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Benchtop Global-Warming Demonstrations Do Not Exemplify the Atmospheric Greenhouse Effect, but Alternatives Are Available

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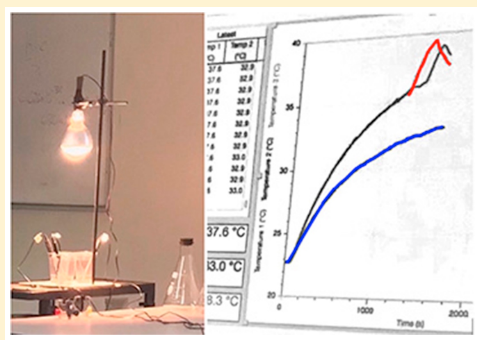
ABSTRACT: The atmospheric greenhouse effect is a topic in many science courses. A number of lecture demonstrations with carbon dioxide purport to show how infrared-absorbing atmospheric gases "trap" energy. The demonstration described here shows that the temperature change observed in these demonstrations is a consequence of the density of carbon dioxide relative to air, not its infrared-absorbing property. Since the pedagogical value instructors report for the usual demonstration is based on an incorrect interpretation of the temperature change and can lead to a misconception about global warming, suggestions are made for possible replacement demonstrations.



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The mechanism of the atmospheric greenhouse effect, including the properties of greenhouse gases like carbon dioxide, is fundamental to understanding global warming. Articles in this *Journal* are among the sources of demonstrations (and student experiments) that purport to provide concrete examples of the global-warming atmospheric greenhouse effect.[1−3] The demonstrations are variants of the setup shown in Figure 1. A bright light (representing the sun) shines down on one or more containers (miniature planets) that have light-absorbing bottom surfaces and temperature sensors to monitor the temperature at the surface. With the light on to warm the surfaces, carbon dioxide is substituted for air in one container, and its temperature is observed to increase. The warming is assumed to be caused by infrared (IR) radiation energy being absorbed by the vibrational motions of carbon dioxide molecules and transferred by collisions to their neighbors. Further, this assumed trapping of IR radiation energy (and increase in temperature) is generally then equated to how IR radiation from the Earth directly causes atmospheric warming. These inferences, drawn from the demonstration results, are incorrect; it is best not to use these demonstrations.

■ THE DEMONSTRATION FLAW

Several years ago, in the physics education literature, Wagoner et al.[4] and Berto et al.[5] reported comparisons of the demonstration results with either carbon dioxide or argon substituted for air. They observed that both IR-absorbing carbon dioxide (molar mass, 44 g) and non-IR-absorbing argon (molar mass, 40 g) produce nearly the same temperature increases. The warming effect has little to do with IR radiation but is mainly due to the denser gas in the container preventing convective exchange with the surrounding air. Without convective exchange, energy from the "sun-warmed" surface is less efficiently lost to the surroundings, so the surface and trapped gas get warmer. An online alert[6] to these results has appeared, but the chemical education community appears to be unaware of this.

Those studies were done under laboratory conditions, with a more sophisticated apparatus than is usually used in a benchtop lecture demonstration. It seems appropriate to bring them to the attention of chemists as an actual classroom demonstration. The demonstration was done in Wisconsin Initiative for Science Literacy[7] climate science workshops for teachers, using the setup in Figure 1. A 128 W flood lamp illuminated the three plastic cups, each with two steel washers at the bottom and a temperature probe in the well formed by the washer holes. Carbon dioxide and argon, from commercial cylinders, were collected in flasks (not shown) by downward displacement of water. The probes were connected to a laptop computer, and output from the software (probe temperatures as a function of time) was projected for the participants to follow in real time.

