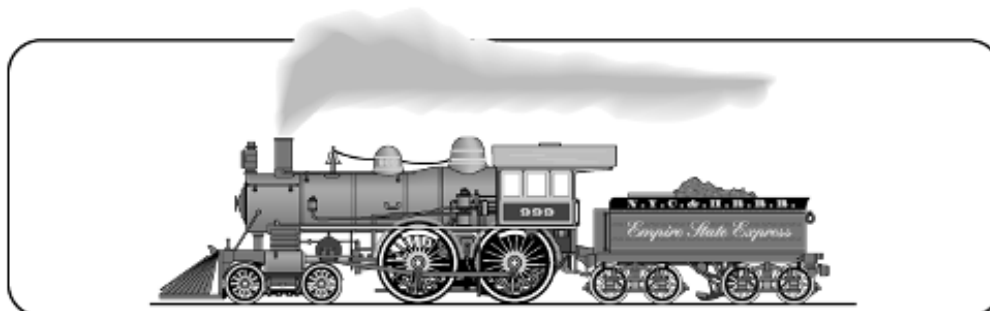


Name \_\_\_\_\_ Date \_\_\_\_\_ Partners \_\_\_\_\_

## HEAT ENGINES AND THE FIRST LAW OF THERMODYNAMICS



. . . the quantity of heat produced by the friction of bodies, whether solid or liquid, is always proportional to the quantity of energy expended.

–James Joule

The production of motion in a steam engine is always accompanied by a circumstance which we should particularly notice. This circumstance is the passage of caloric from one body where the temperature is . . . elevated to another where it is lower.

–S.N.L. Carnot

### OBJECTIVES

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- To quantify the relationship between the heat energy transferred to a system and the change in temperature of the system.
- To understand the meaning of *specific heat* and to measure its value.
- To understand phase changes as processes in which energy is transferred to or from a system without the temperature changing, and to understand the concept of latent heat.
- To understand the energy balance of a system between heat energy transfer, work done, and changes in *internal energy*, as described by the first law of thermodynamics.

### OVERVIEW

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We understand that interactions take place when two substances in thermal contact are at different temperatures. We call these interactions “heat energy transfer.” There are other ways to raise the temperature of an object. For example, by rubbing your hands together rapidly, you feel an increased temperature. Also, you probably have seen it is possible to produce a temperature increase using an electric heater by supplying electrical energy to it. Observations like these caused physicists and engineers in the middle of the nineteenth century to conclude that heat is just a form of energy, the form that flows when there is a temperature difference between two objects.

We want to examine the mathematical relationship between the heat energy transferred to a system and the temperature change of the system. In this lab you will look at the amount of heat energy transfer needed to raise the temperature of one unit of mass of water by one degree, which is called the *specific heat* of the water.

The common unit of heat energy is the calorie. Mechanical energy is measured in joules, a familiar unit used in your study of mechanics. The conversion factor between calories and joules is commonly known as the *mechanical equivalent of heat*.

In one investigation you will consider how the transfer of heat energy can change a system internally without changing its temperature. The process you will examine is the change of a substance from solid to liquid or liquid to gas or vice versa, called a *change of phase*. You will consider an example of a process in which heat energy transfer changes a system internally without changing its temperature. This is a phase change from liquid to gas. You will measure the latent heat of vaporization of water—the amount of heat energy transfer required to transform one unit of mass of water from liquid to steam.

The nineteenth-century industrial revolution was based on the invention of heat engines. Heat engines have much in common with the chemical engines that power humans. For instance, both human engines and heat engines extract heat energy at a higher temperature, do work, and then transfer waste heat energy to lower temperature surroundings. When you complete the third investigation, you will have a better understanding of how the laws of thermodynamics allow us to place absolute limits on the efficiency of heat engines. The steam engine, which ushered in the industrial revolution, and the internal combustion engine both depend on *cycles* in which gases (the working medium of the engine) are alternately expanded and then compressed. The end result of these cycles is that a portion of heat energy transferred to a gas is converted into work. An understanding of the detailed physics of the expansion and compression of gases has helped engineers to design more efficient engines.

Work is associated with a gas that expands or is compressed in a cylinder with a piston. This leads to the idea that the energy stored internally in a system can be increased by either transferring heat energy to it or by doing work on it. The law that keeps track of the *internal energy* of a system, the *work done by the system*, and *heat energy transferred to the system* is the **first law of thermodynamics**. An understanding of this extended conservation of energy law is important in practical endeavors, such as in the design of heat engines.

In this lab we will examine a real heat engine that operates on expansions and compressions of a gas, and attempt to determine the amount of work that it will produce on the basis of our understanding of the physics of gas expansion and compression. Finally, we will calculate the efficiency of this engine and compare it to the maximum possible efficiency for an engine operating between the same temperatures.

## INVESTIGATION 1: RELATIONSHIP BETWEEN HEAT ENERGY AND TEMPERATURE

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**Prediction 1-1:** If you transfer heat energy to a *perfectly insulated* cup of some liquid, consider how much temperature change  $\Delta T$  takes place? How does  $\Delta T$  depend on

A. The amount of heat energy you transfer ( $\Delta Q$ )?

B. The mass ( $m$ ) of liquid in the cup?

C. The kind of liquid you have?

In this investigation you will conduct a series of observations in which you examine *quantitatively* the relationship between  $\Delta T$  and these other variables. To do this you will need to investigate all three factors by changing only one variable at a time. For example, you can use the same mass of room-temperature water for a series of experiments and vary only the amount of heat energy you transfer. Then you can use the same amount of heat energy and vary the mass of the water. Finally, you can use the same mass of liquid and the same amount of heat energy and vary the type of liquid (e.g., use oil instead of water). We will not do the latter experiment.

