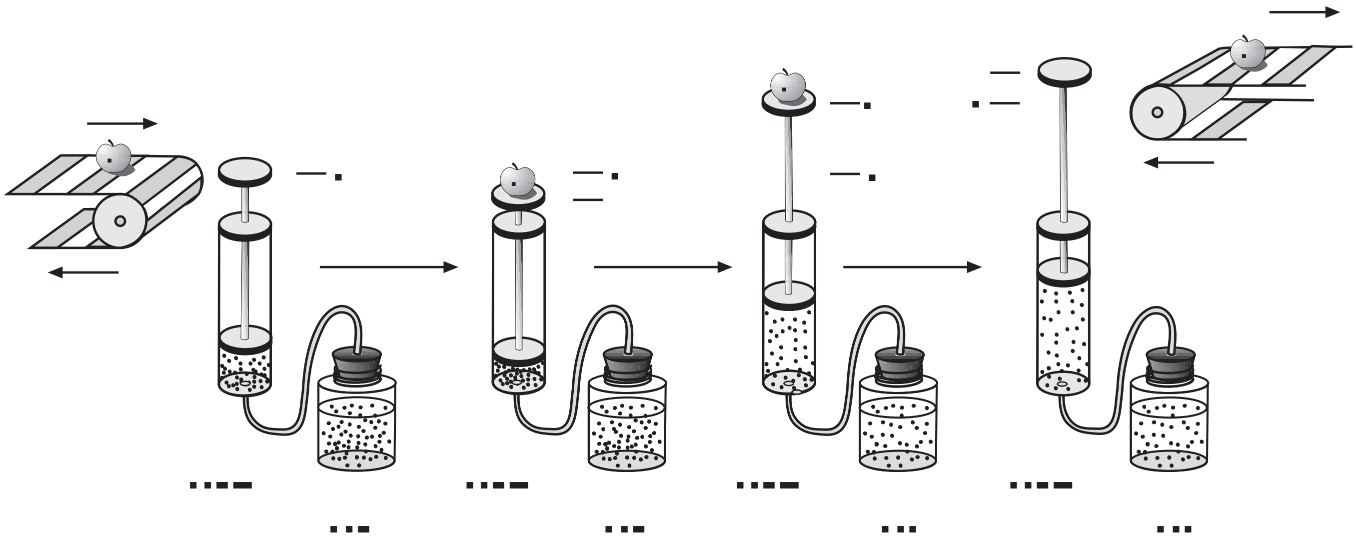


Figure 5.3. A simplified diagram of the mass lifter heat engine at different stages of its cycle.

5.1 Activity: Description of the Engine Cycle

a. Predicted transition *a*→*b*: Close the system to outside air but leave the can in the cold reservoir. Make sure the rubber stopper is firmly in place in the can. What should happen to the height of the platform when you add a mass? Explain the basis of your prediction.

b. Observed transition *a*→*b*: What happens when you add the mass to the platform? Is this what you predicted?

c. Predicted transition *b*→*c*: What do you expect to happen when you place the can in the hot reservoir ?

d. Observed transition *b*→*c*: Place the can in the hot reservoir and describe what happens to the platform with the added mass on it. Is this what you predicted? (This is the engine power stroke!)

e. Predicted transition *c*→*d*: Continue to hold the can in the hot reservoir and predict what will happen if the added mass that is now lifted is removed from the platform and moved onto an upper conveyor belt. Explain the reasons for your prediction.

f. Observed transition *c*→*d*: Remove the added mass and describe what actually happens. Is this what you predicted?

g. Predicted transition *d*→*a*: What do you predict will happen if you now place the can back in the cold reservoir? Explain the reasons for your prediction.

h. Observed transition *d*→*a*: Now it's time to complete the cycle by cooling the system down to its original temperature for a minute or two before placing a new mass to be lifted on it. Place the can in the cold reservoir and describe what actually happens to the volume of the trapped air. In particular, how does the volume of the gas actually compare to the original volume of the trapped air at point a at the beginning of the cycle? Is it the same or has some of the air leaked out?

i. Theoretically, the pressure of the gas should be the same once you cool the system back to its original temperature. Why?

Determining Pressures and Volumes for a Cycle

In order to calculate the thermodynamic work done during a cycle of this engine, you will need to be able to plot a *P*-*V* diagram for the engine based on determinations of the volumes and pressures of the trapped air in the cylinder, tubing, and can at the points *a*, *b*, *c*, and *d* in the cycle.

5.2 Activity: Volume and Pressure Equations

a. What is the equation for the volume of a cylinder that has an inner diameter of *d* and a length *L*?

b. Use the definition of pressure to derive the equation for the pressure on a gas being contained by a vertical piston of diameter *d* if the total mass on the piston including its own mass and any added mass is denoted as *M*. **Hints:** (1) What is the definition of pressure? (2) What is the equation needed to calculate the gravitational force on a mass, *M*, close to the surface of the Earth? (3) Don't forget to add in the atmospheric pressure, P_{atm}, acting on the piston and hence the gas at sea level.

Now that you have derived the basic equations you need, you should be able to take your engine through another cycle and make the measurements necessary for calculating both the volume and the pressure of the air and determining a *P*-*V* diagram for your heat engine. Instead of calculating the pressures, if you have the optional equipment available, you might want to measure the pressures with a barometer or a barometer sensor attached to a computer-based laboratory system.

5.3 Activity: Determining Volume and Pressure

a. Take any measurements needed to determine the volume and pressure of air in the system at all four points in the engine cycle. You should do this rapidly to avoid air leakages around the piston and summarize the measurements with units in the space below.

b. Next you can use your measurements to calculate the pressure and volume of the system at point *a*. Show your equations and calculations in the space below and summarize your results with units. Don't forget to take the volume of the air in the tubing and can into account!

$P_a =$

$V_a =$

c. Use the measurements at point *b* to calculate the total volume and pressure of the air in the system at that point in the cycle. Show your equations and calculations in the space below and summarize your results with units.

$P_b =$

$V_b =$

d. What is the height, *y*, through which the added mass is lifted in the transition from *b* to *c*?

e. Use the measurements at point *c* to calculate the total volume and pressure of the air in the system at that point in the cycle. Show your equations and calculations in the following space and summarize your results with units.

$P_c =$

$V_c =$

f. Remove the added mass and make any measurements needed to calculate the volume and pressure of air in the system at point *d* in the cycle. Show your equations and calculations in the space below and summarize your results with units.

P_d=

V_d=

g. We suspect that transitions from $a \rightarrow b$ and from $c \rightarrow d$ are approximately adiabatic. Explain why.

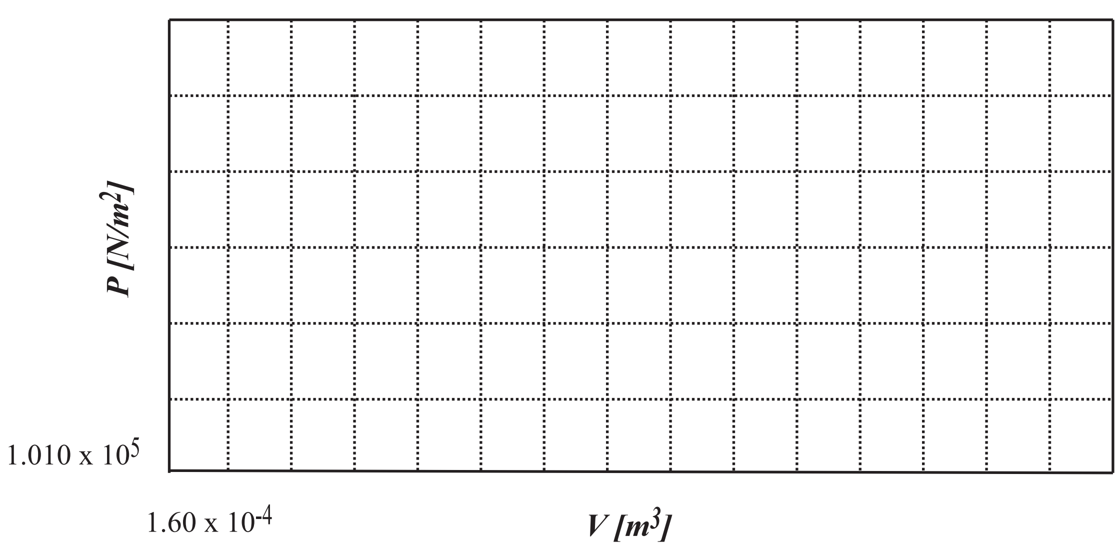
h. You should have found that the transitions from $b \rightarrow c$ and from $d \rightarrow a$ are isobaric. Explain why this is the case.

Finding Thermodynamic Work from the Diagram

In the next activity you should draw a *P- V* diagram for your cycle and determine the thermodynamic work for your engine.

5.4 Activity: Plotting and Interpreting a *P-V* Diagram

a. Fill in the appropriate numbers on the scale on the graph frame that follows and plot the *P-V* diagram for your engine cycle. Alternatively, generate your own graph using a computer graphing routine and affix the result in the space below.



b. On the graph in part a, label each of the points on the cycle (*a*, *b*, *c*, and *d*). Indicate on the graph which of the transitions ($a \rightarrow b$, $b \rightarrow c$, etc.) are adiabatic and which are isobaric.

Next you need to find a way to determine the area enclosed by the *P*- *V* diagram. The enclosed area doesn't change very much if you assume that *P* is approximately a linear function of *V* for the adiabatic transitions. By making this approximation, the figure is almost a parallelogram so you can obtain the enclosed area using one of several methods. Three of the many possibilities are listed below. *Creative students have come up with even better methods than these, so you should think about your method of analysis carefully*.

Method I

Since the pressure doesn't change from point *b* to point *c*, you can take the pressure of those two points as a constant pressure between points. The same holds for the transition from *d* to *a*. This gives you a figure that is approximately a parallelogram with two sets of parallel sides. You can look up and properly apply the appropriate equation to determine the net thermodynamic work performed.

Method II

Display your graph with a grid and count the boxes in the area enclosed by the lines connecting points *a*, *b*, *c*, and *d*. Then multiply by the number of joules each box represents. You will need to make careful estimates of fractions of a box when a "leg" of a cycle cuts through a box.

Method III

$$\oint PdV = \int_a^b PdV + \int_b^c PdV + \int_c^d PdV + \int_d^a PdV$$

Fit a straight line to each of the starting and ending points for the four transitions in the cycle. Each equation will give you a function relating *P* and *V*. Perform an integral for each of these equations, since

5.5 Activity: Comparing the Thermodynamic and Useful Mechanical Work

a. Choose a method for computing the thermodynamic work in joules, describe it in the space below, and show the necessary calculations. Report the result in joules.

b. What is the equation you need to use to calculate the useful mechanical work done in lifting the mass from one level to another?

c. Use the result for the height that the mass is lifted in the power stroke of the engine to calculate the useful mechanical work performed by the heat engine.

d. How does the thermodynamic work compare to the useful mechanical work? Please use the correct number of significant figures in your comparison (as you have been doing all along, right?)

The Incredible Mass Lifter Engine Is Not So Simple

Understanding the stages of the engine cycle on a *P-V* diagram is reasonably straightforward. However, it is difficult to use equations for adiabatic expansion and compression and the ideal gas law to determine the temperature (and hence the internal energy of the air throughout the cycle. There are several reasons for this. First, air is not an ideal gas. Second, the mass lifter engine is not well insulated and so the air that is warmed in the hot reservoir transfers heat energy through the cylinder walls. Thus, the air in the can and in the cylinder are probably not at the same temperature. Third, air does leak out around the piston, especially when larger masses are added to the platform. This means that the number of moles of air decreases over time. You can observe this by noting that in the transition from point *d* to point *a*, the piston can actually end up in a lower position than it had at the beginning of the previous cycle. However, the Incredible Mass Lifter Engine does help us understand typical stages of operation of a real heat engine.

➤ Note: The previous experiment was intended to help students consolidate the concepts of pressure and volume by taking their own data for height and mass in each part of the cycle and then calculating the pressures using the basic definition of pressure vs. force per unit area. An alternate method for doing this experiment is to use the *Science Workshop* computer interface with the Pressure Sensor (CI-6532) in conjunction with either a Motion Sensor (CI-6529) or Rotary Motion Sensor (CI-6538) to detect pressure, volume, and height automatically with a computer.

Technical Support

Feedback

If you have any comments about the product or 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 feedback. 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.

fax: (916) 786-3292

e-mail: techsupp@pasco.com

web: www.pasco.com

Contacting Technical Support

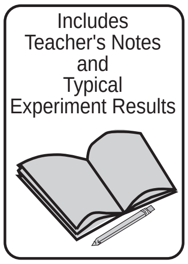
Before you call the PASCO Technical Support staff, it would be helpful to prepare the following information:

➤ 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 to facilitate description of individual parts.

➤ 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.



Instruction Manual and Experiment Guide for the PASCO scientific Model TD-8558A

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THERMAL EXPANSION APPARATUS

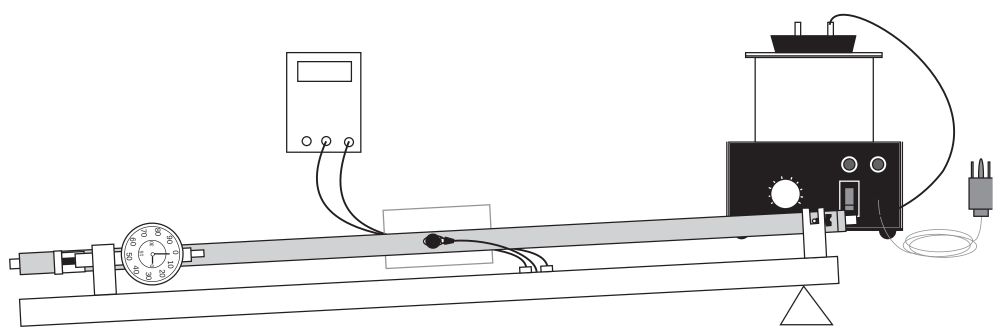

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Table of Contents

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Should the product have to be returned to PASCO scientific for any reason, notify PASCO scientific by letter, phone, or fax BEFORE returning the product. Upon notification, the return authorization and shipping instructions will be promptly issued.

