

Heat transfer and the Greenhouse Effect

Only a short report is required: worksheets, graphs and answers to the questions.

Introduction

In this experiment we study the mechanisms by which heat is transferred, and the greenhouse effect. The data for the greenhouse effect experiment is taken by computer using the Data Studio interface. This part of the experiment can run unattended for periods of 20 to 60 minutes while you perform 5 other simple experiments concerning heat transfer and other thermal phenomena. You will have to use your time efficiently in order to complete the experiments during the lab period. Each group will move through different stations to carry out different experiments.

Heat Transfer

Heat, or thermal energy, can be transmitted by three mechanisms, *convection*, *conduction*, and *radiation*. We will discuss each briefly before discussing the greenhouse effect and the other experiments to be done.

Convection

In *convection*, heat is transferred by the **macroscopic movement** of heated mass inside a body of fluid (gas or liquid). Solids are rigid and so they do not support convection. A fan (or pump) in a household furnace moves heated air (or water) from the furnace to cooler locations in the house. This is called *forced convection*. On the other hand, we can rely on the fact that air and water become less dense when heated, and rise. If we place a hot brick in a room, the air near the brick becomes warm, and rises, carrying heat from the brick to the space above. This is *natural convection*.

Conduction

Heat transfer by *conduction* is due to **molecular vibrations** and, in metals, the motion of electrons. Neighboring particles exchange kinetic energy continuously. Energy is transferred from one part of the material to another whenever there is a difference in temperature. No movement of mass is involved. Solids, liquids and gases all support thermal conduction, but the low density of gases make conduction typically much less important than convection. In all fluids, the relative importance of convection versus conduction depends on the driving force for flow. A large temperature difference would lead to a large density difference between hot and cold regions, and thus a large buoyant force to drive natural convection. Poor heat conductors are used for thermal insulation, and they are typically also poor electrical conductors. Do you know which material has the best thermal conductivity?

Radiation

Energy can also be transferred by the *radiation* of electromagnetic waves that have no mass and can travel through vacuum. EM waves can have any frequency f with the quantum (smallest parcel) of energy transferred being hf , where h is the Planck constant. This implies that since X-

rays have higher frequencies than visible light, the quanta of x-rays have more energy and we would predict they can do more damage to the cells in our bodies.

Every object emits a spectrum of EM waves. The intensity is greatest at a frequency f_{\max} that is proportional to the absolute temperature T (Wein's law). For an ideal "black body", it can be shown that $hf_{\max} \approx 5k_B T$, where k_B is the Boltzmann constant. The radiated power of an ideal blackbody is proportional to the 4th power of the absolute temperature (Stefan's law). Increasing the *absolute* temperature of an object from 300 K to 357 K (27°C to 84°C) doubles the radiated power, because $2^{1/4} = 1.189$ and $300 \times 1.189 = 357$.

The sun is at such a high temperature that it radiates most strongly with visible light. The sun's light has to travel 150 000 km through space (which is a near perfect vacuum) to reach earth. Upon reaching the earth's atmosphere, this light can be reflected, absorbed or transmitted to the earth's surface. At the earth's surface, the light is either absorbed or reflected. Since *all* bodies radiate, the earth will radiate as well, but mostly strongly in the infrared (wavelength > 1000nm) because of its lower temperature (300 K) compared to the sun (6000 K). Materials such as glass or the gases in the atmosphere, may be transparent to visible light yet opaque to infrared, or vice-versa.

Another term we often see is *albedo*. Radiation incident on a surface, is either reflected, transmitted, or absorbed. The fraction which is reflected (diffusely or specularly) is called the albedo. The albedo of shiny aluminum foil is 95%. An ideal *black body* absorbs 100%, so the albedo is zero.

The Greenhouse Effect

Every object receives energy from its surroundings by all three mechanisms, and simultaneously loses energy to its surroundings the same way. If the rate of energy loss is equal to the rate received, the object will stay at the same temperature, i.e., in thermal equilibrium with the surroundings. Otherwise it will heat up or cool down. Since the rate of heat transfer depends on temperature and many other parameters, predicting the steady-state temperature is a complex problem. Further, the environment is always changing, so the temperature of everything in nature is constantly changing, it is just a question of how quickly.

A simple garden plot receives energy radiated from the surroundings on earth and from the sun. The garden loses energy primarily by natural convection, and some by radiation. The balance between the incoming and outgoing energy determines the rate of temperature change. If the environment stayed the same long enough, the garden would reach a steady state temperature. Covering the garden with a greenhouse greatly reduces the convective heat loss, resulting in a new energy balance at a significantly higher temperature. The glass roof of the greenhouse lets in the radiated energy from the sun (visible light), but it reflects the infrared radiation emitted from the plants and soil back into the greenhouse. The glass also prevents heat loss by convection. The temperature in a green house is controlled by painting some roof panels white to reduce the incident sunlight, and by opening roof panels to let some of the warm air out, allowing some convective cooling.