To do the series of observations you should have the following equipment:

- temperature sensor
- coffee cup immersion heater
- Styrofoam cup (8 oz)
- stirring rod
- 400-ml glass beaker (to keep the Styrofoam cup from tipping)
- Vernier Heat Pulser
- 100 mL labeled plastic beaker
- vat (to prevent spills)
- electronic balance
- room-temperature water

**Warnings:**

- 1. Do not plug in the immersion heater unless it is immersed in water.**
- 2. Use enough liquid in each case to make sure the electric coil is just covered in every observation. You may leave the heater on the bottom of the cup. Be careful not to use large amounts of liquid, because the heating process will take too long! Keep stirring the liquid at all times.**

**Activity 1-1: Transferring Different Amounts of Heat Energy to the Same Mass of Water**

1. Mass the empty small Styrofoam cup and write down its mass: Mass \_\_\_\_\_ g
2. Put the foam cup in the glass beaker to avoid injury caused by spillage. Add about 80 g (mL) of room-temperature water to the cup. Be sure that the water will cover the heater coils; add a little more water if necessary. Mass the cup with water and enter the mass of the water (subtract mass of cup) into Table 1-1. Put a temperature sensor and the heater into the small foam cup. Plug the coffee cup heater into the heat pulser.
3. Open the experiment file called **Heating Water L13.1-1**.
4. A window will appear on the computer screen showing a Signal Generator. Note the icons for On and Off in this window. Choose the square wave signal (100 Hz). These buttons turn on and off electrical power that goes to the coffee cup immersion heater. The actual measured wattage (not 200 W) of this heater should be marked on it somewhere. Write down the heater wattage below. The experiment begins with the heater **OFF**.

Immersion heater wattage: \_\_\_\_\_ W

5. Measure the initial temperature of the water and record it in Table 1-1. (The temperature can be read more accurately from the digital display rather than from the graph.)
6. **Start the computer and begin graphing.** *Stir the water vigorously the entire time the computer is graphing the temperature, now and during the rest of these activities.*
7. For the first 10 s, leave the heater off. Then turn the heater **ON** for a total of 20 s and then turn it off. *Keep stirring.*
8. After the temperature stops changing, stop the computer, and record the highest temperature reached as the final temperature in the table. Look on the graph and note the total time that the heater was on by observing when the voltage pulse goes positive and returns to zero. Record this value in Table 1-1.
9. Keep the data on the graph. Do not erase it.
10. Calculate the temperature change, determine the amount of heat in Joules delivered to the water and the temperature change per energy unit (J). Record these in Table 1-1. Use the power rating of the immersion heater to determine the heat energy delivered. Energy (J) = Time (s) x Power (W).

**Question 1-1:** Describe the shape of your graph. What does this say about the relationship between the temperature change and the quantity of heat energy transferred to the water? (Remember that heat was transferred at a constant rate.)

11. Replace the water in the cup with another 80 g (mL) of room-temperature water. Record the beginning temperature of the water in Table 1-1.

12. Repeat this activity, transferring twice as much heat. Leave the heater on for 40 s. Use the same setup as before.

*Remember to stir the water continuously while graphing.* Don't add heat during the first 10 s. When the temperature stops changing, record the final temperature.

13. Calculate the temperature change, determine the amount of heat in Joules delivered to the water and the temperature change per energy unit (J) and record these in Table 1-1.

14. Print your graphs.

**Question 1-2:** Write an equation that shows the relationship between the temperature change ( $\Delta T$ ) and the amount of heat energy transferred ( $\Delta Q$ ) to a fixed mass of water.

**Table 1-1**

Mass of water (g)	Initial temperature ( $^{\circ}\text{C}$ )	Final temperature ( $^{\circ}\text{C}$ )	Temperature change $\Delta C$ ( $^{\circ}\text{C}$ )	Time heater was on (s)	Total heat delivered to water $\Delta Q$ (J)	Temperature change per unit heat energy ( $^{\circ}\text{C}/\text{J}$ )

**Prediction 1-2:** Suppose you transfer heat energy to a larger mass of water. How will the temperature change?

A. You heated 80 g of water with the heater on for 20 s. How long do you think the heater will need to be on to produce the same temperature increase if you heat *twice as much water* (160 g)?  
\_\_\_\_\_ s

B. What will be the temperature increase per unit heat energy input for *twice as much water* (160 g)?  
\_\_\_\_\_  $^{\circ}\text{C}/\text{J}$

15. Replace the water in the cup with 160 g (mL) of room-temperature water. Record the beginning temperature of the water in Table 1-1.
16. Repeat the previous activity and use your prediction to transfer enough heat to produce the *same temperature change as produced previously when you heated 80 g of water for 20 s*. Use the same setup and procedure as before. *Remember to stir the water continuously while graphing.* When the temperature stops changing, record the final temperature. **Do not throw the water out.** We will use this hot water in the next activity.
17. Calculate the temperature change and change per unit energy and record these in Table 1-1.
18. **Print the graph.**

**Question 1-4:** Did the time required to heat 160 g of water agree with your prediction? Explain.

**Question 1-5:** Did the rise in temperature per unit heat energy you determined agree with your prediction? Explain.

**Question 1-6:** Based on your graphs and data, discuss the following mathematical relationship:

$$\Delta Q = cm \Delta T$$

where  $\Delta Q$  is the heat energy transferred to the water,  $m$  is the mass of the water,  $\Delta T$  is the change in temperature, and  $c$  is a constant characteristic of the liquid.