Figure 2 is a plot of the digital data from the software. The placement of the cups was not perfect (one warmed more slowly), but this is irrelevant when looking only for a directional effect. Carbon dioxide was poured from its flask into one of the cups at about 1200 s (blue curve) and argon into a second cup at about 1400 s (green curve). Air in the third cup (red curve) is left undisturbed. Both added gases cause the same effect, warming of the cup contents until the

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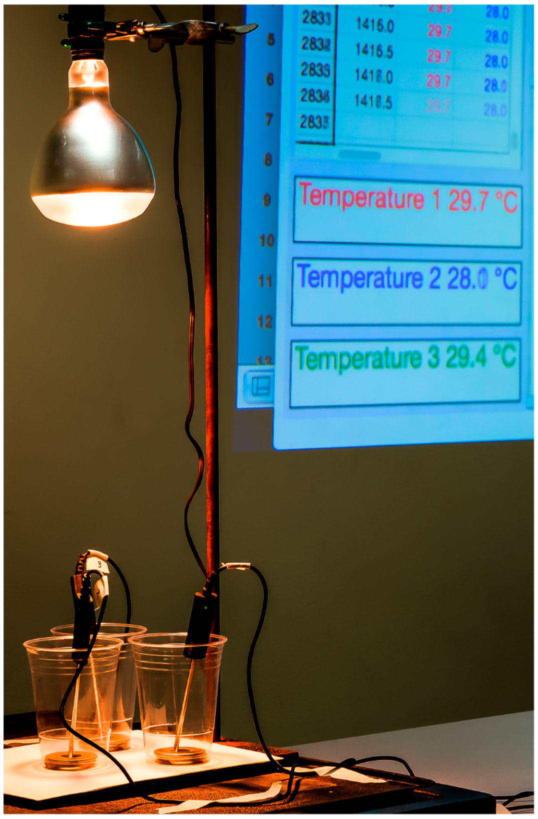

Figure 1. Setup for the demonstration.

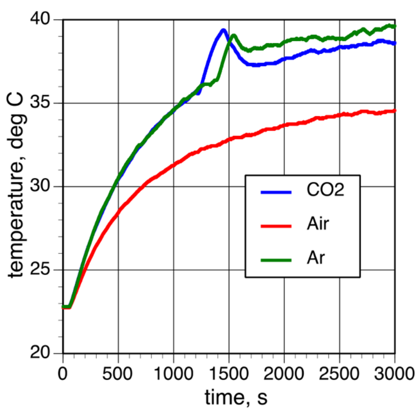

Figure 2. Time course of the probe temperatures. The temperature record begins at time zero, shortly before the irradiating lamp is turned on. Carbon dioxide is added to one of the cups at about 1200 s (blue curve) and argon to a second cup at about 1400 s (green curve). Air in the third cup (red curve) is left undisturbed. Temperatures are digital data (two points per second) from the software application.

gas diffuses out and the temperature begins to fall. (After the argon was gone, its cup was jarred and changed position relative to the light source.)

An IR-absorbing gas is not necessary to cause the warming effect in this demonstration. As in the more elaborate studies, the denser gases prevent convection from outside the cup and are responsible for "trapping" energy within it. The warming effect in the common demonstration, with only carbon dioxide compared to air, has generally been taken as (indirect) evidence for the IR-absorbing property of carbon dioxide. Since IR absorption is, at best, a minor factor in these demonstrations, students are misled by this interpretation, which suggests these demonstrations should not be used.

However, the IR-absorbing property of carbon dioxide is a vital concept for understanding climate science, so a concrete classroom demonstration is useful. An elegantly simple, direct observation of the absorption is possible.[8] The experiment or demonstration requires a laboratory hot plate, an inexpensive infrared thermometer, an empty clear plastic bag, another filled with carbon dioxide and a third filled with air or nitrogen. The objective is to show that, when carbon dioxide is in its path, less energy reaches the thermometer from the hot plate. The effect is modest and reinforces the fact that carbon dioxide absorbs only the few IR wavelengths that can interact with the molecule's vibrational motions.

■ EARTH'S TEMPERATURE AND THE ATMOSPHERIC GREENHOUSE EFFECT

The average temperature of the Earth is determined by a balance between the absorbed incoming energy in sunlight and the outgoing energy from the warmed surface radiated into space. The incoming energy from the high temperature sun is mainly visible light that is not absorbed by atmospheric gases. The outgoing radiation from the cooler surface of the Earth is longer wavelength IR light, which is also not absorbed by the major atmospheric gases, nitrogen, oxygen, and argon. If this was the end of the story, Earth's average temperature would be about 255 K (−18 °C), a frozen planet incapable of life.[9]

The atmospheric greenhouse effect, which maintains the Earth's surface at a temperature suitable for life (as we know it), depends on the presence of trace amounts of IR-absorbing gases (greenhouse gases) in the atmosphere.[9] These gases include carbon dioxide, water vapor, methane, nitrous oxide, ozone, etc., whose vibrations absorb IR wavelengths. The atmospheric greenhouse effect controls the amount of energy that escapes to space from the top of the atmosphere. If the amount of energy that escapes is less than the amount incoming from the sun, the Earth warms until the surface emission increases enough to produce more outgoing energy to keep the planet in energy balance.