Some of the energy received from the sun by radiation is absorbed by the earth's atmosphere, some is transmitted to the earth's surface. The heated atmosphere also radiates energy, some toward the earth. The earth emits thermal radiation as well, and some of it is absorbed in the atmosphere, which radiates both inward and outward. Thus the atmosphere plays the role of a blanket that wraps around the earth to reduce the heat loss and keeps it warm. There are also internal sources of heat within the earth, such as natural radioactivity and geothermal sources. Again, the heat balance determines the steady state temperature. Without the atmosphere the earth would be 30 to 35°C cooler, and life here would be very different. This is called the **greenhouse effect** because the earth would be much cooler without the atmosphere, just as the greenhouse would be much cooler without its roof. However, the physical effects involved are quite different.

The environmental concerns about "**greenhouse gases**" relate to the fact that the degree to which the atmosphere absorbs and transmits radiation of a particular wavelength depends upon its chemical composition. The addition to the atmosphere of gases which change the absorption and transmission of the radiation incident from the sun and earth would most likely change the heat balance, and hence the steady-state temperature of the earth. Water vapor, carbon dioxide and fluorocarbon molecules have strong molecular vibrational modes with natural frequencies in the infrared region. There is evidence that the rapid release of these molecules into the atmosphere over the last century is causing the average temperature of the earth to rise.

The Greenhouse Experiment

Note : while the computer is collecting this data you should do the Heat Circus experiments.

- Log onto the computer using the name and password posted above the monitor screen. Double-click on the Data Studio icon to start the application. Use the File menu in Data Studio to open the **Greenhouse.ds** activity file. (Look in **C:\student temp\p289**)
- The sun is represented by a projector lamp, and the Earth by a metal disc. A timer turns the "sun" on and off. Mount **either** the black or the white disc on the holder, and bring the temperature probe into contact with the disc. Use a small dab of the heat-conducting grease to assure good thermal contact between the temperature probe and the disc.
- Measure the distance from the projector lamp to the disc, and keep this constant for the remainder of the experiment.
- Start recording in Data Studio. Set the data rate to about 1 point every 2 seconds. After 30 seconds you will have enough points to determine the steady-state temperature of the disc. Set the lamp timer for 10 minutes, and turn the timer on. The computer should now be collecting the heating curve. Choose a suitable scale for the time axis to see all the data while they are being recorded. After 10 minutes the lamp will turn off, and the computer will record the cooling curve. Terminate this after 10 minutes. Save your Data Studio activity file with a unique name. **DO NOT REPLACE or DELETE THIS DATA; later you will need to plot this curve along with others.**

- Repeat the above for the *other* disc. Again, record data for 10 minutes with the “sun” on and 10 minutes off. **DO NOT REPLACE the PREVIOUS DATA.** When this is complete, save the file again. Display the two curves on a single graph. Observe the similarities and differences between the black and white discs.
- Now, **change to the disc initially used** (so that you start at room temperature). Cover the disc with a plastic bag. Make a small hole in the bag for the temperature probe. Record the data as before, but with the timer set for 20 to 30 minutes, and 20 to 30 minutes of cooling (depending on the time remaining in the lab period).
DO NOT REPLACE the PREVIOUS DATA.
 - Display all three heating and cooling curves on one graph, print it, and submit it with your lab worksheet.

On your lab worksheet:

- For the two uncovered discs (black and white), compare the temperature ranges and the rates of heating and cooling. Discuss and explain your observations.
- Look at the heating and cooling curves for the covered disc, and for the same disc uncovered. Compare the temperature ranges, and the rates of heating and cooling.
- If possible, look at the curves for the other covered disc from another lab groups, and make the same comparisons
- How do your observations and data relate to greenhouses, and the greenhouse effect?

Heat Circus

The following observations should be made, in any order, while the computer is collecting data. **There are some very hot surfaces. Use caution and avoid burns.**

A. **Boiling Water - Conduction versus Convection**

Heat some water in a large test tube over a bunsen burner. The stand holds the test tube ~30° from **vertical**. Fill the tube ~2/3 full with cold water, and clamp it at the top. Carefully add a crystal of potassium permanganate dye to help see the convection currents in the water. Do **not** stir the water to make the color uniform.