You have examined the relationship between the amount of heat energy transferred to a system and the system's change in temperature. You have seen that the change in temperature is proportional to the amount of heat energy transferred and inversely proportional to the mass of the system. To be more quantitative (e.g., to be able to predict numerical temperature changes), it is necessary to specify what amount of heat energy transfer will produce a one degree change in temperature in unit mass of a material. This quantity is known as the *specific heat* of the material. It is the value  $c$  in the equation in Question 1-6.

$$\text{specific heat} = c = \frac{\Delta Q}{m\Delta T}$$

The standard units for heat energy (J), mass (kg), and temperature ( $^{\circ}\text{C}$ ), give us the unit for specific heat,  $\text{J/kg}\cdot^{\circ}\text{C}$ . In the next activity you will calculate the specific heat of water from your data.

**Activity 1-2: Specific Heat of Water**

1. Enter the mass of water, temperature change, and heat energy transfer data from all the experiments you performed for Activity 1-1 into Table 1-2.
2. Calculate the total heat energy transferred by the heater using the power rating of the heater in watts (W) and the total time the heat energy was transferred to the water in each run of the experiment. (Recall that  $1 \text{ W} = 1 \text{ J/s}$ .)

**Table 1-2**

Mass of water (kg)	Change in temperature ( $^{\circ}\text{C}$ )	Total energy transferred by heater(J)	Specific heat ( $\text{J/kg}\cdot^{\circ}\text{C}$ )

3. Calculate the specific heat for each run.
4. Calculate the average value of the specific heat of water from the three values in your table:

$$c_{\text{water}} = \underline{\hspace{2cm}}$$

**Question 1-7:** How closely did the three values of the specific heat agree with each other? How did the average value agree with the accepted value,  $c_{\text{water}} = 4,190 \text{ J/kg}\cdot^{\circ}\text{C}$ ? What are the possible sources of experimental error that might explain any disagreement?

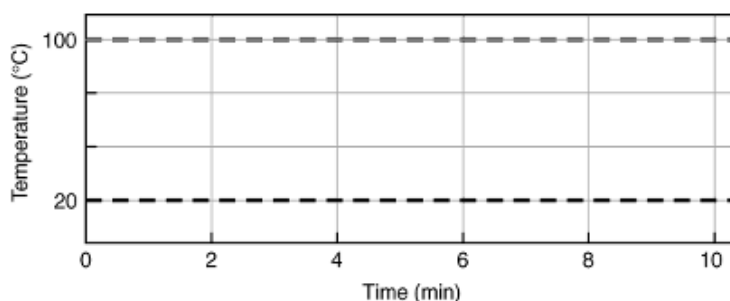
**Question 1-8** How many seconds would it take the heater to raise the temperature of 300 g of water by  $25^{\circ}\text{C}$ ? Show your calculation and explain your reasoning. (Use  $c_{\text{water}} = 4,190 \text{ J/kg}\cdot^{\circ}\text{C}$ .)

**INVESTIGATION 2: CHANGE OF PHASE FROM LIQUID TO GAS**

**Prediction 2-1:** On the axes that follow, sketch a graph of temperature vs. time for a cup of water initially at room temperature that is heated in the following way:

- Heat energy is transferred at a constant rate until the water reaches its boiling-point temperature. (Assume that this happens in the first 6 min.)

- Heat energy is then transferred at the same constant rate as the water boils for the next 4 min.



To test your prediction you will need

- temperature sensor
- coffee cup immersion heater
- container marked in mL (may not need)
- room-temperature water
- Styrofoam cup, 300 mL (12 fl oz.) with tightly fitting cover
- electronic balance
- vat (to prevent spills)
- stirring rod
- 400-600 mL beaker
- Vernier Heat Pulser

### Activity 2-1: Heating Water to Its Boiling Point: A Temperature History

- Open the experiment file called **Water to Steam L13.2-1**.

**Reminder!! Do not plug the heater into the box or press the ON icon button on the computer screen unless the heater is in the water.**

- Accurately measure about 150 g of hot water from the previous activity in the foam cup:

Mass of empty cup with cover: \_\_\_\_\_g      Mass of cup, cover, and water: \_\_\_\_\_g

Initial mass of water: \_\_\_\_\_g      Record in Table 2-1.

- Put the cup with water into the glass beaker for more stability and place the temperature sensor and heater into the cup. Leave the cover off for now. Let the heater sit on the bottom of the cup. **Start the computer** and stir the water and record its initial temperature in Table 2-1.
- Keep stirring vigorously.* Turn the heater **ON** to start heating the water.
- When the water *just* begins to boil vigorously, note the temperature and computer time (in box on upper part of screen) and write them in the table and continue with the heater on. You may stop stirring, since the roiling boil will keep the water mixing.