➤ **NOTE:** NO EQUIPMENT WILL BE ACCEPTED FOR RETURN WITHOUT AN AUTHORIZATION FROM PASCO.

When returning equipment for repair, the units must be packed properly. Carriers will not accept responsibility for damage caused by improper packing. To be certain the unit will not be damaged in shipment, observe the following rules:

① The packing carton must be strong enough for the item shipped.

② Make certain there are at least two inches of packing material between any point on the apparatus and the inside walls of the carton.

③ Make certain that the packing material cannot shift in the box or become compressed, allowing the instrument come in contact with the packing carton.

Address: PASCO scientific
10101 Foothills Blvd.
Roseville, CA 95747-7100

Phone: (916) 786-3800
FAX: (916) 786-3292
email: techsupp@pasco.com
web: www.pasco.com

Introduction

Introduction

The PASCO Model TD-8558A Thermal Expansion Apparatus provides easy and accurate measurements of the coefficient of linear expansion for steel, copper, and aluminum.

To make the measurement, the steel, copper, or aluminum tube is placed on the expansion base. The length of the tube is measured at room temperature, then steam is passed through it. The expansion of the metal is measured with 0.01 mm resolution using the built-in dial-gauge. Temperatures are measured to within 0.5 °C using a thermistor attached to the center of the tube. If you wish to investigate the expansion of the metals at additional temperatures, hot or cold water can be passed through the tubes.

Complete step by step instructions and a data sheet for results are provided on the following pages.

Equipment

Your TD-8558A Thermal Expansion Apparatus includes:

- A 70 cm long expansion base with a built-in dial gauge and thermistor.

> ➤ **NOTE:** The dial gauge can be removed or repositioned by loosening the screw on the dial gauge mounting block.

- Three metal tubes — steel, copper (99.5% Cu, 0.5% Te), and aluminum (98.9% Al, 0.7% Mg, 0.4% Si): 5/8-inch outside diameter with 1/4-inch outside diameter connectors. Each tube has a thumbscrew for attaching the thermistor lug.
- A foam insulator to avoid heat loss at the thermistor connection point.
- Thermoplastic elastometer tubing with 1/4" I.D.

Additional Equipment Required

In addition to the TD-8558A Thermal Expansion Apparatus, the following items are needed to perform the experiment:

① A source of steam or hot water, such as the PASCO Model TD-8556 Steam Generator.

② A digital ohmmeter such as PASCO Model SE-9589 to measure the thermistor resistance. Leads should have banana plug connectors, such as PASCO Model SE-9750 or SE-9751 Patch Cords.

③ A small object to raise the end of the expansion base approximately 2-inches and a container to catch the water as it drains out of the tube.

④ If additional data points are desired you will also need: a source of hot or cold water.

Notes on Temperature Measurement

A thermistor's resistance varies reliably with temperature. The resistance can be measured with an ohmmeter, and converted to a temperature measurement using the conversion table provided on the expansion base and also on the back page of this manual. Although the relationship between temperature and resistance is not linear, a linear approximation can be accurately used to interpolate between table data points with an accuracy of approximately ±0.2 °C.

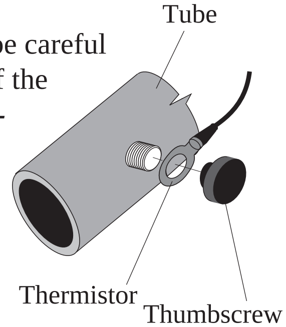
The thermistor used to measure the tube temperature is embedded in the thermistor lug. Once thermal equilibrium has been reached, the heat is highly uniform along the length of the tube. The foam insulator is used to inhibit heat loss through the thermistor lug so the lug temperature closely follows the tube temperature. The insulator does not have any appreciable effect on the local temperature of the tube itself.

Accepted Values for Coefficient of Thermal Expansion

Material	a (x10-6/∞C)
Copper	17.6
Steel	11.3 to 13.5
Aluminum	23.4

Changing Tubes

➤ **Caution:**
When changing tubes be careful not to pull the wires off the thermistor. ***The thumbscrew must be completely removed*** before the thermistor can be lifted off the threaded rod.



Replacement Parts

The following parts can be ordered from PASCO scientific.

Item	PASCO Part #
mod. Thermistor (100 kΩ)	150-03140
Al Tube Assy	003-04413
Cu Tube Assy	003-04412
Steel Tube Assy	003-04414
Foam Insulator	648-03100
Dial Gauge	620-050

Experiment: Measuring the Coefficient of Linear Expansion for Copper, Steel, and Aluminum

Introduction

Most materials expand somewhat when heated through a temperature range that does not produce a change in phase. The added heat increases the average amplitude of vibration of the atoms in the material which increases the average separation between the atoms.

Suppose an object of length L undergoes a temperature change of magnitude ΔT. If ΔT is reasonably small, the change in length, ΔL, is generally proportional to L and ΔT. Stated mathematically:

$$\Delta L = \alpha L \, \Delta T;$$

where α is called the coefficient of linear expansion for the material.

For materials that are not isotropic, such as an asymmetric crystal for example, a can have a different value depending on the axis along which the expansion is measured.
a can also vary somewhat with temperature so that the degree of expansion depends not only on the magnitude of the temperature change, but on the absolute temperature as well.

In this experiment, you will measure α for copper, aluminum, and steel. These metals are isotropic so that a need only be measured along one dimension. Also, within the limits of this experiment, a does not vary with temperature.

Procedure

① Measure L, the length of the copper tube at room temperature. Measure from the inner edge of the stainless steel pin on one end, to the inner edge of the angle bracket at the other end (see Figure 1). Record your results in Table 1.

② Mount the copper tube in the expansion base as shown in Figure 2. The stainless steel pin on the tube fits into the slot on the slotted mounting block and the bracket on the tube presses against the spring arm of the dial gauge.

➤ **NOTE:** Slide or push the tube to one side of the slide support. Drive the thumbscrew against the pin until the tube can no longer be moved. Use this as your reference point.

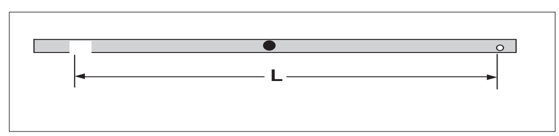


Figure 1 Measuring Tube Length

③ Use one of the provided thumbscrews to attach the thermistor lug to the threaded hole in the middle of the copper tube. The lug should be aligned with the axis of the tube, as shown in Figure 2, so there is maximum contact

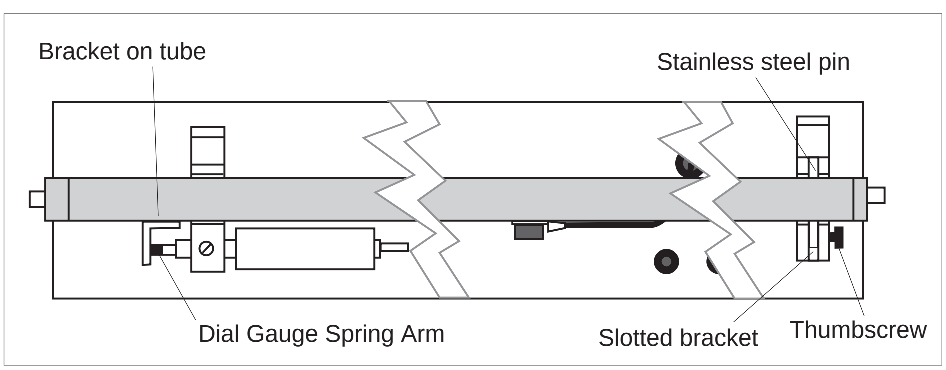


Figure 2 Equipment Setup (Top View)

between the lug and the tube.

④ Place the foam insulator over the thermistor lug as shown in Figure 3.

⑤ Plug the leads of your ohmmeter into the banana plug connectors labeled THERMISTOR in the center of the expansion base.

⑥ Measure and record R_{rm}, the resistance of the thermistor at room temperature. Record this value in the table.

⑦ Use tubing to attach your steam generator to the end of the copper tube. Attach it to the end farthest from the dial gauge.

⑧ Use a book or a block of wood to raise the end of the expansion base at which steam enters the tube—a few centimeters is sufficient. This will allow any water that condenses in the tube to drain out. Place a container under the other end of the tube to catch the draining water.

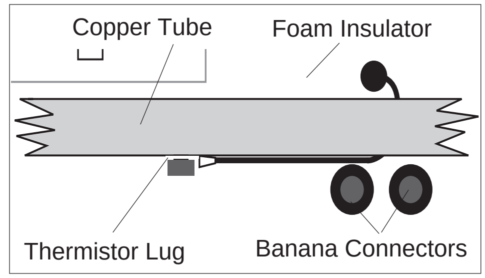


Figure 3 Thermistor Attachment

⑨ Turn the outer casing of the dial gauge to align the zero point on the scale with the long indicator needle. As the tube expands, the indicator needle will move in a counterclockwise direction.

⑩ Turn on the steam generator. As steam begins to flow, watch the dial gauge and the ohmmeter. When the thermistor resistance stabilizes, record the resistance (R_{hot}) in Table 1. Also record the expansion of the tube length (ΔL) as indicated by the displacement of the indicator on the dial gauge. (Each increment on the dial gauge is equivalent to 0.01 mm of tube expansion.) Note that ΔL is the difference betwen the dial gauge readings.

➤ Repeat the experiment for the steel and aluminum tubes.

Data and Calculations

TABLE 1 Data and Calculations

	DATA				CALCULATIONS		
	L (mm)	Rrm (Ω)	ΔL (mm)	Rhot (Ω)	Trm (C°)	Thot (C°)	ΔT (C°)
Copper							
Steel							
Aluminum							

① Use the Conversion Table at the end of this manual, or the one on the top of the expansion base, to convert your thermistor resistance measurements, R_{rm} and R_{hot}, into temperature measurements, T_{rm} and T_{hot}. Record your results in the table.

② Calculate $\Delta T = T_{hot} - T_{rm}$. Record the result in the table.

③ Using the equation $\Delta L = \alpha L \, \Delta T$, calculate a for copper, steel, and aluminum.

α_{Cu} = ____________________

α_{steel} = ____________________

α_{Al} = ____________________

Questions

① Look up the accepted values for the linear expansion coefficient for copper, steel, and aluminum. Compare these values with your experimental values. What is the percentage difference in each case? Is your experimental error consistently high or low?

② On the basis of your answers in question 1, speculate on the possible sources of error in your experiment. How might you improve the accuracy of the experiment?

③ From your result, can you calculate the coefficients of volume expansion for copper, aluminum, and steel? (i.e. $\Delta V = \alpha_{vol} V \, \Delta T$)

THERMISTOR CONVERSION TABLE:

Temperature versus Resistance

Res. (Ω)	Temp. (°C)	Res. (Ω)	Temp. (°C)	Res. (Ω)	Temp. (°C)	Res. (Ω)	Temp. (°C)
351,020	0	95,447	26	30,976	52	11,625	78
332,640	1	91,126	27	29,756	53	11,223	79
315,320	2	87,022	28	28,590	54	10,837	80
298,990	3	83,124	29	27,475	55	10,467	81
283,600	4	79,422	30	26,409	56	10,110	82
269,080	5	75,903	31	25,390	57	9,767.2	83
255,380	6	72,560	32	24,415	58	9,437.7	84
242,460	7	69,380	33	23,483	59	9,120.8	85
230,260	8	66,356	34	22,590	60	8,816.0	86
218,730	9	63,480	35	21,736	61	8,522.7	87
207,850	10	60,743	36	20,919	62	8,240.6	88
197,560	11	58,138	37	20,136	63	7,969.1	89
187,840	12	55,658	38	19,386	64	7,707.7	90
178,650	13	53,297	39	18,668	65	7,456.2	91
169,950	14	51,048	40	17,980	66	7,214.0	92
161,730	15	48,905	41	17,321	67	6,980.6	93
153,950	16	46,863	42	16,689	68	6,755.9	94
146,580	17	44,917	43	16,083	69	6,539.4	95
139,610	18	43,062	44	15,502	70	6,330.8	96
133,000	19	41,292	45	14,945	71	6,129.8	97
126,740	20	39,605	46	14,410	72	5,936.1	98
120,810	21	37,995	47	13,897	73	5,749.3	99
115,190	22	36,458	48	13,405	74	5,569.3	100
109,850	23	34,991	49	12,932	75		
104,800	24	33,591	50	12,479	76		
100,000	25	32,253	51	12,043	77		

Notes

Teacher's Guide

Experiment: Measuring the Coefficient of Linear Expansion for Copper, Steel and Aluminum

Notes on Procedure

⑩ If you allow too much time to elapse before making your length measurement, the guage rod will absorb heat, which will decrease the measurement. The thermistor takes longer to reach equilibrium than the tube, though; so you must allow a fair amount of time for your temperature measurement to stabilize. To get the best results despite these problems, record the maximum change in length recorded by the guage and the minimum resistance recorded by the ohmmeter.

Notes on Questions

① The values for Copper and Aluminum are within 2% of the accepted values, and are both low. The value for steel was within the accepted range. (Steel has a wide range of linear expansion coefficients, due to varying composition.)

② Answers will vary

③ $\alpha_{vol} \approx (\alpha_{linear})^3$

Data and Calculations

TABLE 1 Data and Calculations

	DATA				CALCULATIONS		
	L (mm)	Rrm (Ω)	ΔL (mm)	Rhot (Ω)	Trm (C°)	Thot (C°)	ΔT (C°)
Copper	700	99,100	0.88	5,910	25.1	98.0	72.9
Steel	700	99,300	0.61	5,970	25.1	97.9	72.8
Aluminum	700	102,000	1.19	5,880	24.5	98.5	74.0

$\alpha_{Cu} = 17.25 \times 10^{-6}$ /C°

$\alpha_{steel} = 11.97 \times 10^{-6}$ /C°

$\alpha_{Al} = 23.1 \times 10^{-6}$ /C°

Notes

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

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- If your problem is computer/software related, note:

  Title and Revision Date of software.

