B2 Greenhouse effect in a drinking cup – A model for illustrating climate change

This very simple experiment can be used to teach students to readily recognize and differentiate the physical phenomena underlying the greenhouse effect, such as radiation, reflection, absorption, and heat radiation. The students will need some prior knowledge to be able to interpret the results of the experiment. For this reason, the experiment can be used in two ways: Either as verification of material learned after an introduction of the topics mentioned above, or as an introduction to the greenhouse effect, a hot topic in the news, with further study of the physical principles afterwards. The materials and apparatus supplied for this experiment allow eight groups of students to work simultaneously.

1 Main question

Climate change caused by the greenhouse effect is the subject of national political discussions as well as of international conferences and agreements. The scientific questions are: How is the typical heating effect produced in a greenhouse? And to what extent can this be transferred to the greenhouse effect in the Earth's atmosphere? These questions will of course be highly interesting to the students as teaching based on real-world issues. We will investigate these questions by means of subexperiments using a simple cup made of plastic (polypropylene, PP for short).

- Subexperiment 1:
  Measurements in an open cup
- Subexperiment 2:
  Measurements in a closed cup
- Subexperiment 3:
  Measurements in a closed cup with a black absorber
- Subexperiment 4:
  Measurements in a closed cup with an aluminum foil absorber

Fig. 1: A simple model of a greenhouse: A cup made of transparent plastic (polypropylene), sealed with a cover, and black paper as the absorber.

2 Integrating the experiment into the teaching context

2.1 Basic principles

The students' perception that "the surface of the cup insulates the heat or temperature" is insufficient for explaining all the phenomena of the experiment. Above all, it is insufficient for explaining the effects of climate change from a greenhouse effect.
The students should have prior knowledge of the terms conservation of energy, radiation, reflection and absorption of radiation, and of the three forms of heat transfer (heat conduction/heat convection/heat radiation). To clarify the phenomena, it is crucial to take the differentiated approach to our experiments with respect to these aspects. If all of the students do not yet have this prior knowledge, teachers can of course use the experiment as an introduction to these topics.

2.2 Relevance to the curriculum

For students aged 14 to 15 years, the following task is part of the biology curriculum related to the environment: “Based on selected examples, describe and evaluate the impacts of human intervention in the environment.” The relevant topics in geography class are the various aspects of climate change (global connections; natural and anthropogenic climate changes and their consequences, e.g., through the greenhouse effect, hole in the ozone layer; measures to protect the atmosphere, e.g., climate conferences). In physics, the topics are heat transfer, heat conduction, convection, and heat radiation (emission, reflection, absorption).
For students aged 15 to 16 years, the topics “Greenhouse effect: its significance in nature, everyday life, and technology”, “Oil, natural gas, and coal: suppliers of basic raw materials and energy”, “Carbon cycle and greenhouse effect“, as well as “Alternative sources of raw materials and energy” are part of the physics and/or chemistry curriculum.

Topics and terms: absorption, climate change, climate conference, color temperature, conservation of energy, convection, earth’s atmosphere, emission, global rise in temperature, greenhouse effect, greenhouse gases, heat conduction, heat convection, heat radiation, heating effect, hole in the ozone layer, radiant energy, radiation equilibrium, reflection, sunlight

2.3 Skills

The students will ...

- recognize through observation that the temperature inside an insulated cup will rise when light shines on it, and learn the role of various heat transfer mechanisms: emission, absorption and reflection of heat radiation, as well as heat conduction and convection.
- work out the theory behind the principles of the greenhouse effect.
- investigate on a practical basis the influence that modifications to the experiment setup have on knowledge acquisition.
- independently design the experiment setup such that they will obtain answers to their questions.

2.4 Explaining the experiment in the teaching context

2.4.1 Qualitative approach

In the experiment, radiant energy in the form of light is transferred into the climate cup and stored there by the gas and any absorption materials present. In our experiment setup without absorbers, a relatively high amount of the light passes unabsorbed through the cup. The amount that is absorbed and stored greatly depends on the absorber used in subsequent subexperiments. The temperature rises until equilibrium is reached between energy input and energy output (through heat transfer, convection, and emission).
Convection from the cup into the environment can be completely prevented in our experiment by using a seal. The students will then observe a higher temperature inside the cup.