Keep the heater ON until the water has been boiling for about 5 min.

- Turn the heater OFF, then quickly remove the heater and temperature sensor, shake off any excess water on the heater and sensor into the cup. Put the cover on the cup. Unplug the heater from the heat pulser and stop the computer.



7. Look carefully at the computer screen and make sure the graph for the heat pulser is displayed. Use the SMART TOOL to note the time that the heater was turned off. Subtract the time you noted the water began boiling from the time the heater was turned off to determine the total time the heater was on *after the water started to boil*.

8. Measure the final mass of the cup, cover, and water, calculate the mass of water converted to steam, and record in Table 2-1:

Final mass of cup, cover, and water: \_\_\_\_\_ g      Mass of empty cup with cover: \_\_\_\_\_ g

Final mass of water: \_\_\_\_\_ g      Mass of steam produced: \_\_\_\_\_ g

9. **Print the graph.** Indicate on your graph with an arrow where the water began boiling vigorously.

**Question 2-1:** Does your graph agree with the prediction you made? If not, describe the ways in which the observed behavior of boiling water was different from your prediction.

**Table 2-1**

Initial mass of water (kg)	Initial temperature (°C)	Time when boiling began (s)	Boiling point temperature (°C)	Time heater was turned off (s)	Total time heater boiled water (s)	Final mass of water less steam (kg)	Mass of steam produced (kg)

**Question 2-2:** During the time that the temperature remained constant, what do you think happened to the heat energy you were transferring if it wasn't raising the temperature?

**Comment:** Most substances can exist in three states—solid, liquid, and gas. As you have seen, these *changes of state or phase changes* usually involve a transfer of heat energy. During a phase change, the substance can absorb heat energy without changing its temperature until the phase change is complete. The transferred energy increases the *internal energy* of the system.

The amount of heat energy transfer required to transform one kilogram of water at its boiling point into steam is called the *latent heat of vaporization*. (This amount of energy is the same as the amount transferred away from one kilogram of steam when it condenses.)

## Activity 2-2: Latent Heat of Vaporization of Water

1. Calculate the total heat energy transferred to the water *after it was boiling*. Use the power rating of the heater and the total time the heater was boiling water from Table 2-1. Show your calculations below. (Remember,  $1\text{ W} = 1\text{ J/s}$ .)

Power rating marked on the heater: \_\_\_\_\_W    Total time heater boiled water \_\_\_\_\_s

Total heat energy transferred: \_\_\_\_\_ J

2. Calculate the latent heat of vaporization of the water. Use the amount of heat energy transferred from the immersion heater after the water was boiling and the mass of steam produced from Table 2-1 to find the amount of heat energy needed to convert one kilogram of water to steam. Show your calculations.

Latent heat of vaporization: \_\_\_\_\_ J/kg

**Question 2-3:** Compare the heat energy needed to convert one kilogram of water to steam to that needed to convert one kilogram of ice to water ( $3.34 \times 10^5\text{ J/kg}$ ). Why do you think that one is much larger than the other?

**Question 2-4:** Compare your value for the latent heat of vaporization to the accepted value,  $2.26 \times 10^6\text{ J/kg}$  (or  $2,260\text{ J/g}$ ). Discuss the limitations in the experimental method you used that might account for any differences between these two values.

## INVESTIGATION 3: HEAT ENGINES

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Internal combustion engines inside cars and trucks are examples of heat engines that burn a gasoline—air mixture in the cylinders. The railroad steam engine, which spanned the American continent in the mid-nineteenth century, is another example of a heat engine. The word “engine” conjures up an image of something that we start up, runs, and provides a continuous flow of work. In the case of a car, the work done by the engine accelerates us until we reach a suitable speed and then helps us maintain that speed by overcoming friction and air resistance.

The basic goal of any heat engine is to convert heat energy into work as efficiently as possible. This is done by taking a *working medium*—some substance that can expand and thus do work when heat energy is transferred to it—and placing it in a system designed to produce work in continuous, repeated cycles.

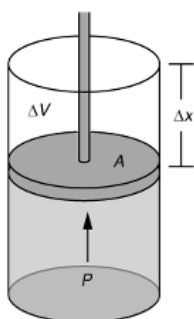
An engine that is 100% efficient would have a working medium that transforms all of the heat energy transferred to it to useful work. Such a process would not violate the first law of

thermodynamics, since energy would be converted from one form to another, and conserved. However, no heat engine has ever been capable of transforming *all* of the heat energy transferred to it into useful work. Some of the heat energy transferred in is always transferred back to the engine's surroundings at a lower temperature as waste heat energy. The universal existence of waste heat energy has led scientists to formulate the *second law of thermodynamics*. A common statement of the second law is simply that *it is impossible to transform all of the heat energy transferred to a system into useful work*.

In this investigation you will explore the actual behavior of a simple heat engine. We can use any substance that changes its volume when heat energy is transferred to it as the working medium for a heat engine. The working medium is capable of transforming a fraction of the heat energy transferred into it to useful work. You will study the compression and expansion of gases used as working substances in heat engines. As you complete this investigation, we hope you will begin to understand that there are general principles that govern the operation of heat engines that do not depend on the detailed nature of the *working medium*.