  Type of Computer (Make, Model, Speed).

  Type of external Cables/Peripherals.

- 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.

Includes Teacher's Notes and Typical Experiment Results

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

012-05443A
3/94

THERMAL EFFICIENCY APPARATUS

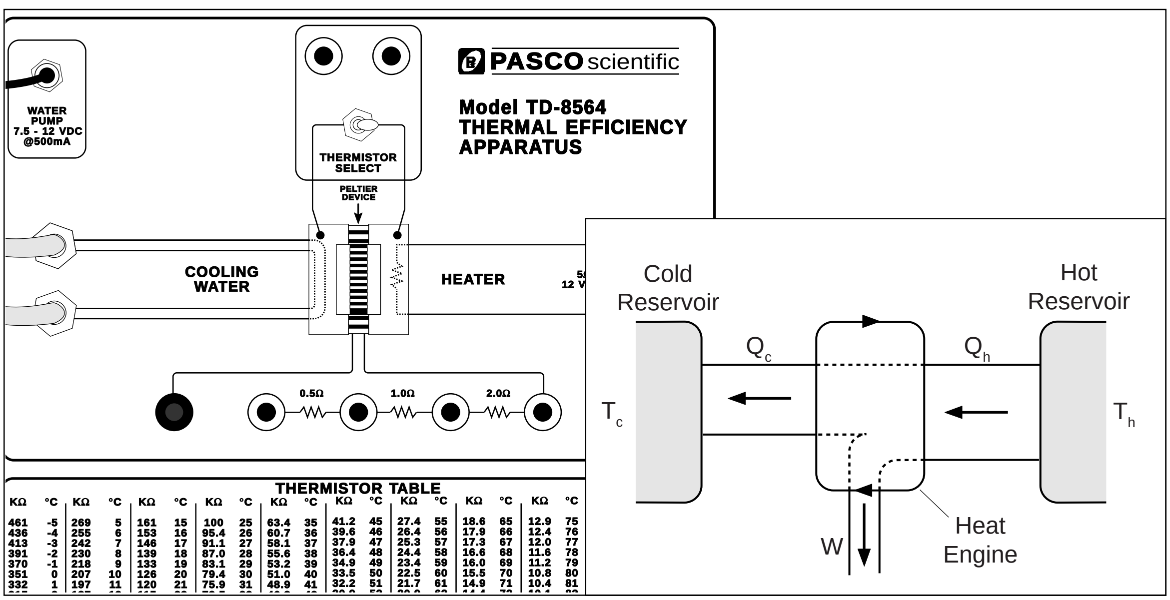

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Table of Contents

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This manual authored by: Ann Hanks

This manual edited by: Ann Hanks and Eric Ayars

Teacher’s Guide written by: Eric Ayars

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③ Make certain that the packing material cannot shift in the box or become compressed, allowing the instrument come in contact with the packing carton.

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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]

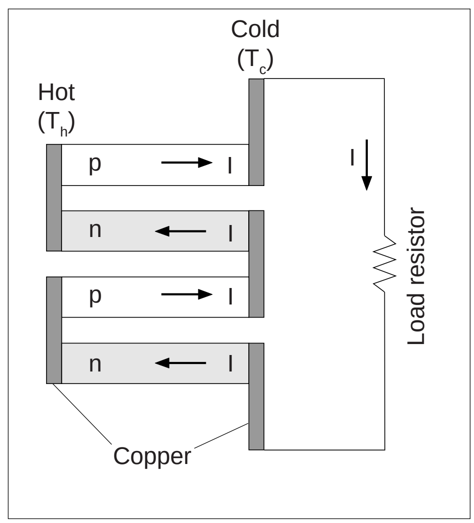

Figure 1: Arrangement of Thermocouples

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.

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.

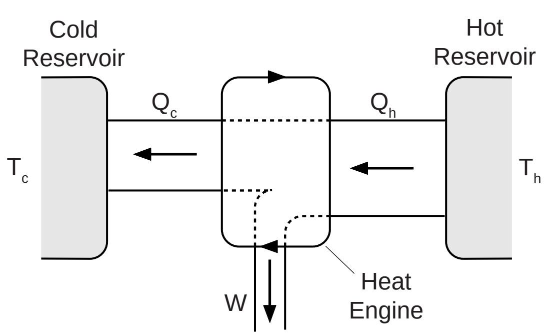

Figure 2: Heat Engine

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

$$P_C + P_W = P_H.$$

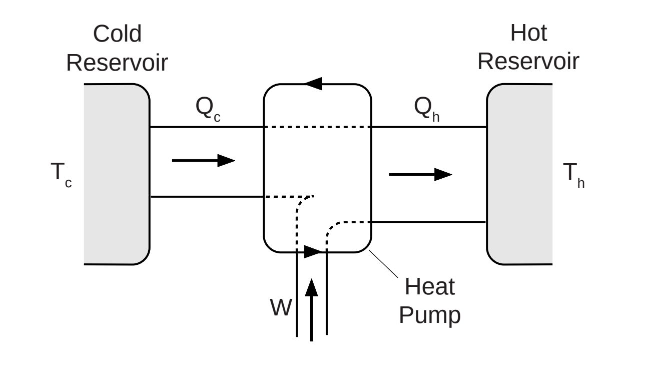

Figure 3: Heat Pump

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.

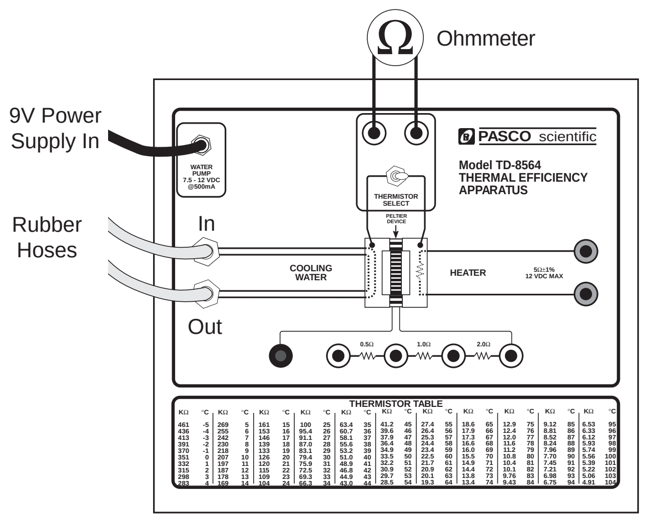

Figure 4: Thermal Efficiency Apparatus

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

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 heat pumped from the cold reservoir. These quantities may be determined indirectly with the Thermal Efficiency Apparatus in the following ways.

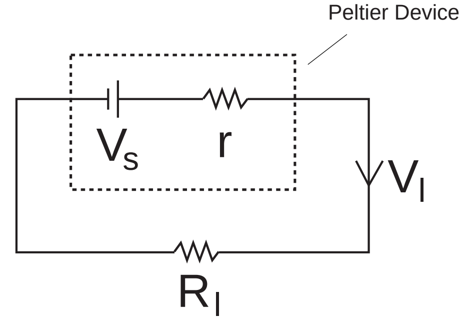

Figure 5: Procedure for Finding Internal Resistance

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 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).

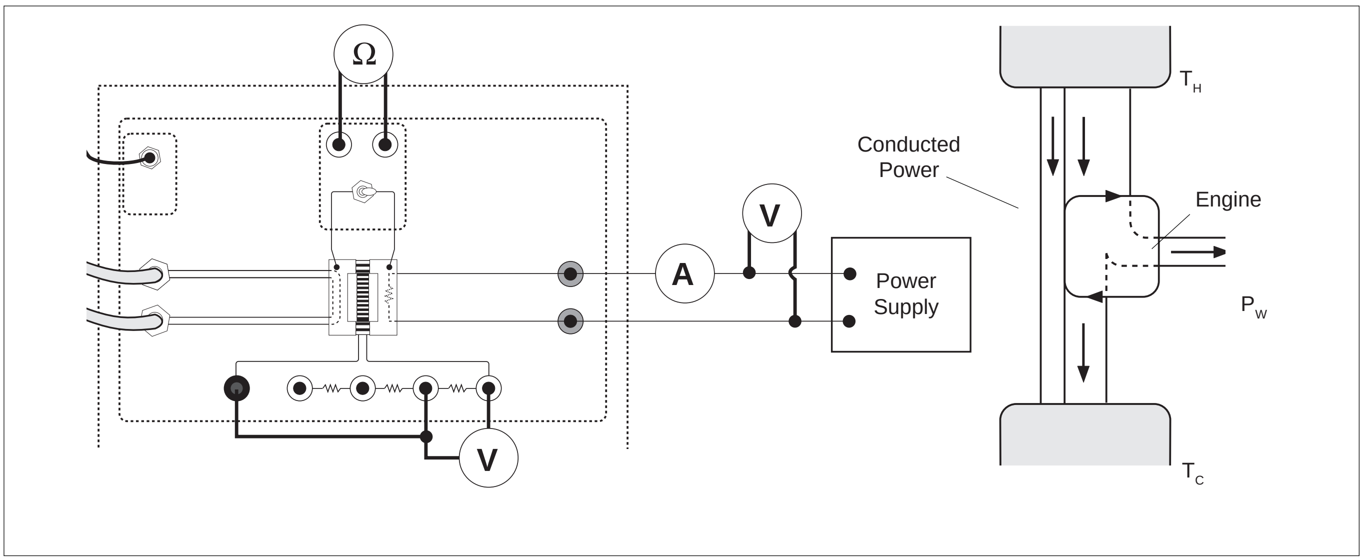

Figure 6: Heat Engine With A Load

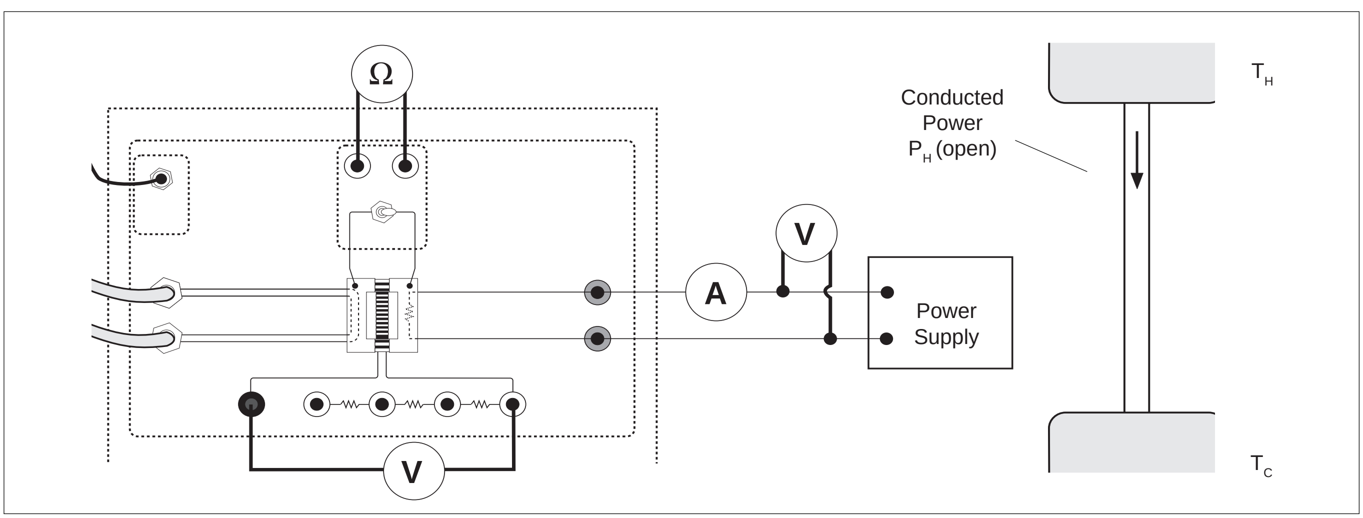

Figure 7: No Load

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 requirements 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.

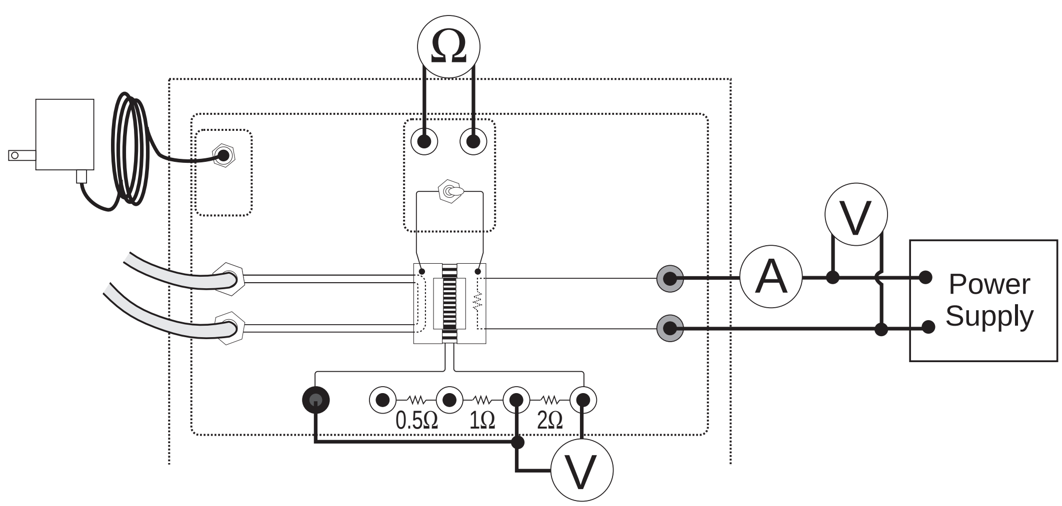

Figure 1.1

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:

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.

