The Laws of Thermodynamics

There is no such thing as a free lunch.

Student Performance Objectives for this Unit

- Define a *thermodynamic system.*
- Differentiate between state and phase. Identify the state functions - temperature pressure, volume, and the number of moles of a gas. Reinforce the phase concepts of solids, liquids, and gases.
- Give two examples in which the internal energy of a system can be changed.
- State the First Law of Thermodynamics, give two examples in which the law is demonstrated, and represent the first law mathematically. Make sure that the student recognizes that the first law is a statement of conservation of energy.
- Define and give illustrated examples of each of the following thermodynamic processes: (a) isobaric, (b) isochoric, (c) isothermal, and (d adiabatic.
- Write First Law of Thermodynamics solutions for each of the following thermodynamic processes: (a) isobaric, (b) isochoric, (c) isothermal, and (d) adiabatic.
- Calculate the work done for each of the following thermodynamic processes: (a) isobaric, (b) isochoric, (c) isothermal, and (d) adiabatic.
- Explain the significance of a P-V diagram in describing (a) adiabatic, (b) isochoric, (c) isothermal, and (d) isobaric thermodynamic processes.
- State the Second Law of Thermodynamics.
- Define the Entropy of a system.
- Explain the operation and the limitations of the efficiency of a heat engine.
- Determine the efficiency of a heat engine in terms of heat input and heat output.
- Determine the efficiency of a heat engine in terms of input temperature and output temperature.
- Differentiate between Carnot Efficiency and actual efficiency as applied to heat engines.
- State the Third Law of Thermodynamics
- Experimentally determine the relationship between pressure and temperature.
- Experimentally determine the relationship between pressure and volume.
- Using a deck of cards, design and conduct an experiment showing the entropy of a system

Pacing Guide:
The First Law of Thermodynamics – days 1 and 2
Applications of the First Law –days 1 and 2
The Second Law of Thermodynamics – days 2 and 3
Heat Engines – days 3 and 4
Refrigerators, Air Conditioners, and Heat Pumps– day 3
Entropy and the Second Law of Thermodynamics– days 3 and 4
Disorder– days 3 and 4

Statistical Interpretation of Entropy – day 4
Each of the following labs may be completed in 1 period. They may be done on separate days or on the same day.

Labs – Charles' Law and Boyle's Law
Lab- Entropy lab may be performed in class or at home

Vocabulary

Thermodynamics
equations of state
systems
isolated system
open system
First Law of Thermodynamics
thermodynamic processes
internal energy
isothermal process
heat reservoir
PV-diagram and area under a curve
Adiabatic process
isobaric process
isochoric process (isometric)
isothermal process
Metabolism
Second Law of Thermodynamics
Engine operating temperatures
efficiency
Carnot engine
reversibility
irreversible
Kelvin-Planck Statement
Third Law of Thermodynamics
heat pump
entropy
order
disorder
heat death
microstates
macrostates
greenhouse effect

Charles' Law

Object: To determine the relationship between the pressure and the temperature of a confined amount of gas.

Apparatus: Charles' Law Apparatus, thermometer, bicycle tire pump, 2-liter beaker, water, ice, and rock salt.

Theory:

The ideal gas law equation is given by:

$$pV = nRT$$

where $\frac{nR}{V}$ is a constant for this experiment, and

$$\frac{P_1}{T_1} = k$$

$$\frac{P_2}{T_2} = k$$

then

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

Procedure:

1. Using the bicycle tire pump, trap gas in the metal bulb of the Charles' Law apparatus. Make sure the pressure is at least10 to 20 psi over atmospheric pressure. Record this reading and convert your pressure to absolute pressure in Pascals. Record this value.

2. Record the room temperature and convert the reading to absolute temperature in Kelvin.

3. The 2-liter beaker should be half-fill with water, crushed ice, and rock salt. Record the temperature. Submerge the bulb and wait for thermal equilibrium. Read and record the gauge pressure and temperature, Convert all values to absolute SI units. Why was rock salt added to the beaker in this step?