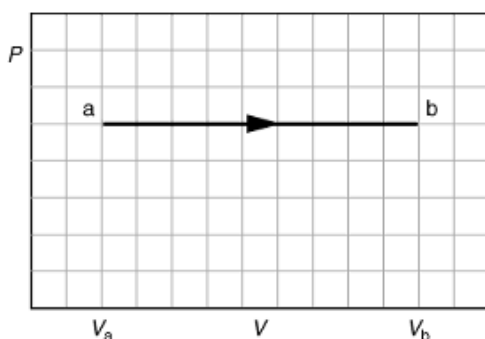
### Background 3-1: Work Done by an Expanding Gas

A system we have already met in our study of thermodynamics is a mass of gas confined in a cylinder with a movable piston. The behavior of a gas compressed and expanding in a cylinder is a simulation of what goes on in the cylinders in a real engine like the internal combustion engine in your car, or, in fact, even more like a steam engine.



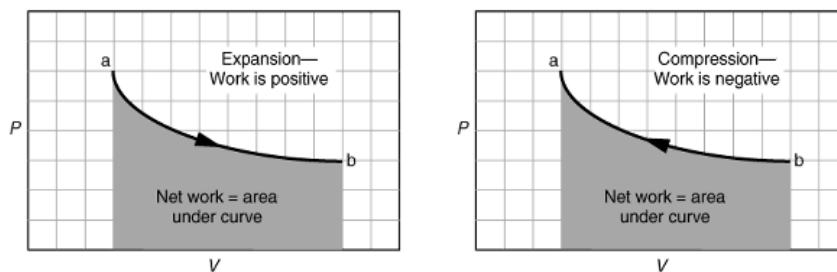
**Question 3-1 (review):** If a gas expands inside a cylinder with a movable piston so that the volume changes by an amount  $\Delta V$  while the pressure is kept constant at a value  $p$  (isobaric process), what is the mathematical expression to calculate the amount of work done by the gas?

**Question 3-2 (review):** The graph that follows shows an isobaric expansion from a volume  $V_a$  to a volume  $V_b$  represented on a  $p$ - $V$  diagram. How can you find the work done in the expansion from a to b *from the graph*? (**Hint:** Use your answer to review Question 3-1.)



Hopefully, you answered  $W = p \Delta V$  and that this is just the area under the  $p$  vs.  $V$  curve. It turns out mathematically that you can always calculate the work done by finding the area under the curve, even if the pressure does not remain constant during the process. Also, the work calculated in this

way is *positive* if the gas *expands* in the process. If the gas is compressed during the process, then work is done on the gas by the surroundings, and the work done by the system is *negative*. Examples are shown below.



You have already seen in your study of the first law of thermodynamics that transferring heat energy to a system can increase its internal energy, but it might result instead in the system doing work on its surroundings. In applying thermodynamics to the operation of heat engines, we are interested in the relationships between the heat energy transferred to a system and the work done by the system.

According to the first law of thermodynamics, the conservation of energy, including the internal energy, is

$$\Delta E_{\text{int}} = Q - W$$

where  $Q$  is the net heat energy transferred to the system (a positive number if heat energy is transferred *into* the system) and  $W$  is the work done by the system (a positive number if work is done *by the system*). That is, *transfer of heat energy into the system increases* the internal energy, and *work done by the system decreases* the internal energy. (For a monatomic ideal gas, the internal energy  $E_{\text{int}}$  is just the sum of all the kinetic energy associated with the random translational motions of molecules.) For one cycle of a heat engine, the system is in the same *thermodynamic state* that it was in at the start. In other words, all its properties, including its internal energy, are the same. *For one complete cycle of a heat engine,  $\Delta E_{\text{int}} = 0$ .*

If  $Q_H$  is the heat energy transferred to the system from the hot reservoir and  $Q_C$  is the heat energy transferred from the system to the cooler room air, the net heat energy transferred to the system in the cycle is  $Q = Q_H - Q_C$  and the first law of thermodynamics becomes

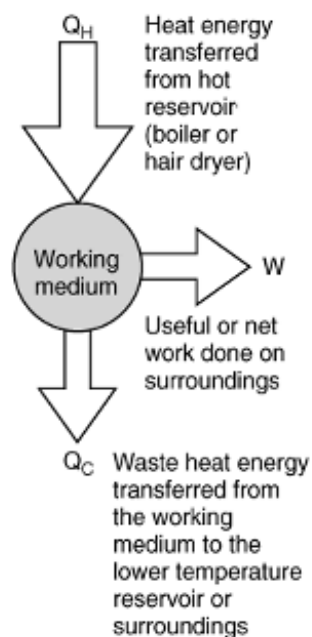
$$\Delta E_{\text{int}} = Q - W = (Q_H - Q_C) - W$$

Since  $\Delta E_{\text{int}} = 0$  for our *complete cycle*, we can simplify this by writing

$$W = Q_H - Q_C$$

This basic fact about heat engines is often illustrated by an energy flow diagram such as the one shown on the right. This diagram would work equally well for an old-fashioned steam engine or the simple heat engine we will use.

The figure on the right is a pictorial representation of what we have written in words: Our engine has heat energy  $Q_H$  transferred to it, does heat engine schematic work  $W$ , and transfers some of the original heat energy  $Q_C$  to the lower temperature surroundings.