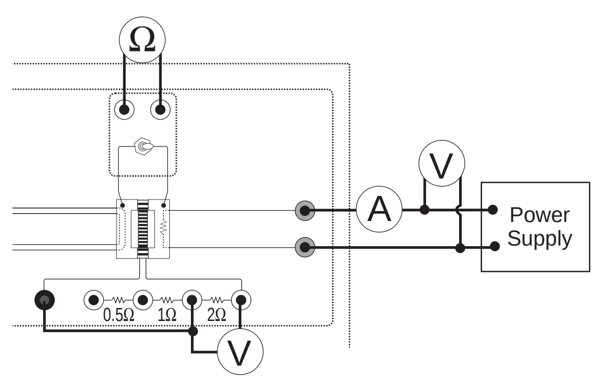


Figure 2.1

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 $P_W = \frac{V_W^2}{R}$ 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?

Experiment 3: Heat Pump Coefficient of Performance

EQUIPMENT NEEDED:

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

➤ **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).

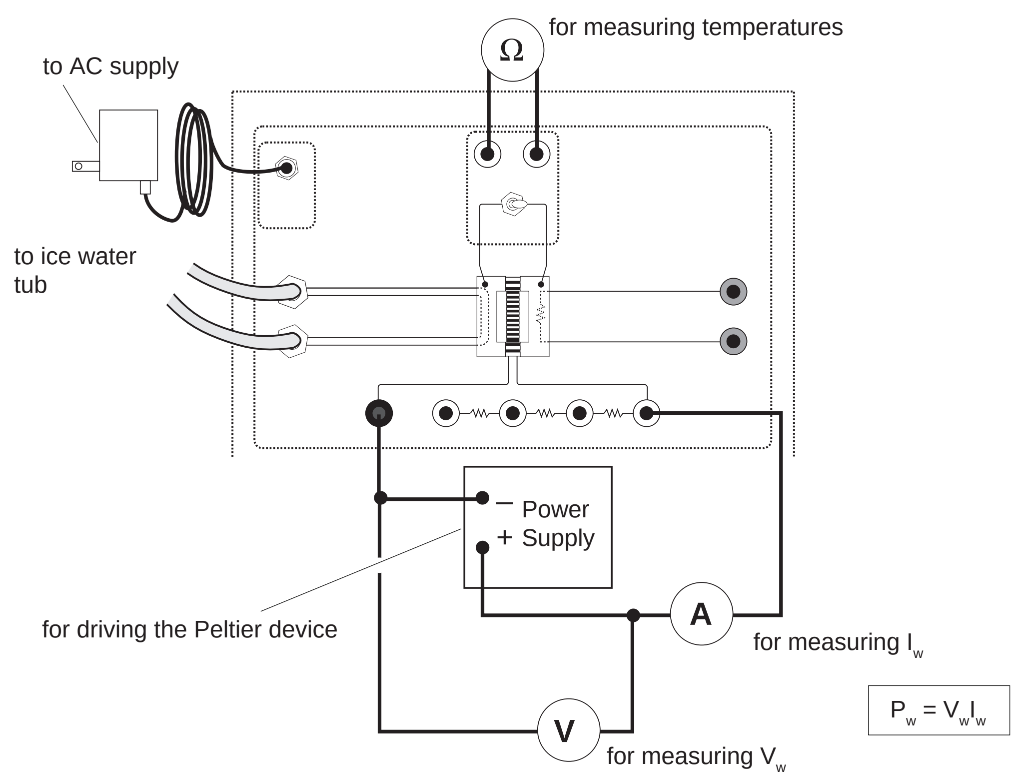


Figure 3.1 Heat Pump Mode

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.

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 $\frac{x}{A} = \frac{8.460 cm^{-1}}{142}$. 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?

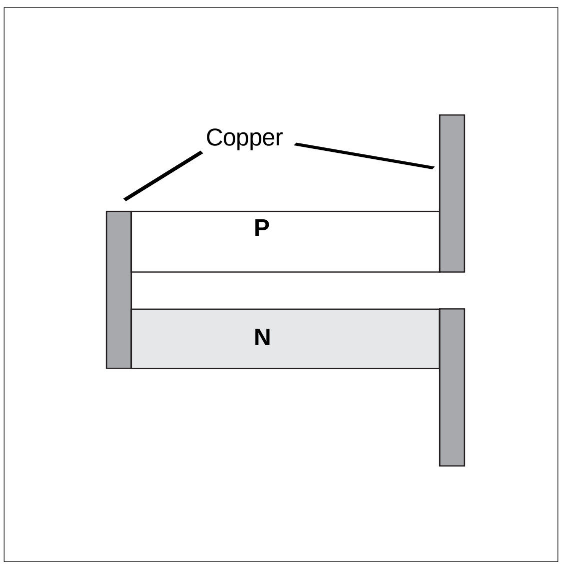


Figure 4.1 One Couple Equals Two Elements

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

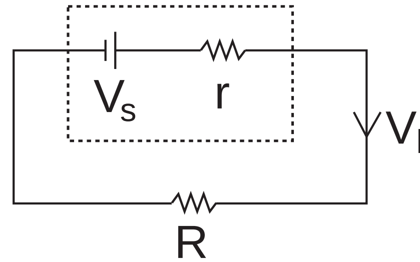


Figure 5.1 Peltier device connected to a load resistor

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* $P = I^2R$. 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.

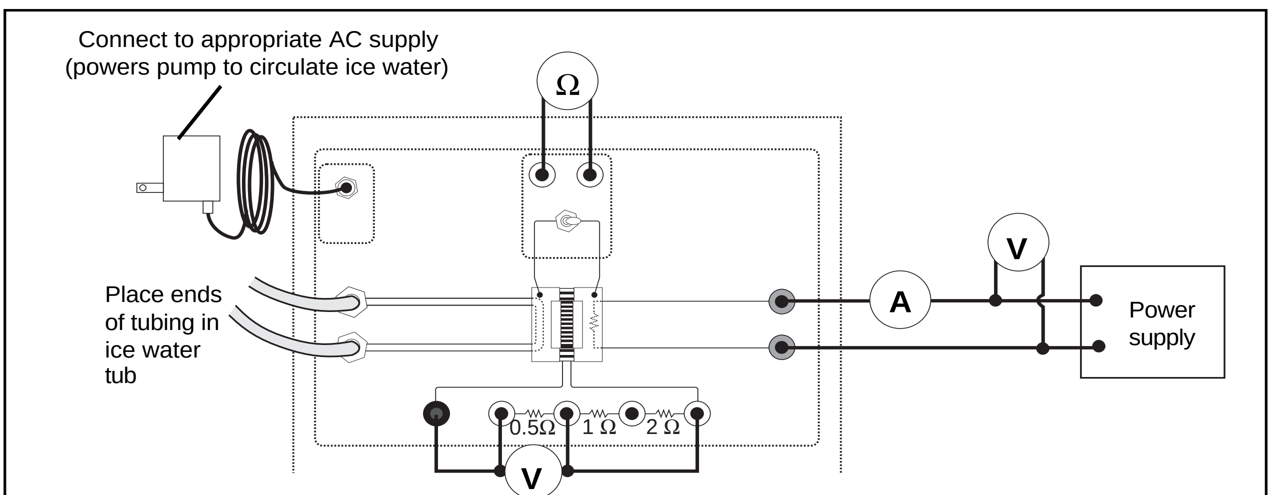


Figure 5.2 Connecting the 0.5Ω load resistor

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										

⑥ Calculate the power input to the hot side, $P_H = I_H V_H$, and the power dissipated by the load resistor, $P_L = \frac{V_W^2}{R}$. Calculate the efficiency, $e = \frac{P_L}{P_H}$. 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.

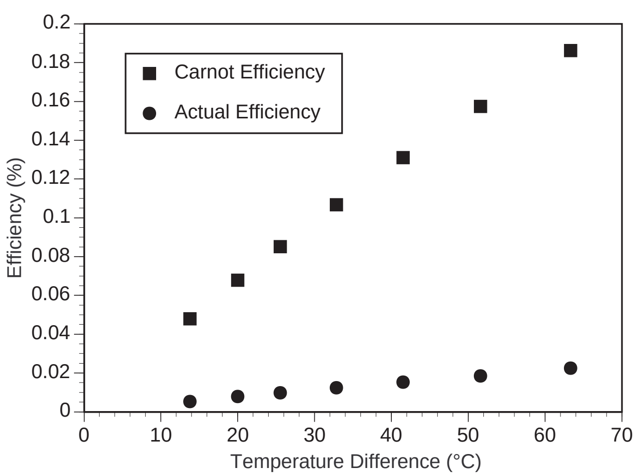
Notes on Calculations

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

③ $efficiency = \frac{P_W}{P_H}$

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

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 = 1.36Ω

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

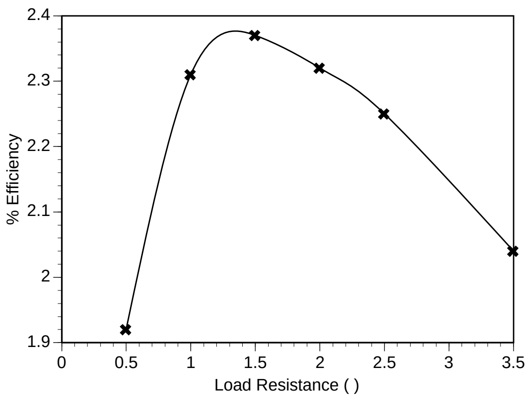
Answer to Questions

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

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  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.

Instruction Manual and Experiment Guide for the PASCO scientific Model SE-8575

012-06055A
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Introduction

The PASCO Visible Stirling Engine is a tool to teach students how engines work and to excite them about physics.

Stirling engines have the most efficient cycle in the world. Does that mean the Model SE-8575 engine is the most efficient engine in the world? No. It means that Stirling engines with regenerators have a cycle that matches the Carnot cycle. The Carnot cycle determines the maximum theoretical efficiency of a heat engine.

$$\frac{temp\ hot - temp\ cold}{temp\ hot} \times 100 = \%\ efficiency$$

The temperatures must be measured in absolute degrees (Kelvin or Rankine) for this formula to work.

No real engine (one that could be built in a machine shop) can achieve the Carnot theoretical efficiency. But real Stirling engines come closer to the Carnot cycle than any other engine! Some research Stirling engines have attained 50 percent of the theoretical Carnot efficiency!*

The efficiency of the SE-8575 is calculated in the experiments section of this manual.

* "Stirling Machines: An Emerging Technology Paradigm" by B. Ross and L.B. Penswick, page 8.

If Stirling engines are so efficient, why don't we have them in automobiles? The best answer to this question is an easy demonstration. Start the SE-8575 on nearly boiling water and wait for it to get up to full speed. Then remove the engine from the heat source and notice that it keeps running for a few minutes.

It is very easy to do an engineering trick to make the engine stop instantly, but there is nothing in the world that can be done to make a Stirling engine start instantly. Today's drivers want to be able to start their cars instantly (if not sooner) and some of them want to burn rubber across the parking lot. Stirling engines can't do that.

Research automobile Stirling engines generally take about 30 seconds before the car can be driven away. Modern drivers do not want to wait.

Computer Compatibility

Photogates may be used to measure the engine rpm.

Additional Equipment Recommended

You may also find it convenient to use:

- A coffee cup.
- A clear water glass
- A Styrofoam dinner plate or a Styrofoam bowl.

History and Theory of Operation

Why STIRLING Engines are important

Every practical engine ever built compresses a gas then expands it and moves it through a cycle.

The Reverend Robert Stirling, a minister of the Church of Scotland, was troubled by some of the dangerous engines that were used at the beginning of the industrial revolution. Steam engines would often explode with tragic effects to anyone unfortunate enough to be standing nearby. So in 1816 he invented and patented "A New Type of Air Engine With Economizer."

Hot air engines, as they were initially called, couldn't explode and often put out more power than the steam engines of their day. The only trouble was that the readily available metal of the early 1800's was cast iron, and cast iron oxidizes rapidly when you leave it in a very hot flame.

In spite of these difficulties, Stirling engines were widely used as water pumping engines at the turn of the century. They required little service, never exploded, were fairly quiet and the water provided a good cooling source for the cold side of the engine. Thousands of these engines were sold .

In the mid 1800's a bright Frenchman named Sadi Carnot figured out the maximum limits on efficiency. His formula is an accepted standard for determining the maximum possible efficiency of an engine. No engine can exceed the Carnot efficiency. [*The first law of Thermodynamics says you can't get out more than you put in. You can only break even.*] In fact no real engine can achieve carnot efficiency. [*The second law of thermodynamics says you can't break even.*]

It takes good engineering and complex machines to achieve a significant fraction of the Carnot efficiency.

On the simplest level, a Stirling engine operates as follows. When a gas in a closed cylinder is heated it expands and pushes up on a piston. When the same gas is cooled, it contracts and pulls down on the piston.

The next level of understanding is to realize how regeneration works. Robert Stirling realized that the engines he built would be much more efficient if some of the heat that was used to heat the air for one cycle was saved and used again in the next cycle. Robert Stirling called the device that saved heat in his engines an economizer. Today, these are usually called regenerators and probably are Robert Stirling's most important invention.

In the model SE-8575, regeneration works as follows. When the yellow foam inside the engine is near the top of the cylinder (and the engine is running on a cup of hot water) most of the air is on the bottom side (the hot side) where it is heated. When the air gets hot it expands and pushes up on the piston. When the foam moves to the bottom of the engine it moves most of the air (it displaces the air) to the top of the engine. The top of the engine is cool, allowing the air inside the engine to cool off (reject heat to the environment) and the piston receives a downward push. This engine would run even if the "displacer" (the yellow foam) was made of solid Styrofoam. It runs much better because it is made of a special air filter foam.

When the air is flowing from the hot side of the engine to the cold side it flows through and around the yellow foam (the displacer). Since the air is hotter than the foam, some of the heat from the air will flow into the foam. The air cools off and the foam heats up. This is called regeneration and is very important in many industrial processes.

When the air makes the return trip to the hot side of the engine it once again flows through and around the foam. This time the air heats up and the foam cools off. The heat that would have been wasted in an engine without regeneration is saved and a much more efficient engine is the result.