2.4.2 More detailed explanation of the phenomena

In the experiment, energy is introduced into the climate cup in the form of radiation, but energy output through radiation is “restricted”. How is this so? It’s easiest to understand this if the process is observed in several stages.

Short-wave irradiation: Sunlight shines at a temperature (= color temperature; see Planck’s radiation curve) of up to 6,000 K, a halogen light bulb at a temperature of up to 3,400 K. Compared with far infrared, these two sources of light mainly correspond to ultra-short-wave radiation of approx. 250 nm to approx. 1,000 nm (thus UV light, visible light, and near infrared). Almost 100 percent of this short-wave radiation goes through the sides of the plastic cup without being absorbed. This is similar for the Earth's atmosphere, which allows nearly two-thirds of the irradiated sunlight to pass through (approx. one-third is reflected).

Absorption: If material such as black paper is in the cup, it will absorb nearly 100 percent of the short-wave light and will warm up as a result. The same is true for the Earth’s surface.

Long-wave emission: The absorption material is warmed up to approx. 310 K. It then partly emits heat into the air inside the cup through collisions of its smallest particles, and partly emits absorbed radiation. Due to the low temperature, the spectrum of emission of the heated air and the absorber covers only wavelengths of several µm in the long-wave infrared range. When the Earth’s surface is heated up, it also emits its warmth primarily through radiation. A good amount, however, is dissipated through so-called convection. This means that air and water vapor heated up by the Earth’s warm surface rise and transport heat away. We experience this effect in our cup, which is why the inside of the cup becomes warmer when the cup is covered.

Reflection and absorption by the cup’s surface: The long-wave radiation is partially reflected, partially absorbed by the cup’s surface. The surface is heated up through this absorption, and it radiates part of the energy back into the inside of the cup and part into the environment outside of the cup. As a result of direct reflection on the cup surface and emission of the heated cup surface, the emission of energy is halted and the inside of the cup remains warmer than the environment. Thus, the inside of our cup cannot emit radiant energy directly to the environment, because only a small part of this energy can penetrate the cup’s surface. The same effect occurs with the Earth’s surface: Part of the energy radiated from the Earth’s surface is absorbed in the clouds and the gas particles in the air. And these clouds and particles radiate only part of the energy into space and the rest back to the Earth again. This reflection significantly helps to increase the Earth’s temperature. And it is even stronger if proportionately more gases that absorb radiation in the long-wave range, such as CO_2, are present in the atmosphere. However, we must note that in our experiment setup, a considerable amount of heat is lost not through radiation, but through convection inside on the cup’s surface and through direct heat conduction through the cup’s surface.

But aspects other than the global rise in temperature caused by greenhouse gases can also be addressed. Our experiment also provides insight into practical applications of the greenhouse effect, such as greenhouses and energy-saving houses. Another phenomenon that students have probably experienced is that the inside of a car can get very hot in the sun, even in the winter when the temperature is below freezing.

Important note: In the experiment with the curved aluminum foil, the aluminum does not absorb the light, but reflects it. You can expect this to result in a lower rise in temperature than the experiment with the black paper. But there is also an opposite effect: Depending on the light source and the distance from it, and depending on the curvature of the aluminum foil, the foil can also work like a parabolic trough mirror and concentrate the light onto the probe. The temperature will rise greatly as a result. (In this case, teachers can point out specially designed solar collectors.) From a didactic standpoint, it is not a problem that this experiment does not always lead to the same result. This would be a good occasion to discuss with the students the conditions under which laws of nature are clearly recognizable.