4. Fill the 2-liter beaker half way with water and and crushed ice. Repeat your measurements in the same manner as in the above step.

5. Increase the temperature of the water to 10C° and determine the pressure reading.

6. Continuing doing this by 10C° increments until you have taken at least eight readings of pressure and temperature. Do not exceed 85C°

7. Calculate the reciprocal of the pressure for each reading and record. What are your units for this calculation?

8. Plot graphs of P vs. T and $\frac{1}{P}$ vs. T.

Analysis:

1. Design the data sheet for this experiment.

2. Which of the graphs will give you a straight line? Why?

3. Interpret this graph by determining the slope of the line. Obtain the intercept of the graph and write its equation.

Questions:

1.What would occur if you started with a different initial pressure?

2.Would you get a different result if you had another type of gas in the container?

3. We make the assumption that the volume of the container and the trapped gas does not change in this experiment. How accurate is this assumption?

4. What other factors might attribute to your error in this experiment?

Boyle's Law

Object: To determine the relationship between the volume of a confined gas and the pressure exerted on it.

Apparatus: Boyle's Law apparatus – syringe form, masses, weight hanger, and a Vernier caliper.

Theory:

The ideal gas equation is given by:

$$pV = nRT$$

Since this experiment is an isothermal process the temperature of the system is constant. By trapping mass in the syringe, nRT will be a constant in this experiment. The volume of the gas will vary inversely with the absolute pressure.

Since

$$P_1V_1 = k$$

$$P_2V_2 = k$$

then

$$P_1V_1 = P_2V_2$$

Procedure:

1. Using the Vernier caliper, measure and record the diameter of the plunger of the syringe in cm. (If you need instruction in the use of the Vernier caliper, you should ask your instructor to aid you.) Convert your reading to SI units and record.

2. Calculate the area of the plunger in m^2 and record.

3. Record the atmospheric pressure in the room in Pascals.

4. Trap air in the syringe and record the initial volume of the confined gas.

5. Place a mass on the weight hanger. After the plunger has stopped descending, record the volume of the confined gas and the mass on the system. Remember to add the mass of the hanger to the total mass.

6. Repeat procedure 5 by adding an additional mass to the hanger. Again record the mass and the volume readings.

7. Continue adding masses to the system until you have obtained at least eight sets of readings of mass and the corresponding volume.

8. Calculate the force on the plunger for each reading. Calculate the gauge pressure and the absolute pressure for each reading. Record all values.

9. Calculate the reciprocal of the volume for each reading. What is the correct unit for $\frac{1}{V}$?

10. Calculate the product of PV for each reading. What is the unit for the product?

11. Plot graphs of V vs. P and $\frac{1}{V}$ vs. P

Analysis:

1. Design a data sheet for this experiment.

2. Which of the graphs will give you a straight line? Why?

3. Was the product of PV for each reading a constant? If not, why?

Questions:

1. Boyle's Law is an isothermal process. What happens to your readings if you handle the barrel of the syringe as you add the masses to the system?

2.What happens to your readings if you rushed through the experiment and did not let the system adjust?

3. If you were asked to determine the number of moles of gas trapped in the syringe, what additional step would you needed to do? What additional equipment, if any, would you need?

INQUIRY LAB

Given a deck of cards, design and conduct an experiment to show the entropy in a system.

RUBRIC

Student develops an appropriate scientific experiment in which they formulate their hypothesis, designs their experiment where they recognize the variables, manipulates the variables, interprets the data, and organizes this data in a accurate and logical manner.

5 Student designs an experiment (beginning with an ordered deck) in which they shuffle the cards and looks at the disorder after one shuffle. (Since disorder is hard to gauge, they must indicate their marker in the hypothesis.) Student continues to shuffle the deck and look for the disorder. Student will continue this a multi-number of times, recording their data in an appropriate table.

4 Student designs an experiment (beginning with an ordered deck) in which they drop the cards and look at the disorder after one drop. (Since disorder is hard to gauge, they must indicate their marker in the hypotheses. Student drops the cards a multi-number of times, recording their data in an appropriate table.