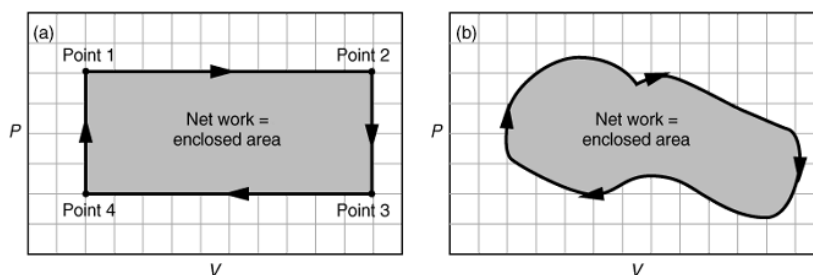
### Background 3-2: Finding Net Work Done in a Complete $p$ - $V$ Cycle

As we have seen, during parts of a cycle when a gas is expanding it is doing *positive work on the surroundings*. When it is being compressed, work is being *done on the gas by the surroundings*, so the work done comes out *negative*.

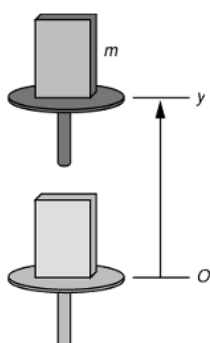
Typically, at the completion of a heat engine cycle, the gas has the same internal energy, temperature, pressure, and volume that it started with. It is then ready to start another cycle. During various phases of the cycle, (1) heat energy transferred to the gas from the hot reservoir (e.g., a boiler) causes the gas to do work on its surroundings as it expands, (2) the surroundings do work on the gas to compress it, and (3) the gas transfers waste heat energy to the surroundings or cold reservoir.

Real heat engines have linkages between a moving piston and the gas or other working medium, which allows the expansion and compression phases of the cycle to run automatically. Thus, some of the work done on the surroundings provides the work needed to compress the gas to return it to its starting point. The useful or net work done in an engine cycle must account for the positive work done during expansion and the negative work done during compression.

Because the work done going from one state to another in one direction is positive and the work done in the other direction is negative, it can be shown mathematically that the work done around a closed loop on a  $p$ - $V$  diagram, representing a complete cycle of the engine, is the same as the area enclosed by the trace of the process on the diagram. This is illustrated below for two different imaginary cycles.



In the next investigation, you will attempt to verify this relationship between useful work and the area on a  $p$ - $V$  diagram for a real engine.



Doing useful mechanical work by lifting a mass  $m$  through a height  $y$ .

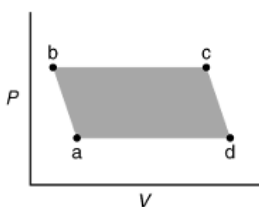
### Background 3-3: The Incredible Mass-Lifting Heat Engine

Your working group has been approached by the Newton Apple Company about testing a heat engine that lifts apples that vary in mass from 50 to 100 g from a processing conveyor belt to the packing conveyor belt, which is 5 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. 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  $mgy$  work (which we hope you believe in and understand

from earlier labs) with the accounting of work in an engine cycle *given by the area enclosed by the*

*cycle.*

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. In addition, it will be possible to calculate the heat energy transferred into the heat engine, and compare this to the useful work output.

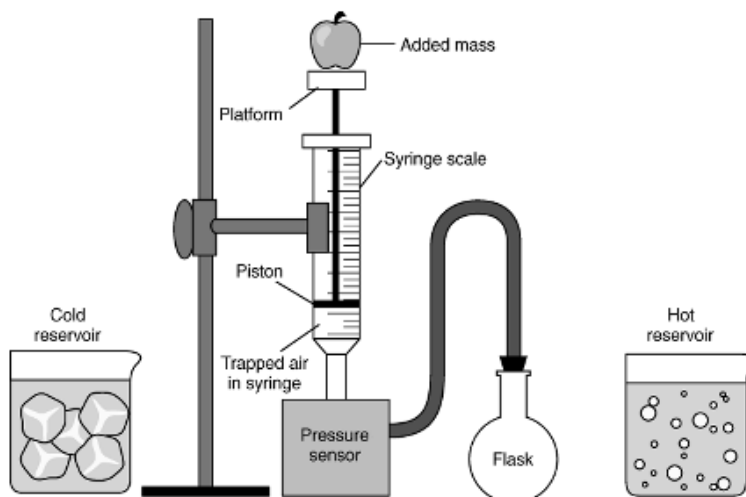


Doing thermodynamic work in a heat engine cycle

To carry out this experiment you will need

- 10-cm<sup>3</sup> low-friction glass syringe with ring stand support
- several lengths of Tygon tubing
- flask (test tube) with one-hole rubber stopper
- 2 insulated (e.g., Styrofoam) containers (to use as reservoirs)
- ruler
- 50-g mass
- hot water (about 80–90°C)
- ice water
- a pressure sensor and a temperature sensor
- distilled water

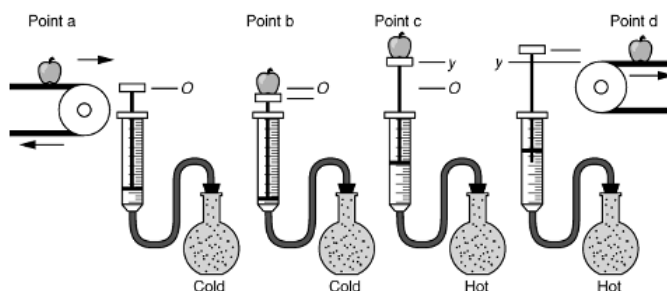
The cylinder of the incredible mass-lifter engine is a low-friction glass syringe. The flat top of the handle of the piston serves as a platform for lifting masses. The flask and pressure sensor can be connected to the syringe with short lengths of flexible Tygon tubing, and the flask can be placed alternately in a cold reservoir and a hot reservoir. A schematic diagram of this mass lifter follows.