A Stirling engine with a regenerator has a cycle that matches the Carnot cycle. It has the same theoretical maximums and the same theoretical efficiencies.

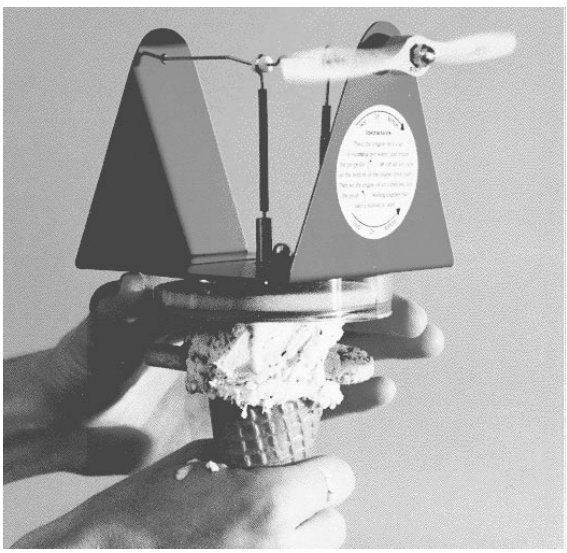
Operation

Operating On Ice

Running the engine on ice is a quick and interesting way to start the engine. Pick up the engine and rub an ice cube vigorously around the bottom (the blue part) of the engine. Then place the engine on a pile of ice cubes (ice chips work best) and flip the prop in the direction indicated on the label.

Ice cream or frozen yogurt also work well as ice substitutes. Ice cream provides a good heat sink, (when compared to ice cubes) because it makes such good thermal contact with the bottom of the engine. Ice cubes tend to provide only limited points of contact on the top edges of the cubes.

If you run the engine on ice cream or frozen yogurt, take extra care to clean it after you are done. Carefully run the bottom of the engine under some warm water to clean it.



Stirling Engine on an Ice Cream Cone

Stirling Engine on a Bowl Filled with Ice

Power From Your Fingertips!

When running the engine on ice in a room that is 72° to 75°F the temperature of the top of the engine will drop to about 68°F. When this occurs an interesting demonstration can be performed.

Palm over LCD Thermometer

Place a warm hand (as many fingers as fit) over the LCD thermometer and the surrounding area. Within 20 seconds you will observe a significant increase in the operating speed of the engine. Engines run on heat, and in this case body heat can be used to increase the output power of the SE-8575.

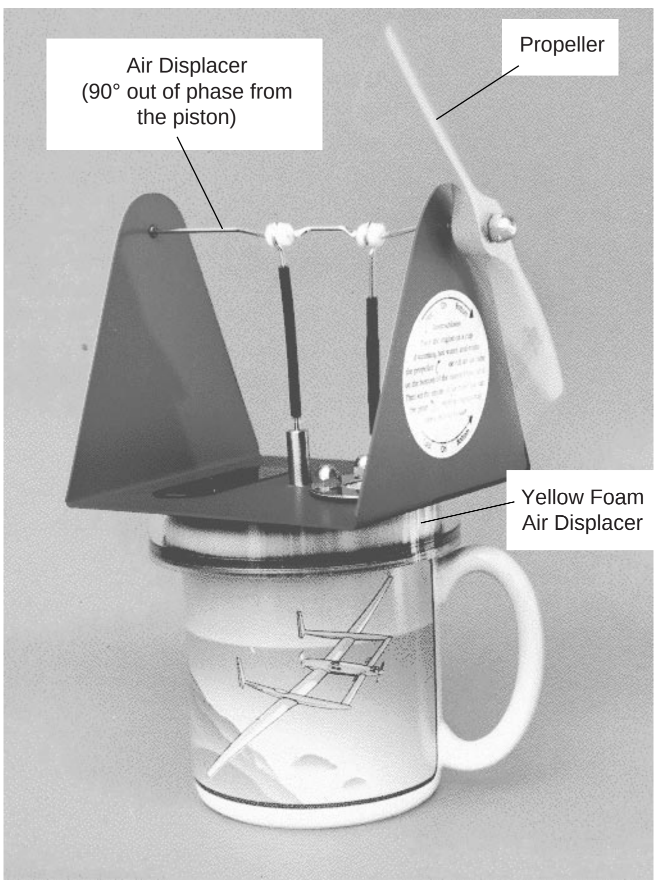
Operating with Hot Water

Water is a very good thermal transfer medium. The visible Stirling engine will run well on a cup of hot water. Does the water have to be in contact with the bottom of the engine? No. Steam rising off the water and then condensing on the bottom of the engine moves the heat to the hot side of the engine. Here’s how to start the engine in a hurry.

Fill a coffee mug about 1/3 full of hot tap water then microwave it until the water is boiling vigorously. Place the engine on the top of the coffee mug, wait 20 seconds, and flip the prop in the direction indicated on the label.

This also works well with a clear water glass. Using a clear glass has the added benefit of letting students see the steam rise and the water condense on the bottom of the engine. Make sure to use a glass that is safe for the temperature of water you will be putting in it.

The engine should start immediately and run at a high rate of speed.



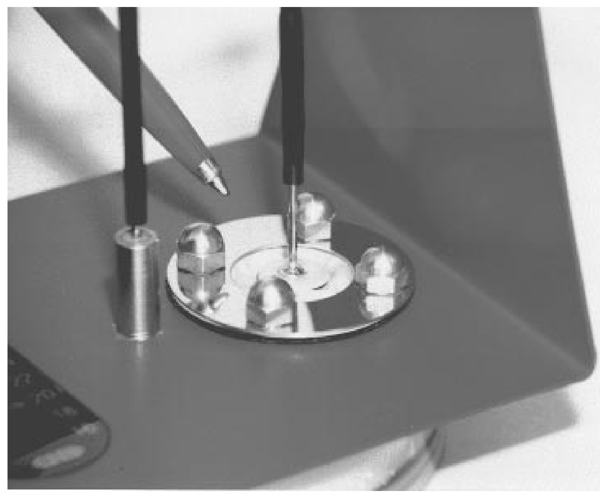
Stirling Engine on a Cup of Hot Water

Operating On Maximum Power

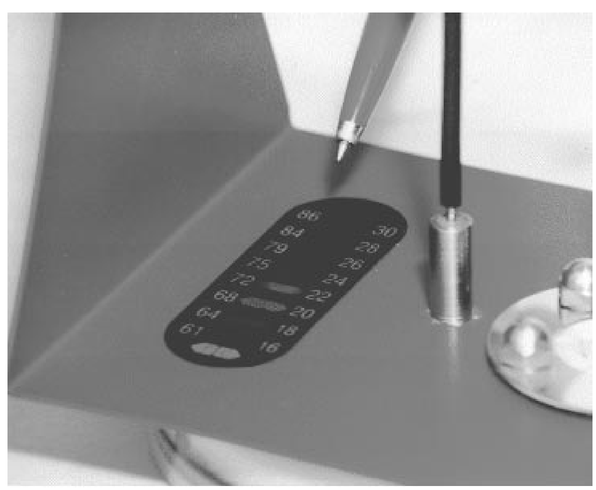
The way to get the most power out of the model SE-8575 is to increase the temperature difference between the top and bottom plates. The maximum operating temperature is 212°F and the minimum operating temperature is -40°F.

> ➤ **NOTE:** Do not apply direct flame to the unit!

The best way to achieve maximum power is to put boiling water on the bottom (do not use a Bunsen burner) and ice cubes on the top. Be careful not to get water down inside the engine or on top of the piston. Water on the top of the LCD thermometer is okay.



Piston



Liquid Crystal Thermometer

Experiment

Equipment needed

– Model SE-8575 Visible Stirling Engine
– (2) Styrofoam cups
– Thermometer
– Hot water (boiling is preferred)
– Paper towels to wipe up water
– **Optional:** Basic Calorimetry Set (TD-8557)

Purpose

The purpose of this experiment is to get a physical feel for the loss mechanisms in any engine.

Theory

Engines are made to do something. They take in energy from a source, they reject waste heat to a reservoir, and they do useful work. Every engine has losses. The purpose of this experiment is to identify the loss mechanisms and determine what could be done to reduce those losses.

Setup

① Nest one Styrofoam cup inside the other to make a two cup calorimeter. Weigh the cups.

➤ **NOTE:** The TD-8557 styrofoam Calorimeter works well to replace the cups.

② Fill the cups half full with very hot water. Put a lid over the assembly and weigh it again.

③ Measure the temperature of the water. Convert the temperature to Kelvin or Rankine.

④ Measure the temperature of the air in the room. Convert this temperature to Kelvin or Rankine.

⑤ Place the engine on top of the hot water and start it. After it gets up to speed stop the engine and turn it slowly by hand. Watch what happens to the piston when the air shifts from the hot side to the cold side.

Calculation

Calculate the theoretical efficiency of the engine operating between these two temperatures using the following formula. $\frac{\textit{temp hot} - \textit{temp cold}}{\textit{temp hot}} \times 100 = \%\ \textit{efficiency}$

What is the theoretical efficiency of a Carnot engine operating between these temperatures?

Questions

① Which would do more for efficiency of the engine, raising the temperature hot by 50°, or lowering the temperature cold by 50°?

② The hot water in the cups is a form of stored energy available to do work. Would it be possible to run a car on very hot water?

③ How much energy is stored in the hot water?

④ When you buy gasoline to run your car, what is it that you are really buying?

⑤ If hot water could be used to run a car, why do we buy gasoline instead of hot water? Hot water would be a zero pollution engine.

⑦ How much stored energy is there in a gallon of gasoline?

⑧ Some of the air makes the piston bulge up around the edges when the air moves to the hot side. Does this air do any useful work?

⑨ Would the engine put out more power if this flexible piston was replaced with a very tight fitting light weight graphite piston?

DEMONSTRATION: An Engine That Runs On Ice

Setup

Set the SE-8575 up to run on ice chips, ice cream, or frozen yogurt. Detailed instructions are in the *Operation* section of this manual. Start it running and ask the following questions.

Questions

① What is the source of energy to run this engine?

② Since there is no such thing as a free lunch, who paid for the energy to make this engine run and what company did they pay it to?

③ After the SE-8575 has been running for some time, do the Power From Your Fingertips demo as explained in the operations section. Who paid for this energy to make the engine run faster and who did they pay it to?

④ Would it be possible to have a full power engine that had zero pollution and used the heat from the room as a hot source.

⑤ Calculate the Carnot efficiency of an engine running with liquid nitrogen as a cold sink and a 72°F (23°C) ambient hot source.

⑥ Liquid nitrogen is readily available. What determines whether it would be a good idea to build an engine like this?

⑦ Since the air is roughly 80% nitrogen, would an engine like this cause any pollution?

⑧ When an engine is running on a heat source the Carnot formula determines how much of the heat can become useful work. In this engine as in most engines the majority of the heat that could become useful work doesn't become useful work. What happens to this heat? Identify the specific loss mechanisms.

⑨ Internal combustion four stroke engines have one power pulse every other trip of the piston. Stirling engines have two power pulses per trip of the piston (one going up, and one going down). All other things being equal (which they never are) how much smoother should a Stirling engine be than an Otto cycle engine?

⑩ Are you likely to see a Stirling engine offered for sale in a car? Why or why not?

⑪ Would Stirling engines be good candidates for powering submarines? Stirling engines are quiet and submarines like quiet.

⑫ Would Stirling engines be a good source of auxiliary power generation for yachts? Good cooling water is available, and people on yachts like it quiet too.

Maintenance

The PASCO Visible Stirling Engine SE-8575 is a delicate apparatus. Treat it like a fine piece of laboratory equipment and it will last a very long time.

Maximum Operating Temperature

The engine is made for intermittent use with a maximum operating temperature of 100°C (212°F).

For Intermittent Use Only

> ➤ **IMPORTANT:** The PASCO SE-8575 Stirling Engine is not made for continuous use.

It may be tempting to find a source of waste heat and let the engine run continuously. Do NOT do this!

- The piston has a limited life time. While it should last for years with occasional use, it will only last for about 6 weeks running 24 hours a day.
- To extend the life of the engine, do not exceed its maximum operating temperature. Do not run the engine on heat sources other than hot water.

Non-Acceptable Heat Sources

> ➤ **IMPORTANT:** Do NOT heat the engine using any type of flame!

The SE-8575 will indeed run very fast on the heat from a candle flame, but you will exceed the maximum temperatures of the materials in the engine and ruin it.

If you use a burner to heat the water, put the engine on top of the water ***after the burner is shut off***.

Running the engine on top of a lamp or a similar heat source is likely to raise the temperature of the acrylic above its yield temperature and ruin the engine.

DO NOT USE LIQUID NITROGEN!

> ➤ **IMPORTANT:** Liquid nitrogen is far too cold for this engine and very likely will break it. Dry ice would probably be okay but has not been tested.

A good cooling source is "freeze spray". This is sold in an aerosol can at Radio Shack and other electronics supply stores. It's a lot of fun to make the engine appear to run on "nothing".

DO NOT OIL THE BEARINGS!

During the development of this engine, many different lubricants were tried in an effort to improve performance. None of them improved performance at all, and most of them made the engine run less well or not at all.

All the bearing surfaces contain Teflon. It is unlikely that any lubricant you might use would improve performance.

To Remove Oil:

Oiling the engine will probably degrade performance or cause the engine to quit. Use a TINY drop of WD-40 (a very light dispersant petroleum based product) to clean off the oil. Be careful to keep the oil from running over the red anodized surface as it will stain the anodizing.

KEEP THE ENGINE DRY!

After running the engine, make sure it is completely dry before putting it away. The metal ring that holds the blue plate on the bottom of the engine in place is made of a stainless steel alloy that contains some iron. It can rust if not put away dry. Towel dry the engine carefully before you put it away. Blow drying it is also a good idea.