3 Student designs an experiment (beginning with an ordered deck) in which they deal the entire deck to a number of "players" and looks at the disorder after one deal. Student continues to deal a multi-number of times, recording their data in an appropriate table.

2 Student designs an experiment in which they turn cards over one at a time looking at black or red cards. Shuffling the deck after each complete deal. Student performs this a multi-number of times and records the data in an appropriate table.

1 Student designs an experiment in which they turn cards over one at a time and records their data in a table.

Student collects and summarizes their experimental data in an appropriate manner.

5 Student develops an appropriate data table, accurately and logically displaying the data gathered in the experiment, constructs and analyzes the data by way of a graph.

4 Student develops an appropriate data table, accurately and logically displaying the data gathered in the experiments, and constructs a graph.

3 Student develops an appropriate data table, accurately and logically displaying the data gathered in the experiment, but does not construct a graph.

2 Student data is displayed in a table, but not in an accurate or logical manner.

1 Student has obtained no appropriate data

Student communicates in a logical and concise manner.

5 Student analyzes the data, making conclusions that are supported by the data and explains the experimental design in a clear and logical manner.

4 Student analyzes the data, making conclusions not supported by the data, but explains the experimental design in a clear and logical manner.

3 Student analyzes the data, making conclusions not supported by the data.

2 Student analyzes the data, and makes no conclusions.

1 Student makes no conclusion.

Inquiry Lab

Using a deck of cards design and conduct an experiment to determine the entropy of a system.

Prentice Hall has a web page titled WWW.phschool.com. It is a site listing advanced placement material where you may download free lesson plans for various courses. The chapter focus lessons for:

Giancoli Physics: Principles with Applications, 5th Revised edition
2002 published by Prentice Hall

Wilson and Buffa: Physics, 4th edition
2000 published by Prentice Hall

These may be accessed from:

/WWW.phschool.com/advanced/lesson_plans/index.cfm

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Critical Thinking Questions and **End of Activity Questions** have been added to this unit plan from the web site to illustrate the availability of these types of activities

Critical Thinking Questions:

1. A special case of an adiabatic process is called the throttling process. An example of this is air trapped in a basketball escaping through a needle valve. Write the first law of thermodynamics for such a process. Can you find any another examples of this type of process? If so, do any involve a phase change?

2. A gas expands against a movable piston, lifting it 5.0 cm at constant speed. If the piston has a mass of 90.0 kg and a cross-section of 70 cm^2:
(a) How much work does the expanding gas do?
(b) If the process is adiabatic, what is the change in internal energy?
(c) Is ΔU an increase or decrease in the internal energy?

3. Exactly 5.00 g of water at 100°C is converted to steam at 1.0 atm of pressure.
(a) What thermal energy is added?
(b) What work is done in expansion?
(c) Find the change in the internal energy.
(d) What is the change in entropy?

4. One mole of an ideal gas at STP undergoes a series of steps in a cyclic process.
Step 1: The gas is heated at constant pressure until its volume triples.
Step 2: It is then heated at constant volume until the pressure doubles.
Step 3: It is compressed to its original volume.
Step 4: Finally, it is cooled until it reaches its original pressure.
(a) Graph P vs. V indicating the pressure, volume, and temperature at the end of each step.
(b) What is the net work done?
(c) What is the net heat into the system?
(d) What is the change in the internal energy?

5. Calculate ΔW and ΔU for a 1.00 L cube of aluminum as it is heated from 0°C to 320°C. The specific heat of aluminum is 920 J/kg C°, its coefficient of volumetric expansion is 7.2×10^{-5} 1/C°, and its mass is 2.70 kg.