To understand the role of a greenhouse gas like carbon dioxide, consider a thin layer of the troposphere (atmosphere closest to the surface). Its temperature is related to its altitude and decreases with altitude. Collisions keep the trace of carbon dioxide in the layer in thermal equilibrium with the surrounding vast bath of air molecules. Photons of IR energy can be absorbed by the carbon dioxide vibrations and energy transferred by collisions to the surrounding molecules, increasing their kinetic energy. In order to maintain thermal equilibrium, photons with an equal amount of IR energy are emitted from carbon dioxide molecules in the energetic end of the Boltzmann distribution. The emission is in all directions, so we might characterize this as about half in a direction toward space and half toward the surface. This process of IR absorption and emission occurs in layer after layer of the troposphere, from the surface on up through the colder and lower pressure layers. The upshot is that a steady state transfer of energy is set up, such that, at an appropriate surface temperature, the total energy of the infrared photons that finally emerge from the top of the atmosphere (including those that have not interacted with a greenhouse gas) balances the incoming absorbed solar radiation.

Before the industrial revolution, the surface temperature, accounting for all the greenhouse gases (and feedback effects

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not included in this discussion), was about 288 K (15 °C). Human activities, principally fossil fuel burning, are adding more greenhouse gas to the atmosphere, changing the steady state radiative transfer of energy, and causing the Earth's surface to warm, at least 1 °C, since the end of the 19th century. The fundamental infrared radiative transfer mechanism of the atmospheric greenhouse effect is well-characterized,[10] but it is complex, unfamiliar to and misunderstood by many of us. A very simplified model, that complements the qualitative discussion above, is readily available online.[11,12]

A fundamental characteristic of the radiative transfer mechanism is that the gain and loss of energy by the atmospheric layers is balanced. That is, global atmospheric warming does not result simply from direct collisional transfer of excitation in greenhouse molecules to the other atmospheric molecules. The latter idea is an incomplete representation of the greenhouse effect that is reinforced by the temperature increase in the demonstration under consideration here, when incorrectly interpreted as an IR absorption effect. From one recent article,[3] an explicit and succinct expression of this connection between the demonstration result and atmospheric warming is the learning objective that "...collisional relaxation of vibrating greenhouse gas molecules results in an increase in the kinetic energy of the surrounding gas molecules, resulting in a warmer atmosphere." Since it can create or reinforce an incomplete idea, this is another reason not to do the demonstration.

This is a pity, because even the simplest explanations of the atmospheric greenhouse mechanism are still relatively abstract mathematical models of the physics at play. For classrooms, a more concrete model would be useful. Although a demonstration involving IR radiation does not seem feasible, an analogy using water flow to simulate steady state transfer of energy through the atmosphere is available.[13] The demonstration involves water flowing through a series of compartments connected by tiny openings and observation of a steady state of water levels in the compartments. Increasing the number of compartments (analogous to increasing the concentration of carbon dioxide in the atmosphere) without changing the inflow rate (analogous to constant solar energy input) changes the steady state. In particular, the water level increases in the first compartment (analogous to energy at the surface of the planet). An important comment from the authors is that the demonstration "...takes the emphasis off of *additional absorption* as being the cause of global warming and emphasizes climate change as being a change in a steady-state" (emphasis in the original).

Coping with anthropogenic climate change is the most serious challenge facing humanity. Understanding correct basic climate science concepts is important for meeting the challenge and is the reason for including them in as many biology, chemistry, earth science, and physics courses as possible. All the concepts are actually already included in these courses and simply need to be correctly connected to the climate. Climate can be a context for a concept or a concept can be the context for introducing a climate connection. It is a win−win situation fostered by content available online.[7]

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Notes

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