Most Common Reason for Engine Failure

- The most common reason for the engine failing to run is inadequate thermal transfer. If the engine won't run try putting about an inch of water in a coffee mug and microwaving it until it is boiling vigorously!
- Remove the mug from the oven and place the engine on top of the boiling water, wait 15 seconds, and turn the prop the direction indicated on the instruction label for "hot on the bottom." The engine should start quickly and run rapidly.

> ➤ **NOTE:** Boiling water is dangerous. **Handle with care!**

If the engine still does not work or runs very slowly, refer to the *Troubleshooting* section.

Troubleshooting

There are three general reasons why the SE-8575 Stirling Engine might not run.

① Not enough temperature difference between the hot and cold side of the engine. This Stirling engine needs about a 40°F (23°C) difference in temperature to run. If the room is at 72°F (23°C) and the ice temperature is 32°F or cooler the engine should run at 100 rpm or faster.

If ice is used as the "cold" source, it is possible to have the bottom of the engine rest on only a few high points on top of the ice cubes. The best solution is to pick up the engine and rub an ice cube vigorously around its bottom. Then place the engine on a pile of ice cubes (ice chips are best). Push down on the LCD thermometer with your warm hand to help establish contact with the ice. This will simultaneously warm up the top of the engine and help establish better ice contact with the cold side of the engine.

② The engine may have developed a leak in the system. The Stirling cycle engine is a sealed system. It can only tolerate one tiny leak. If there are any obvious holes in the grey diaphragm (which is the piston) the engine will not run. Contact the Magic Motor Company 1-800-503-2906 for replacement parts or service.

③ There might be internal friction in the system. Every engine ever built has internal friction losses. However this engine when operating between such small temperature differences does not have room for much wasted power.

There are two things that have been observed to sometimes cause problems. There must be about slight looseness in the collars where the crankshaft goes through the aluminum upright near the propeller. In other words, If the engine is held in one hand and the prop is moved back and forth along the axis of the crankshaft it should be possible to hear the collars make a clicking sound, and see the bushings which hold the crankshaft in place move back and forth about the distance of 2 to 4 sheets of notebook paper.

This looseness is essential to proper operation of the engine. If one of the bushings has moved slightly and becomes a tight fit on the aluminum upright, the engine will run poorly or not at all. The solution to this problem is to use a knife blade to move one of the collars slightly away from the aluminum uprights.

Also, the piston must move freely without binding at the top or bottom of its travel. This should never need adjustment, but it can be adjusted if someone accidentally moves it out of its range. The piston (grey rubber diaphragm) should, at the bottom of its travel, be almost (but not quite) tight. At the top of its travel it should also be almost but not quite tight. If the piston is tight at either end of its travel it can be adjusted slightly by hand.

The black tubing that covers the rod connecting the piston and the crankshaft is a slip adjustment mechanism. If the piston is too tight at the bottom of its travel, shorten the connecting rod by pushing in (ever so slightly) on the piston end and the crankshaft end. Hold one hand at the crankshaft end of the connecting rod and the other at the piston end and push these ends together. If the piston is too tight at the top end of its travel then lengthen the connecting rod (very slightly) by pulling down the piston and pulling up on the crankshaft end of the connecting rod. In other words, reverse the previous process.

Adjusting the Regenerator

The regenerator is the yellow piece of foam inside the engine that moves the air from the hot side to the cold side. In normal use this should never need adjusting. However if someone grabs it and pulls on it, the regenerator can be moved out of adjustment. Ideally the displacer should just barely touch (or not quite touch) the top side of the engine when it is at the top end of its travel. It also should not quite touch (or barely touch) the blue plate when it is at the bottom end of its travel.

Turn the propeller slowly through by hand and watch the regenerator. If it is adjusted as indicated in the above paragraph then don't do anything with it. If it hits the bottom enough so that the flexible rubber linkage tubing bows out when the regenerator is at the bottom of its travel then push the black tubing slightly down onto the regenerator shaft. The regenerator shaft is the shiny piece of wire that goes down into the engine and attaches to the yellow foam.

If the LCD Thermometer Turns Black

LCD thermometers of this type have specific operating ranges. When the temperature is within their range they display colors. When the temperature is out of their range they turn black.

If the LCD thermometer is black it means that the temperature of the thermometer is out of the range of the thermometer. Either the temperature is above 86°F (30°C) or below 61°F (16°C). The thermometer is not damaged by this at all and will again indicate colors when the temperature returns to its operating range.

The Thermometer Shows 86° But the Engine Still Does Not Run

Operation of Stirling engines is dependent on a temperature difference. If the engine was running on hot water and the thermometer now shows a temperature of 86° it is likely that there is no longer a temperature difference of 40°F or more. This is a normal condition. Reheat the water (boiling is acceptable) and start the engine again.

Credits

Acknowledgments

This type of Stirling engine is relatively new. The first Stirling engine ever built to run on small temperature differences was built in 1983 by Ivo Colin of the University of Zagreb in what was then Yugoslavia.

Jim Senft, a mathematics professor at the University of Wisconsin River Falls, built engines that substantially improved on those built by Ivo Colin. This engine is a follow up design to those built by Jim Senft. The concept for this engine was created by Darryl Phillips of the Airsport Corporation, Sallisaw Oklahoma. The detail design and engineering was done by Brent H. Van Arsdell of the Magic Motor Company.

More STIRLING Information

Additional information on Stirling engines is available from:

Stirling Machine World [Brad Ross, Editor]
1823 Hummingbird Court
West Richland, WA 99353 9542
(509)-967-5032

Stirling Machine World publishes a quarterly newsletter. Additional books and video tapes on Stirling engines are also available.

How to Get A FREE Book

If you have any experiments that you feel should be included in the next edition of this manual, we would love to hear from you. If we use your experiment in the next edition of the manual we will give you a Free copy of "Introduction to Stirling Engines" by Jim Senft. Write up your experiment and mail it to

Magic Motor Company
1945 N. Rock Rd. Suite
1012 Wichita, KS 67206

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.

email: techsupp@PASCO.com

Tech support fax: (916) 786-3292

Contacting Technical Support

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:

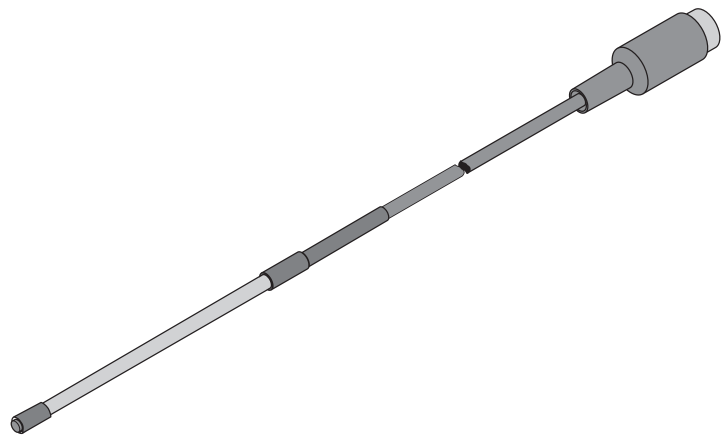
  Part number and Revision (listed by month and year on the front cover).

  Have the manual at hand to discuss your questions.

012-05642C
9/98
$1.00

Instruction Sheet for the PASCO Model CI-6505A

TEMPERATURE SENSOR



Introduction

The PASCO Model CI-6505A Temperature Sensor is designed to be used with a PASCO Computer Interface (such as the Series 6500 or CI-6550 Mac65).

The Temperature Sensor uses a precision temperature sensitive integrated circuit whose output voltage is linearly proportional to temperature (°Celsius). The Temperature Sensor is covered with Teflon* FEP (fluorinated ethylene propylene) heat-shrink tubing. This type of Teflon is very resistant to chemical solutions, including oxidizing agents and organic solvents. The Temperature Sensor comes with a removable Teflon FEP sensor cover that is highly resistant to chemicals. (*Teflon is DuPont's registered trademark for its fluoropolymer resins.)

Additional Equipment Required:

- Signal Interface such as the CI-6500 (IBM PC), AI-6501 (Apple II), or CI-6550 (Macintosh)

Setup Procedure

① Insert the 8-pin DIN plug into Analog Channel A, B, or C of the interface box.

② Touch the sensor end of the sensor to the object to be measured or place the sensor end into the solution to be measured.

Things to Note

- The Temperature Sensor is designed to be used in water and mild chemical solutions when measuring the temperature of a liquid. When immersing the sensor into a liquid, the liquid level should not be above the rigid body portion of the sensor. If the heat shrink tubing at the sensor end is damaged, liquid may get into the sensor and cause faulty readings. To repair a leaky sensor, contact PASCO scientific. DO NOT place the Temperature Sensor in a direct flame or on a hot plate. To prevent damage to the internal components of the Temperature Sensor, do not exceed the maximum operating range of -5 °C – +105 °C.
- Chemical Solutions: Be careful when using the Temperature Sensor in laboratory chemicals, particularly over long periods of time. The heat shrink tubing does not cover the end of the sensor.

> **WARNING:** Always use glycerine or equivalent lubricant when inserting or removing the sensor from rubber stoppers

This instruction sheet written by: Dave Griffith

PASCO® scientific

10101 Foothills Blvd. • Roseville, CA 95747-7100
Phone (916) 786-3800 • FAX (916) 786-8905 • www.pasco.com

The sensor has been tested for several minutes in the following chemicals:

household bleach	water
sulfuric acid (battery acid)	ethanol
isopropyl alcohol	vinegar
ethylene glycol (antifreeze)	glacial acetic acid
naphthalene (moth balls)	acetone
sodium hydroxide (lye)	

- Chemical Resistant Sensor cover: A protective Teflon FEP sensor cover is included with the Temperature Sensor. It can be used to completely cover the Temperature Sensor when it is used in strong chemicals. The Chemical Resistance Classification for Teflon FEP is "E" (excellent) for a wide range of chemicals (from Acetaldehyde to Zinc Stearate), meaning that there is no damage during 30 days of constant exposure to the reagent at 20 ½C. (See the Chemical Resistance Chart.)

The Teflon sensor cover is about twelve inches long, and one end is sealed. Carefully open the unsealed end and insert the sensor. (You may want to cut the cover to a shorter length.)

> ➤ **NOTE:** The Teflon sensor cover will cause the Temperature Sensor to have a slower response to changes in temperature. The figure below shows temperature versus time for two Temperature Sensors, one with the Teflon cover, plunged into ice water and then into boiling water.

To improve response to temperature changes, make sure the end of the sensor is in close contact with the inside of the cover. One way to do this is to press the end of the sensor on a hard surface such as a table top to flatten the cover against the end of the sensor. The Teflon cover is reusable. Be sure to rinse off all chemicals before storing the cover or sensor.

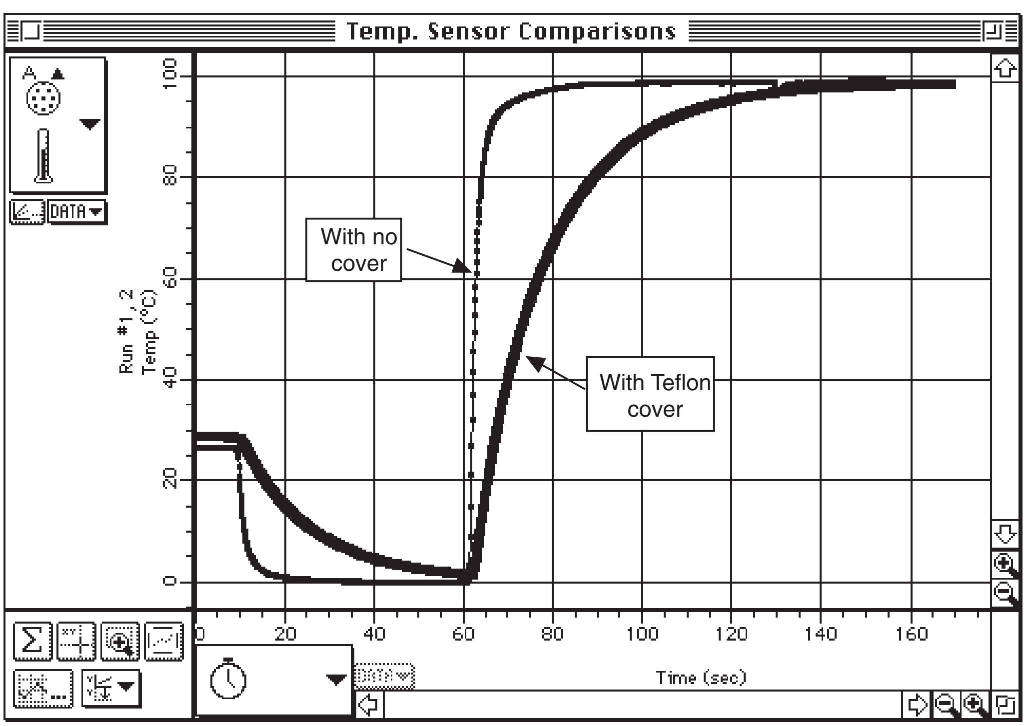
> ➤ **NOTE:** Teflon sensor covers are available from PASCO scientific in a package of ten. Order part number CI-6549.

Sensor Specifications;

Range: -5 °C to +105 °C
Accuracy: ±1 °C
Output: 10 mV/°C

Teflon FEP Specifications

Maximum Temperature: 205 °C
Brittleness Temperature: -270 °C
Specific Gravity: 2.15
Water Absorption: <0.01%



PASCO scientific

Chemical Resistance Chart

This Chemical Resistance Chart is intended to be used as a general guide only. Since the ratings list is for ideal conditions, all factors affecting chemical resistance must be considered. Teflon FEP is rated “EE” (excellent at 20½C and at 50½C) for all the following chemicals except Fluorine and Perchloric Acid. It is rated “EG” for Fluorine and “GF” for Perchloric Acid.

E – No damage during 30 days of constant exposure.

G – Little or no damage after 30 days of constant exposure to the reagent

F – Some effect after 7 days of constant exposure to the reagent. The effect may be crazing, cracking, loss of strength, or discoloration.