End of Chapter Activity:

1. An adiabatic process is a process where
(a) no heat enters or leaves the system
(b) the temperature of the system is constant
(c) the pressure of the system is constant
(d) the volume of the system is constant
(e) the mass of the system is constant

2. The net work that is done by an engine undergoing adiabatic compression is

(a) ΔU (b) $-\Delta U$ (c) ΔQ (d) $-\Delta Q$ (e) $\Delta Q - \Delta U$

3. If the compression ration in a gasoline engine is 6 and the adiabatic constant is 1.4, then the efficiency of the engine is

(a) 27% (b) 45% (c) 51% (d) 54% (e) 57%

4. In order for a Carnot engine to operate at 100% efficiency, the exhaust temperature is

(a) 0° C (b) 0 K (c) 100 K
(d) infinite (e) equal to the input temperature

5. A heat engine absorbs heat at 600 K and expels heat at 200 K. The efficiency of the engine is

(a) 31% (b) 43% (c) 50% (d) 67% (e) 82%

6. The work done by an ideal gas can be found from a P vs. V graph as the
(a) slope of the curve at a given point
(b) area beneath the curve
(c) intercept of the P-axis
(d) intercept of the V-axis
(e) logarithm of the slope at a given point

7. The work done by a system is
(a) a variable dependent on the state of the system
(b) zero for a cyclic process
(c) equal to the heat added to the system
(d) dependent on the path taken by the process
(e) equal to the change of the internal energy in the system

8. When a total of 60.0 J of heat is added to a thermodynamic system that does 25.0 J of work, the net change in the internal energy of the system is

(a) +35 J (b) zero (c) –35 J (d) +85 J (e) –85 J

9. The First Law of Thermodynamics is a statement of the conservation of

(a) temperature (b) heat (c) energy
(d) work (e) reversibility

10. The amount of work that is done by a system during an isobaric process is

(a) $P\Delta V$ (b) $V\Delta P$ (c) zero (d) $-Q$ (e) $+Q$

answers: 1 (a), 2 (b), 3 (c), 4 (b), 5 (d), 6 (b), 7 (d), 8 (a), 9 (c), 10 (a)

Academic Standards for the Unit Lesson.

3.1.10. C
Apply pattern as repeated processes or recurring elements in science and technology

3.1.12.C
Assess and apply patterns in science and technology.

3.1.10.D
Apply and scale as a way of relating concepts and ideas to one another by some measure.

3.1.12.D
Analyze scale as a way of relating concepts and ideas to one another by some measure.

3.1.10.E
Describe patterns of change in nature, physical and man made systems.

3.1.12.E
Evaluate change in nature, physical systems and man made systems.

3.2.10.A
Apply knowledge and understanding about the nature of scientific and technological knowledge.

3.2.12.A
Evaluate the nature of scientific and technological knowledge.

3.2.10.B
Apply process knowledge and organize scientific and technological phenomena in varied ways

3.2.12.B
Evaluate experimental information for appropriateness and adherence to relevant science processes.

3.2.10.C
Apply the elements of scientific inquiry to solve problems.

3.2.12.C
Apply the elements of scientific inquiry to solve multi-step problems.

3.2.12.D
Analyze and use the technological design process to solve problems.

3.4.10.A
Explain concepts about the structure and properties of matter.

3.4.12.A
Apply concepts about the structure and properties of matter.

3.4.10.B
Analyze energy sources and transfers of heat.

3.4.12.B
Apply and analyze energy sources and conversions and their relationships to heat and temperature.

3.4.10.C
Distinguish among the principles of force and motion.

3.4.12.C
Apply the principles of force and motion.

3.7.10.A
Identify and safely use a variety of tools, basic machines, materials and techniques to solve problems and answer questions.

3.7.12.A
Apply advanced tools, materials and techniques to answer complex questions.

3.7.10.B
Apply appropriate instruments and apparatus to examine a variety of objects and processes.

3.7.12.B
Evaluate appropriate instruments and apparatus to accurately measure materials and processes.

First Law of Thermodynamics

$$\Delta Q = \Delta W + \Delta U$$

Work done in an adiabatic process $(\Delta Q = 0)$

$$W = \frac{P_1V_1 - P_2V_2}{1-\gamma}$$

Work done in an isothermal process $(\Delta U = 0)$

$$W = nRT\ln\frac{V_2}{V_1}$$

Work done in an isobaric process

$$W = p\Delta V$$

Work done in an isochoric (isometric) process

$$W = 0 \text{ since } \Delta V = 0$$