If the temperature of the air trapped inside the cylinder, hose, and flask is increased, then its pressure will increase, causing the platform to rise. Thus, you can increase the volume of the trapped air by moving the flask from the cold to the hot reservoir. Then when the mass 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 flask 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 the diagrams that follow.



The lifting and lowering parts of the cycle should be approximately *isobaric*, since the pressure in the air trapped in the syringe is determined by the weight of the piston (and the mass on top of the handle) pushing down on the gas. The other two parts of the cycle, when the mass is added and removed from the piston handle, should be approximately *adiabatic*, because they occur very quickly, little heat can flow during the process.



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 ice water and the other with hot tap water or preheated water at about 80–90°C.

The engine cycle is much easier to describe if you begin with the piston resting above the bottom of the syringe. **Thus, we suggest you raise the piston so that the volume of air trapped in the syringe is about 3–4 mL before inserting the rubber stopper firmly in the flask.** Also, air does leak out of the syringe slowly. If a large mass is being lifted, the leakage rate increases, so we suggest that you limit the added mass to 50 g.

**IMPORTANT:** As you take the engine through its cycle, observe whether the piston is moving freely in the syringe. If it is sticking, it should be removed and dipped into *distilled* water to free it up. It may be a good idea to do this as a precaution. If it continues to get stuck, ask your instructor for help.

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 should reflect on your observations by answering the questions in the next activity. 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.

### Activity 3-1: Description of the Engine Cycle

**Prediction 3-1:** With the system closed to the outside air and the flask in the cold reservoir, what should happen to the height of the platform during transition **a**→**b**, as you add the mass to the platform? Explain the basis of your prediction.

1. Dip the piston into the distilled water and place back into the cylinder. Make sure the rubber stopper is firmly in place in the tube. Make sure that you start with the piston with about 3-4 mL of gas in the cylinder. Add the mass to the platform.

**Question 3-1:** Describe what happened. Is this what you predicted? Why might this process be approximately adiabatic?

**Prediction 3-2:** What do you expect to happen during transition **b**→**c**, when you place the flask in the hot reservoir?

2. Place the flask in the hot reservoir. (This is the engine power stroke!)

**Question 3-2:** Describe what happens. Is this what you predicted? Why should this process be isobaric?

**Prediction 3-3:** If you continue to hold the flask in the hot reservoir, what will happen when the added mass is now lifted and removed from the platform during transition **c**→**d** (and moved onto an upper conveyor belt)? Explain the reasons for your prediction.

3. Remove the added mass.

**Question 3-3:** Describe what actually happens. Is this what you predicted? Why might this process be approximately adiabatic?

**Prediction 3-4:** What do you predict will happen during transition **d**→**a**, when you now place the flask back in the cold reservoir? Explain the reasons for your prediction.

4. 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 flask in the cold reservoir.

**Question 3-5:** Describe what actually happens to the volume of the trapped air. Why should this process be isobaric?

**Question 3-6:** 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?

**Question 3-7:** Theoretically, the pressure of the gas should be the same once you cool the system back to its original temperature. Why?

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, Tygon tubing, and flask at the points **a**, **b**, **c**, and **d** in the cycle. You can do this by hand, or you can have your computer-based system do it for you.

### Activity 3-2: Work Done by the Heat Engine

1. We have estimated the total volume of the tube, tubing, and pressure sensor and entered this into Table 3-2a.
2. Connect the pressure sensor and temperature sensor to the interface and start up the software.
3. Open the experiment file called **Pressure and Temperature L13.3-2**. This will set up the software in **prompted event mode** so that you can continuously measure pressure and decide when you want to **keep** a value. Then you can enter the measured volume.

Table 3-2a

State of system	Volume of air in syringe (cm <sup>3</sup> )	Volume of flask, tubing, & sensor (cm <sup>3</sup> )	Total volume of air (cm <sup>3</sup> )
a		15	
b		15	
c		15	
d		15	
a'		15	

4. Record the value of the mass to be lifted in Table 3-2b.

Now you should be able to take your engine through another cycle and make the measurements of volume and pressure of the air needed to determine the  $p$ - $V$  diagram for your heat engine. You should take your data *rapidly* to minimize air leakage around the piston.