Acetaldehyde	Acetamide, Sat.	Acetic Acid, 5%	Acetic Acid, 50%
Acetone	Acetonitrile	Acrylonitrile	Adipic Acid
Alanine	Allyl Alcohol	Aluminum Hyroxide	Aluminum Salts
Amino Acids	Ammonia	Ammonium Acetate, Sat.	Ammonium Glycolate
Ammonium Hydroxide	Ammonium Oxalate	Ammonium Salts	n-Amyl Acetate
Amyl Chloride	Aniline	Benzaldehyde	Benzene
Benzoic Acid, Sat.	Benzyl Acetate	Benzyl Alcohol	Bromine
Bromobenzene	Bromoform	Butadiene	n-Butyl Acetate
n-Butyl Alcohol	sec-Butyl Alcohol	tert-Butyl Alcohol	Butyric Acid
Calcium Hydoxide, Conc.	Calcium Hypochlorite, Sat.	Carbazole	Carbon Disulfide
Carbon Tetrachloride	Cedarwood Oil	Cellosolve Acetate	Chlorine, 10%
Chloroacetic Acid	p-Chloroacetophenone	Chloroform	Chromic Acid, 50%
Cinnamon Oil Citric Acid	Cresol	Cyclohexane	DeCalin
o-Dichlorobenzene	p-Dichlorobenzene	Diethyl Benzene	Diethyl Ether
Diethyl Ketone	Diethyl Malonate	Diethylene Glycol	Dimethyl Formamide
Dimethylsulfoxide	1,4-Dioxane	Dipropylene Glycol	Ether
Ethyl Acetate	Ethyl Alcohol, 40%	Ethyl Benzene	Ethyl Benzoate
Ethyl Butyrate	Ethyl Chloride, liquid	Ethyl Cyanoacetate	Ethyl Lactate
Ethylene Chloride	Ethylene Glycol	Ethylene Oxide	Fluorides
Fluorine (EG)	Formaldehyde, 40%	Formic Acid, 80-100%	Freon TF
Fuel Oil	Gasoline	Glacial Acetic Acid	Glycerine
n-Heptane	Hexane	Hydrochloric Acid, 35%	Hydrofluoric Acid,
48%	Hydrogen Peroxide, 90%	Isobutyl Alcohol	Isopropyl Acetate
Isopropyl Alcohol	Isopropyl Benzene	Kerosene	Lactic Acid, 85%
Methoxyethyl Oleate	Methyl Alcohol	Methyl Ethyl Ketone	Methyl Isobutyl Ke-
tone	Methyl Propyl Ketone	Methylene Chloride	Mineral Oil
Nitric Acid, 70%	Nitrobenzene	n-Octane	Orange Oil
Ozone	Perchloric Acid (GF)	Perchloroethylene	Phenol, Crystals
Phosphoric Acid, 85%	Pine Oil	Potassium Hydroxide, Conc	Propane Gas
Propylene Glycol	Propylene Oxide	Resorcinol, Sat.	Salicylaidehyde
Salicylic Acid	Salt Solutions, Metallic	Silver Acetate	Silver Nitrate
Sodium Acetate, Sat.	Sodium Hydoxide, Sat.	Sodium Hypochlorite, 15%	Stearic Acid, Crystals
Sulfuric Acid, 98%	Sulfur Dioxide	Sulfur Salts	Tartaric Acid
Tetrahydrofuran	Thionyl Chloride	Toluene	Tributyl Citrate
Trichloroethane	Trichloroethylene	Triethylene Glycol	Tripropylene Glycol
Turpentine	Undecyl Alcohol	Urea	Vinylidene Chloride
Xylene	Zinc Stearate		

Limited Warranty

PASCO scientific warrants this product to be free from defects in materials and workmanship for a period of one year from the date of shipment to the customer. PASCO will repair or replace, at its option, any part of the product which is deemed to be defective in material or workmanship. This warranty does not cover damage to the product caused by abuse or improper use. Determination of whether a product failure is the result of a manufacturing defect or improper use by the customer shall be made solely by PASCO scientific. Responsibility for the return of equipment for warranty repair belongs to the customer. Equipment must be properly packed to prevent damage and shipped postage or freight prepaid. (Damage caused by improper packing of the equipment for return shipment will not be covered by the warranty.) Shipping costs for returning the equipment, after repair, will be paid by PASCO scientific.

Equipment Return

Should this product have to be returned to PASCO scientific for any reason, notify PASCO scientific by letter or phone BEFORE returning the product. Upon notification, the return authorization and shipping instructions will be promptly issued.

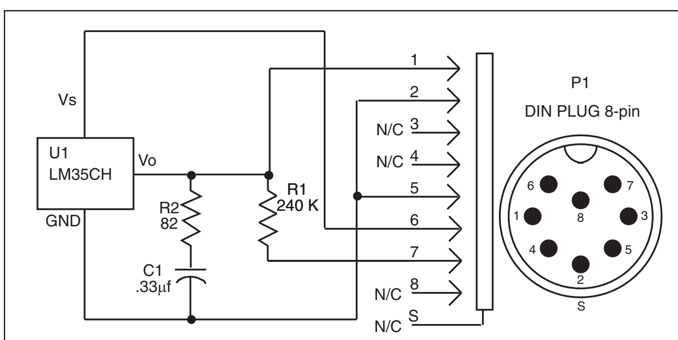
> ➤ **NOTE:** NO EQUIPMENT WILL BE ACCEPTED FOR RETURN WITHOUT AN AUTHORIZATION.

When returning equipment for repair, the units must be packed properly. Carriers will not accept responsibility for damage caused by improper packing. To be certain the unit will not be damaged in shipment, observe the following rules:

① The carton must be strong enough for the item shipped.

② Make certain there are at least two inches of packing material between any point on the apparatus and the inside walls of the carton.

③ Make certain that the packing material can not shift in the box, or become compressed, thus letting the instrument come in contact with the edge of the box.



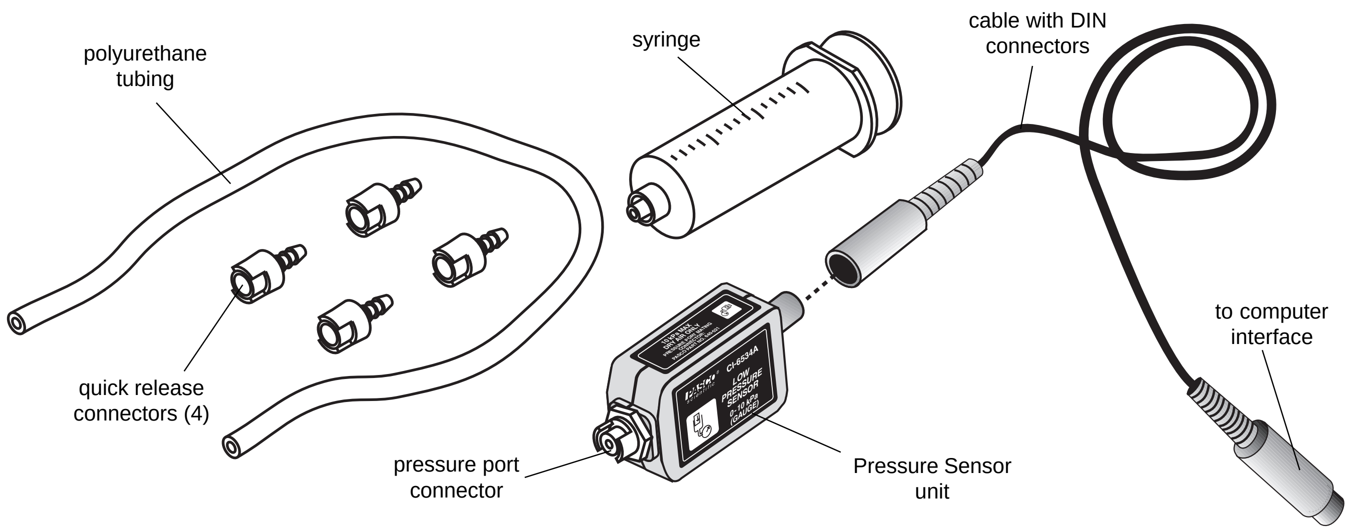
PIN	SIGNAL
1	ANALOG IN (+)
2	ANALOG IN (-)
3	GAIN SELECT
4	+5V
5	POWER GROUND
6	+12V POWER
7	-12V POWER
8	ANOLOG OUT

Schematic Diagram

012-07034A
3/99
$1.00

Instruction Sheet for the PASCO Model CI-6534A and CI-6535

CI-6534A LOW PRESSURE SENSOR (0-10kPa)
CI-6535 RESPIRATION RATE SENSOR



Introduction

The PASCO Model CI-6534A Low Pressure Sensor (0-10kPa) is a pressure sensor that is designed to be used with a PASCO computer interface. This low pressure sensor is ideally suited for use with the PASCO Respiration Belt or the PASCO Heat Engine Apparatus.

CI-6534A Low Pressure Sensor

The low pressure sensor consists of the electronics box with a cable that has a DIN plug for connecting to a PASCO computer interface. The pressure sensor uses a 10 kiloPascal transducer. This type of transducer has two ports. The reference port of the transducer is inside the electronics box. It is always open to the atmosphere and not available to the user. The other port is connected to the atmosphere via the pressure port connector at the front of the pressure sensor unit. It has a “quick-release” style connector for attaching accessories such as the PASCO CI-6535 Respiration Belt accessory (which includes a Low Pressure Sensor). The pressure sensor gives a reading of “zero” when there is no pressure difference between the internal reference port and the external pressure port connector.

The transducer is durable, but it is designed to be used with non corrosive gases such as air, helium, nitrogen, etc. Do not let the transducer get wet. The maximum short-term pressure that the sensor can tolerate without permanent damage is about 100 kPa (14 psi). Please be careful to not apply high pressure to the sensor.

The electronics box contains a precision operational amplifier (op amp) that can drive a heavy capacitive load, such as a six meter extender cable (CI-6515). There is a resistor in parallel with the transducer to compensate the sensor for temperature induced variations. The sensor has a negative temperature coefficient (resistance decreases as temperature increases) and the resistor has a positive temperature coefficient.

CI-6535 Respiration Rate Sensor

The CI-6535 Respiration Rate Sensor consists of the CI-6534A Low Pressure Sensor and the PASCO Respiration Belt (003-05936). See Figure 1.

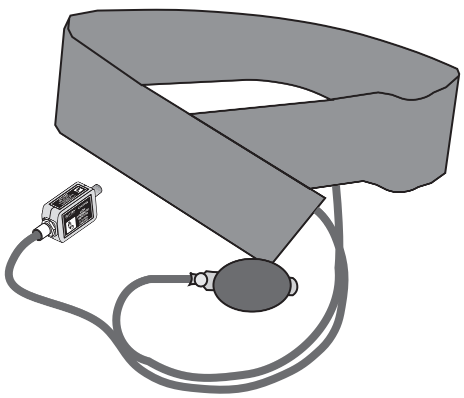


Figure 1
Respiration Rate Sensor

The belt has the following features:

- hook-and-pile strips sewn onto opposite ends of the belt
- attached squeeze bulb for inflating the rubber bladder inside the belt
- quick-release connector that can be attached to the pressure port on the Low Pressure Sensor.

Equipment

INCLUDED

- Low Pressure Sensor (Gauge) unit
- quick-release connectors (4)
- polyurethane tubing (0.6m)
- plastic syringe (20cc, calibrated)

ADDITIONAL REQUIRED

- computer (PC or Macintosh)
- *Science Workshop*® computer interface
- *Science Workshop*® software version 2.2 or higher

ADDITIONAL RECOMMENDED

- Respiration Belt (PASCO part no. 003-05936, included in the CI-6535 Respiration Rate Sensor)
- Heat Engine/Gas Law Apparatus (PASCO part no. TD-8572)

Extra parts are available as follows:

Item	Part Number
plastic syringe	699-084
polyurethane tubing	640-023
quick-release connector	640-021
Respiration Belt	003-05936

Range and Resolution

The range of the CI-6534A Low Pressure Sensor is between 0 and 10 kiloPascals. The resolution of the sensor is 0.005 kiloPascals (kPa) when used with a PASCO computer interface. The output voltage from the sensor is +1.00 Volts when the pressure is 1 kiloPascal (kPa), and the output voltage is linear. Therefore, the output voltage should be +10.00 Volts at the top of the range (10 kPa). Atmospheric pressure is normally around 101.326 kiloPascals (kPa). Pressure can be measured in many different units (e.g., atmospheres, inches of mercury, millimeters of mercury, kiloPascals, Bar, pounds per square inch). Some equivalent values for pressure are:

1 atmosphere	= 30.00 in of Hg (at 16ºC)
	= 760 millimeters of Hg
	= 101.326 kiloPascals (kPa)
	= 1.013 Bar = 1013 milliBar
	= 14.696 pounds per square inch (psi)

Operation

Setting up the Equipment

1. Connect the Pressure Sensor unit to analog channel A, B, or C of the *Science Workshop* computer interface box using the cable with the DIN connectors (Figure 2). Alternatively, the unit can be plugged directly into the analog channel jack.

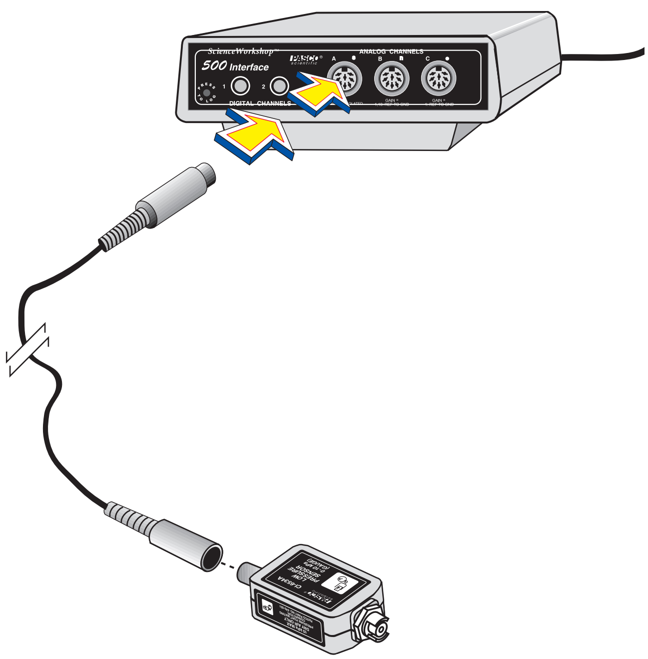


Figure 2
Connecting the amplifier box to the interface box

2. Connect the quick release connector to the pressure port connector on the Pressure Sensor unit.

The sensor is temperature compensated, therefore changes in room temperature will not interfere with the data.