2.5 Experimental variations

- The subexperiments work best in bright sunlight.
  (The sky should be relatively free of clouds.)
- On days with little sunshine, teachers should have the students use suitable, bright light sources. Measurements with a 20-watt halogen reflector bulb (at a distance of approx. 10 cm from the cup) at a room temperature of 21°C yielded the following results after approx. 8 minutes: open cup without black paper, 25.3°C; closed cup without black paper, 27.3°C; and closed cup with black paper, 30.7°C. Fluorescent tubes are unsuitable due to their wide area of emission.
- Normal, 60-watt incandescent lamps have lower radiation power by about a factor of 20 compared with sunlight. If the distance from the incandescent bulb is then half a meter, the students must take very precise measurements to even qualitatively recognize the temperature effects of the respective subexperiment. Furthermore, it will take longer (up to approx. 30 minutes) for each subexperiment until the temperature has stopped changing.
- Teachers can have the students conduct individual subexperiments in different groups and the present the results to the class. In this case, it should be pointed out to the students that they should conduct the subexperiments under the same conditions, as far as possible (shade, draft, same duration of the experiment, etc.).
- Or the teachers can let the students conduct the various subexperiments in succession. In this case, it's also important to point out the need to conduct the subexperiments under the same conditions.

3 Additional information on the experiment

You will find additional media for preparing or for further study of this experiment on the Siemens Stiftung Media Portal:
https://medienportal.siemens-stiftung.org

4 Notes on conducting the subexperiments

4.1 Facilities

Bright, direct sunlight is recommended for the subexperiments (in both summer and winter). The experiment can be conducted either outside (but the students should still prepare the experiments in the classroom so that they have the material ready) or in rooms where the sun shines in brightly (on the windowsill or on desks by the window).

4.2 Time required

<table>
<tr><th></th><th>Preparation</th><th>Measurement</th><th>Analysis</th><th>Discussion</th></tr>
<tr><td>Preparation</td><td>5 min.</td><td>5 min.</td><td rowspan="5">10 min. together</td><td rowspan="5">Can take place during the next class session; teacher may have individual students present their results as a report.</td></tr>
<tr><td>Subexperiment 1</td><td>5 min.</td><td>5 min.</td></tr>
<tr><td>Subexperiment 2</td><td>5 min.</td><td>5 min.</td></tr>
<tr><td>Subexperiment 3</td><td>5 min.</td><td>5 min.</td></tr>
<tr><td>Subexperiment 4</td><td>5 min.</td><td>10 min.</td></tr>
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If artificial light is used, the individual measurements will each take approx. 15 minutes.

4.3 Safety aspects

The students may conduct the experiments only in the presence and under the supervision of the teacher.
The teacher is to point out to the students that the provided materials may be used only according to the respective instructions.

4.4 Apparatus and materials

Required materials that are not supplied:

- If bright, direct sunlight is not available, a highly focused source of light, e.g., at least a 20-watt halogen reflector lamp.
- A ruler (optional), to measure the distance from the lamp.
- Clock

Supplied:
Enough apparatus and materials are supplied to allow **eight** groups of students to conduct the experiments simultaneously.
The following materials included in the kit are needed for **one** group of students:

Material	Quantity
Aluminum foil, roll*	1x
Coaster	1x
Digital thermometer**	1x
Nail (steel, “iron”)	1x
Paper, black, DIN A4*	1x for entire class
Plastic cup (clear), 500 ml	1x
Scissors	1x
Test tube clamp, wooden	1x

*The cut-out black paper and the cut-out aluminum foil should be saved. They can be used repeatedly for the experiment.
**Remove the plastic sleeve before the first use. Press the “on/off” button to turn on the thermometer. After completing the experiment, turn off the thermometer again (press “on/off” again). Press the “°C/°F” button to switch between the Celsius and Fahrenheit temperature scales.

Fig. 2: Apparatus and materials supplied for one group of students.

4.5 Cleanup, disposal, and recycling

All apparatus and nearly all materials from the kit can be reused. Therefore, after the students have completed the respective experiment, they should put the apparatus and materials back in the appropriate boxes and return them to the kit. This practice will ensure that you and your colleagues will find everything again quickly the next time the kit is used.
Apparatus that become dirty during the experiment, such as cups, bowls, spoons, and test tubes, should be cleaned before being returned to the kit. We recommend that you have the students do this immediately after they have completed the experiment.
Also make sure that the apparatus are in working order for the next time. For example, recharge used accumulators immediately. (It makes sense to charge the accumulators even if they will not be used for an extended period.)
Materials that cannot be reused, such as used pH test strips and filter paper, should be disposed of properly.
The waste that accumulates during this experiment can be disposed of in the regular trash or poured down the sink.