5. Begin with the flask and temperature sensor in the ice water, and without the mass on the handle of the syringe (state **a**). Stir the ice water. **Begin collecting** data. When the temperature and pressure seem to be fairly stable, **keep those data values**.
6. Read the volume of air in the syringe, enter it in Table 3-2a, calculate the total volume of air, and **enter this value** into the computer.
7. *Quickly* place the mass on top of the handle of the syringe (state **b**).
8. When the temperature and pressure seem to be fairly stable, **keep those data values**. Again, record the volume of air in the syringe in Table 3-2a, calculate the total volume of air, and **enter this value** into the computer.
9. Quickly move the flask and temperature sensor to the hot water reservoir (state **c**). When the temperature and pressure seem to be fairly stable, **keep those data values**. Again, record the volume of air in the syringe in Table 3-2a, calculate the total volume of air, and **enter this value** into the computer.
10. Quickly remove the mass (state **d**). When the temperature and pressure seem to be fairly stable, **keep those data values**. Again, record the volume of air in the syringe in Table 3-2a, calculate the total volume of air, and **enter this value** into the computer.
11. Finally, move the flask and temperature sensor back to the ice-water reservoir (state **a'**). Stir the ice water. When the temperature and pressure seem to be fairly stable, **keep those data values**. Again, record the volume of air in the syringe in the table, calculate the total volume of air, and **enter this value** into the computer.
12. Measure the height that the mass was raised. This can easily be done after all measurements by going back, looking at your volume data, and measuring the difference in positions of the piston from state **b** to state **c**. Record in Table 3-2b.
13. Read the temperatures of the two water reservoirs (states **a** and **c**) from the data table and record them in Table 3-2b.

**14. Print the graph and the data table.****Table 3-2b**

Mass to be lifted $\therefore m$ (g)	
Height mass was raised $y$ (m)	
Hot reservoir temperature $T_h$ (C°)	
Cold reservoir temperature $T_c$ (C°)	

**Question 3-8:** You expected that the transitions from **b**→**c** and from **d**→**a** were isobaric. According to your data, were they? Explain.

**Activity 3-3: Calculating the Work Done by the Heat Engine**

There are several ways to find the area of the cycle that gives the work done by the heat engine:

*Method I:* You can use the area function in the **Statistics  $\Sigma$**  menu in *Data Studio* to find the area under a line, but not the area contained by the cycle. By finding the area under various lines and doing some manipulation, you can find the enclosed area.

*Method II:* Because the pressure doesn't change (much) from point **b** to point **c**, you can take the average pressure of those two points as a constant pressure. 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 area and net thermodynamic work performed.

*Method III:* 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 cycle cuts through a box.

Find the work in joules (J) by one of these methods. Show all work below. Be sure that your units are correct. (Pressure will need to be in Pa and volume in  $\text{m}^3$ .)

If you use the computer method, you will need to be careful if the cycle did not close on itself. You should measure the work done in each part of the cycle (**a**→**b**, **b**→**c**, etc.) and combine these together.

1. Work done by heat engine. Show all calculations and describe which method you used below.

2. Use the equation  $W = mgy$  to calculate the useful mechanical work done in lifting the mass from one level to the other in joules (J).

**Question 3-9:** 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?)

If you have time, carry out Extension 3-4 to calculate the efficiency of your heat engine.

### Extension 3-4: Efficiency of the Mass-Lifting Heat Engine

The efficiency  $e$  of a heat engine is defined in the following way:

$$e = 100\% \left( \frac{W_{\text{out}}}{Q_{\text{in}}} \right) = 100\% \left( \frac{W}{Q_{\text{H}}} \right)$$

You have just found  $W$ . The heat energy input from the hot reservoir takes place in the process **b** → **c**. (Remember that **c** → **d** is an *adiabatic process with no heat energy transfer*.)

The heat energy transferred into a gas during an isobaric process in which the temperature changes by  $\Delta T$  is given by

$$Q = nC_P \Delta T$$

where  $n$  is the number of moles of gas and  $C_P$  is the molar heat capacity at constant pressure, which is 29.0 J/mol-K for air.

The most efficient possible heat engine operating with a hot reservoir at  $T_H$  and a cold reservoir at  $T_C$  is called a Carnot engine, after Sadi Carnot, the French engineer who studied engine efficiencies in the early nineteenth century. According to his theoretical calculations, the maximum possible, or Carnot, efficiency is given by

$$e_c = 100\% \left( 1 - \frac{T_C}{T_H} \right)$$

where both  $T_C$  and  $T_H$  are in K.

In the following activity you will determine the efficiency of your engine and of a Carnot engine operating between the same two reservoirs.

1. Calculate the number of moles of gas in your system. (**Hint:** Use the ideal gas law  $pV = nRT$  and your data for state **a**, with  $p$  in Pa,  $V$  in  $\text{m}^3$ , and  $T$  in K,  $R = 8.314 \text{ J/mol-K}$ .)
2. Calculate the heat energy transferred into the gas during the process **b**→**c**. (**Hint:** Use the equation above for  $Q$ , and the temperatures of the two reservoirs.)
3. Calculate the efficiency of the mass-lifting heat engine.
4. Calculate the efficiency of a Carnot engine operating with the same hot and cold reservoirs.

**Question E3-10:** Is the mass-lifting heat engine very efficient? What percentage of the input heat energy is converted to useful work? What percentage is lost as waste heat energy?

**Question E3-11:** How does the efficiency of the mass-lifting heat engine compare to the maximum possible efficiency (the Carnot efficiency)? Are you surprised by the answer?

**Comment:** Note that the incredible mass-lifting engine is actually 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-lifting 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 flask and the air 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-lifting engine does help us understand typical stages of operation of a real heat engine.