Using the Syringe and Quick-Release Connectors

The Pressure Sensor is designed for experiments such as those that study the gas laws or for the rate of a chemical reaction by monitoring the increase or decrease in pressure. For example, Boyle's Law is a classic physics (and chemistry) concept that can be demonstrated using the sensor and the syringe. See Figure 3.

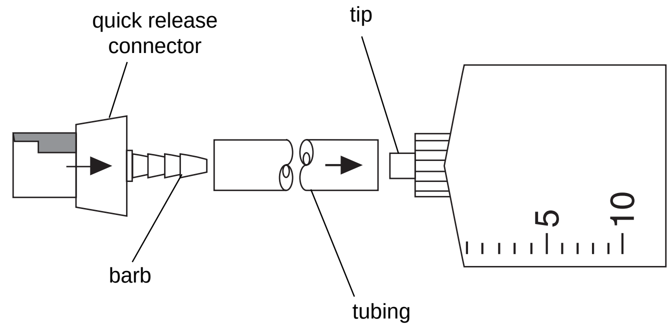


Figure 3
Using the syringe

To connect the syringe to the sensor, cut a short length of tubing (about one inch). Put the "barb" end of one of the quick-release connectors into one end of the short piece of tubing. Put the other end of the tubing over the tip on the end of the syringe.

Note: You can lubricate the end of the barb to make it easier to put into the short piece of tubing. Put a very small amount of silicon oil or saliva onto the barb and then wipe the barb with a cloth so there is only a thin layer of lubricant on the barb.

Align the quick-release connector with the pressure port connector of the sensor. Push the connector onto the port, and then turn the connector clockwise until it "clicks" into place (less than one-eighth of a turn). The barb of the quick-release connector is free to rotate even when the connector is firmly attached to the port. See Figure 4.

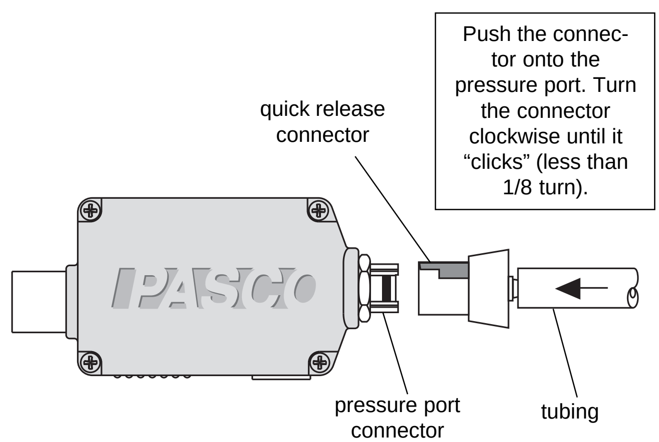


Figure 4
Using the quick release connectors

Mounting on an Experimental Apparatus

Use the 1/4-20 threaded connector located on the bottom of the sensor box to secure the Pressure Sensor to an experimental apparatus (Figure 5). The alignment hole fits over an alignment pin included on some PASCO apparatuses.

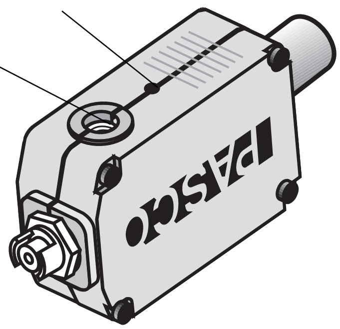


Figure 5
Mounting connector and alignment hole

Using the Respiration Belt

To measure respiration rate (breaths per minute), place the respiration belt around your chest or upper abdomen, connect one tube from the belt to the low pressure sensor, inflate the respiration belt with the squeeze bulb, and monitor the respiration rate with the computer interface.

Placing the Respiration Belt

Arrange the belt around your body so the part of the belt that has the tubes on it is on the right side of your body with the tubes hanging down from the bottom edge of the belt.

Place the part of the belt that has the tubes against your chest first. When this part is against your chest, the strips of ‘pile’ should face away from your chest. Then place the left side of the belt over the first part so the hook-and-pile strips match each other. The belt should be <u>snug</u> around the chest, but not so tight that breathing is restricted. See Figure’s 6 and 7.

Connecting the Belt to the Sensor

Align the quick-release connector on the end of one of the respiration belt’s tubes with the pressure port connector at the front of the pressure sensor unit.

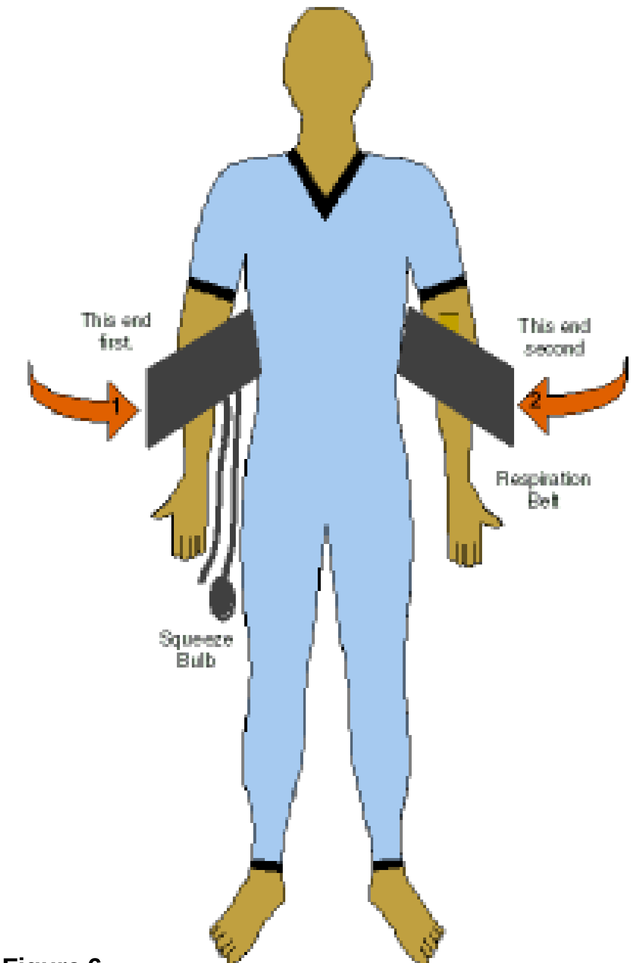


Figure 6
Connecting the Respiration Belt, Right Side First

Inflating the Respiration Belt

Turn the knurled knob that is on the squeeze bulb fully clockwise to <u>close</u> the release valve. Squeeze the bulb several times to inflate the rubber bladder. You may have to squeeze the bulb more than twenty times in order to inflate the bladder. When the bladder is inflated, the belt will be more snug against your chest.

Warning: Over inflation can damage the air bladder.

Deflating the Respiration Belt

Turn the knurled knob on the squeeze belt counterclockwise to <u>open</u> the release valve. Use your hands to push the air out of the bladder. You can also deflate the respiration belt by disconnecting the tube from the pressure port on the sensor. Turn the quick-release connector counterclockwise to disconnect it from the pressure port.

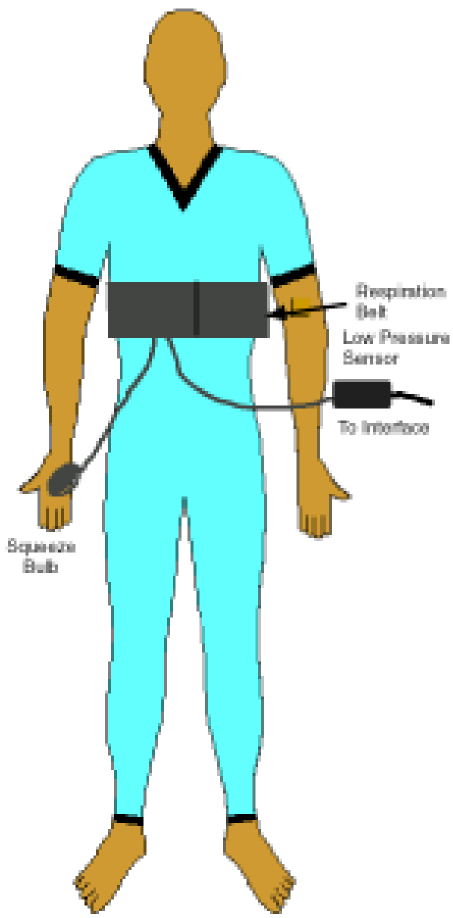


Figure 7
Respiration Belt In Place

Lift up on the top flap of the respiration belt to disengage the hook-and-pile strips from each other when you want to remove the belt.

Suggested Experiments

Respiration Rate versus Activity

Monitor respiration rate before and after exercise. Measure the respiration rate while resting. Then exercise vigorously. Measure the respiration rate immediately after exercise, and the measure how long it takes for the respiration rate to return to the resting ("normal") rate.

Respiration rate (number of breaths per unit of time) depends on several factors: altitude, lung capacity, health, and level of activity. Higher altitudes and levels of activity would tend to increase respiration rate. Larger lung capacity and generally good health would tend to decrease respiration rate.

Gay-Lussac's Law (pressure vs. absolute temperature)

Gay-Lussac's Law states that if the volume remains constant, the pressure of a container of gas is directly proportional to its absolute temperature. Set up a sealed container of air by attaching the longer piece of plastic tubing to a stopper in a 125 mL Erlenmeyer flask. Put a drop of glycerin on the bottom of one hole of a two-hole rubber stopper. Put the glass part of an eyedropper tip end up through one hole in the rubber stopper. CAREFULLY put the end of the plastic tubing over the tip of the eyedropper. Connect the other end of the tube to the pressure port connector at the front of the pressure sensor unit.. Put a drop of glycerin on the top of the other hole. Insert a temperature sensor through the hole. Place the stopper in the top of the flask. See Figure 8.

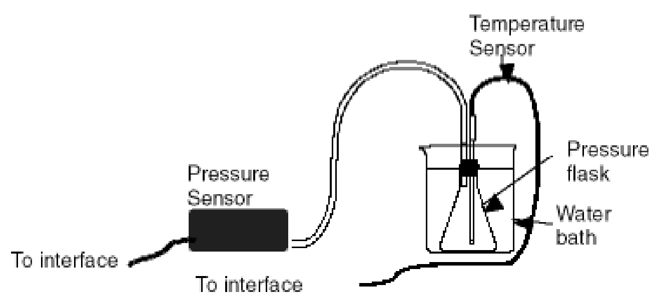


Figure 8
Experiment Setup For Gay-Lussac's Law

Place the flask in water baths of different temperatures. Record data on how the pressure changes with the temperature changes.

Pressure in Liquids

Put the end of the longer piece of tubing under water. The pressure reading should increase by 0.0978 kPa (0.02896 in of mercury) per centimeter of depth below the surface. You can also use a "J" shaped tube to study how pressure relates to the difference in heights of the liquid in the two parts of the tube.

Studying Chemical Reactions by Monitoring Pressure

Many chemical reactions produce gases that can cause an increase in pressure in a sealed container. The pressure change can be used to monitor the rate of the reaction.

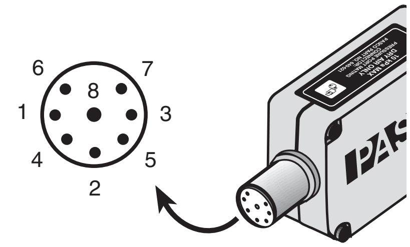
Other

PASCO scientific also produces an Absolute Pressure Sensor (Model CI-6532A), a Differential Pressure Sensor (Model CI-6533) and a Barometer (Model CI-6531A). The Absolute Pressure Sensor has a range from 0 to 700 kiloPascals. The Differential Pressure Sensor is similar to the CI-6532A, except that both ports of the transducer are open to the atmosphere. It is designed for experiments where pressure differs from one part of the apparatus to another, such as in a Venturi tube or for a demonstration of Bernoulli's principle. The Barometer has a range from 800 to 1100 milliBar (24 to 32 inches of mercury). It is designed to be a reliable, accurate pressure sensor for weather studies. It is temperature compensated and has a voltage regulator, so changes in temperature or changes in the computer's power supply will not interfere with the data.

Note: This instruction sheet was written assuming that the user has a basic familiarity with *Science Workshop* and has access to the *User's Guide for Science Workshop*. Users can gain basic skills by working through the tutorial within *Science Workshop*. Another useful resource is the *Quick Reference Card for Science Workshop*.

DIN Connector Specifications

1: analog output (+), -10 to +10 V
2: analog output (-), signal ground
3: (no connection)
4: + 5 V DC power
5: power ground
6: +12 VDC power
7: -12 VDC power
8: (no connection)



Limited Warranty

PASCO scientific warrants the product to be free from defects in materials and workmanship for a period of one year from the date of shipment to the customer. PASCO will repair or replace, at its option, any part of the product which is deemed to be defective in material or workmanship. The warranty does not cover damage to the product caused by abuse or improper use. Determination of whether a product failure is the result of a manufacturing defect or improper use by the customer shall be made solely by PASCO scientific. Responsibility for the return of equipment for warranty repair belongs to the customer. Equipment must be properly packed to prevent damage and shipped postage or freight prepaid. (Damage caused by improper packing of the equipment for return shipment will not be covered by the warranty.) Shipping costs for returning the equipment after repair will be paid by PASCO scientific.

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