Do this twice, starting each time with cold water and new dye.:

1. First apply the heat near the bottom of the test tube. Observe what happens in the test tube. How long can you hold your fingers near the water level at the **top** of the tube?
 2. This time apply the heat just below the water surface. Observe what happens in the test tube. How long can you hold your fingers on the **bottom** of the test tube?
- Compare conduction and convection as heat transfer mechanisms.

B. **Conductors and Insulators**

Short rods of various materials (aluminum, copper, glass, and iron) are held in an aluminum block heated to a uniform temperature. Note the variations in the temperature of the ends of the rods. Your finger tips make a reasonable sensor, and the time required to feel significant heat is a rough measure of thermal conductivity. If the end feels cold, work your way down the rod toward the aluminum base block.

- Rank the materials from the best conductor of heat to the worst.

To rank the thermal conductivities of these materials you can also use the Data Studio activity called “Conductors_and_Insulators”. This measures the temperatures at the tops of the rods. By turning the heater on/off, and/or touching the tops of the rods near the temperature sensors, use your observations to rank the materials from the best conductor to worst conductor.

C. Radiation Reflection

An electric heater is placed at the focal point of one parabolic reflector. At the other end of the lab bench there is a second parabolic reflector. Move your finger along the axis of the reflectors to determine the focal point of the second reflector. Try to block as little of the radiation as possible as you do this, and be careful - the focal point is surprisingly hot. Next, move the radiometer along the axis of the reflectors to find the focal point. How does the radiometer work? How can you tell when the light intensity is greatest? Finally, see if you can light a match by using the stand to position it at the focal point.

- Find the focal point of the second reflector. The heat intensity there may be large enough to ignite a match in about a minute.

D. Radiation Transmission

An electric heater is behind a hole in a sheet of insulating material. Hold your cheek or the back of your hand in front of the hole and feel the heat. Have your lab partner insert the insulating tile between you and the heater. Repeat with other materials (glass, plexiglass, and mica).

- Record your observations about the transmission of thermal radiation and visible light through these materials. Does the passage/blockage of visible light through the material necessarily imply that heat (thermal radiation) passes or is blocked through it? Explain.

E. Radiation Absorption

Here we investigate how the amount of radiation absorbed by an object is affected its surface qualities. An electric heater is behind a hole in a sheet of insulating material. Hold the back of your hand in front of the hole and feel the heat. Repeat with a piece of aluminum foil on the back of your hand. Moisten the back of your hand in order for the foil to stick to it. The foil has a bright side and a dull side. Try flipping the foil over and see if you feel a difference. Repeat the test with a wrinkled aluminum foil with one side blackened. Again, compare the difference with either side facing the hole.

- Record your observations about the absorption of thermal radiation. Is there an effect due to surface roughness? Which absorbs more – a dull surface or bright surface? Are the effects significant (*i.e.* easily observed)?

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NAME _____ DATE _____

LAB PARTNER _____ Lab Sec. _____
1 Wed. 2:30
2 Thu 12:10**Heat Circus**

This lab involves many hot surfaces and the potential to burn yourself. Please be careful !

A. Boiling Water - Conduction versus Convection

1. (heating from the bottom)

2. (heating near the top of the water)

B. Conductors and insulators Rank in order from the best (1) to worst (4) heat conductor.

aluminum copper iron glass

Look up the thermal conductivities of these materials online or in a reference book such as the CRC Handbook of Chemistry and Physics. List the values below. Are the values in agreement with your sensations?

C. Radiation Reflection

Record your observations about the reflection of thermal radiation.

Explain the principle behind the radiometer.

D. Radiation Transmission

Record your observations about the transmission of thermal radiation and of visible light through the materials supplied.

Visible Light

Thermal Radiation (Heat)

Glass

Insulating Tile

Mica

Plexiglass

Are there situations in which your hand does not feel the heat but visible light is passed? What about the converse? How can this be?

E. Radiation Absorption

Record your observations about how the absorption of thermal radiation is dependent on surface properties such as dullness, shininess, and color.

The Greenhouse Experiment

1. Attach the three heating and cooling curves.
2. Discuss and *explain* the temperature ranges and the rates of heating and cooling for:
 - Uncovered white vs. uncovered black disc.
 - Covered disc vs. uncovered disc.

Try to justify your explanations using observations you have made in the “Heat Circus” part of the lab if you can. (To help organize your thoughts, you may want to discuss how each of the three heat transfer mechanisms is affected by the different conditions)

3. Use your observations to explain the principles behind the greenhouse effect. Specifically, use your observations from the “Heat Circus” labs and questions 1 and 2 above to discuss how the heat transfer mechanisms and steady-state temperature of the earth are affected by the atmosphere and by surface conditions.