Cost-Effective Teacher

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Photoacoustic Experimental System To Confirm Infrared Absorption Due to Greenhouse Gases

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Global warming is one of the most serious issues of today and detailed analyses have been carried out on this issue *(1)*. Many efforts have been made in chemical education to stimulate the interest of students in this serious environmental problem *(2−7)*. The atmosphere's transparency to visible light and semiopacity to infrared (IR) light owing to the absorption by greenhouse gases (GHGs) are the key points for understanding the mechanism of global warming. It is instructional for students to examine the difference in IR absorption between GHGs and other atmospheric gases.

We have been involved in a project that helps high-school students understand the IR-absorbing property of GHGs by conducting simple experiments. Although the Fourier-transform infrared (FTIR) spectrometer is useful for obtaining detailed information about the characteristics of GHGs *(4, 5)*, we did not use this technique because the mechanism of an FTIR spectrometer is too complicated for high-school students to understand and the students are unfamiliar with interpreting information from an IR chart. Also because of its price, it is difficult to provide an FTIR spectrometer to each group of students. Seeking an alternative, simple, and instructive experiment, we developed an experimental system using the photoacoustic (PA) effect, because the basic theory of the PA effect due to IR absorption is straightforward and the configuration of the nondispersive PA device is simple. This experimental system can be built inexpensively with readily available components and is useful for understanding the IR absorption properties of various gases.

Background

The PA effect is a transformation of light energy absorbed by a material into acoustic waves *(8, 9)*. This effect was first discovered by telephone inventor Bell in 1880 *(10)*, who found that an audible sound was produced by radiating modulated light on a light-absorbing material. The frequency of the sound wave is the same as that of the modulation, and the intensity is directly proportional to the quantity of light absorbed. In 1938, Veingerov first applied the PA effect to gas analysis and was able to detect the PA signal of CO_2 diluted in N_2 gas *(11)*.

When an IR-absorbing gas in a closed cell with IR-transmitting windows is irradiated by IR radiation, the gas molecules become vibrationally excited. The excess vibrational energy of the excited molecules flows into the surrounding gas and the temperature of the gas increases, resulting in an increase of the pressure of the gas. Therefore, the periodic IR irradiation causes a pressure wave that can be measured with a microphone.

Experiment and Results

Nondispersive PA System

The overall experimental system is composed of a light source, a gas cell, a chopper, and an oscilloscope (Figure 1). The IR light source is a continuous 8 W source with a coiled wire filament (IR System Co., IRS-001C). The gas cell consists of a stainless-steel tube (20 mm i.d. and 100 mm length), a gas inlet and outlet with an airtight valve, a pair of KBr windows, and an electret condenser microphone (Sony Corp., ECM-C115). The chopper consists of a five-bladed disk, a dc motor, and a reflection-type microphotosensor (SUNX Ltd., PM2-LH10) whose sensitivity is constant up to ~1200 Hz. An oscilloscope with a maximum sensitivity of 1 mV/div and two channel inputs (Hitachi, V-252 20 MHz) is employed. The components can be substituted with other products of similar quality.

The IR radiation emitted by the light source passes through the five-bladed disk producing cyclic modulation of the IR radiation, and then the modulated IR radiation is directed to the gas cell. The disk rotation is monitored by the microphotosensor that generates a reference signal as the disk blades reflect light from an LED to the sensor. The reference signal is fed into the oscilloscope as a trigger signal. The pressure variation of the inner gas owing to its IR absorption is detected by the microphone whose signal is sent to the oscilloscope and synchronized with the trigger signal. The PA and reference signals are observed with the oscilloscope under dc mode. The modulation frequency can be adjusted by changing the input voltage applied to the dc motor of the chopper.

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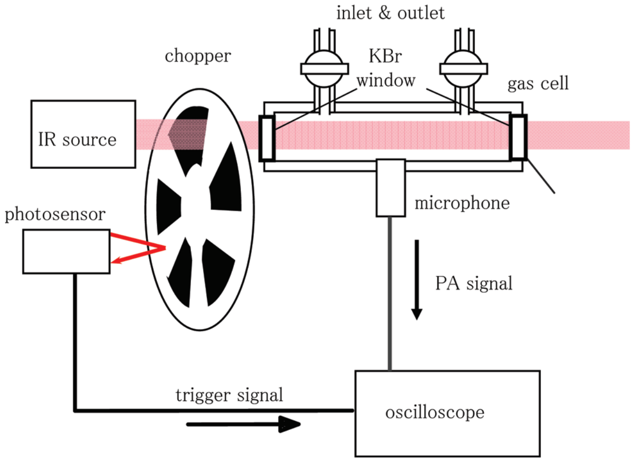

Figure 1. Schematic diagram of a PA experimental system for IR absorption of gases.

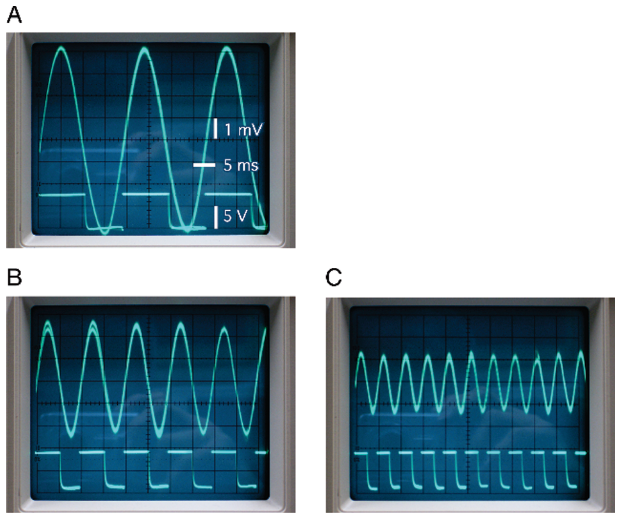

Figure 2. Modulation frequency dependence of PA signal intensity: (A) 53 Hz, (B) 100 Hz, and (C) 200 Hz. The sample gas is CO_2. The wave on the upper side is the PA signal and the rectangular wave on the lower side is the reference signal. The horizontal scale is 5 ms/div, and the vertical scale is 1 mV/div for the PA signal and 5 V/div for reference signal.

Procedure

Both the inlet and outlet valves of the cell are opened when loading the sample gas and closed when measuring the PA signal. When the sample gas is flammable, the IR light source should be turned off during the loading. The modulation frequency is set in the range of 40–100 Hz. The PA signal is displayed on a scale of 1–5 mV/div.

Hazards

In case the sample gas is supplied from a pressured gas cylinder, the experiment should be carried out with the support of assistants who are accustomed with handling of pressured gas cylinders. Ventilation of the classroom should be carefully monitored. Some of GHGs such as methane are flammable. A protective plate should be placed around the disk blade of the chopper.

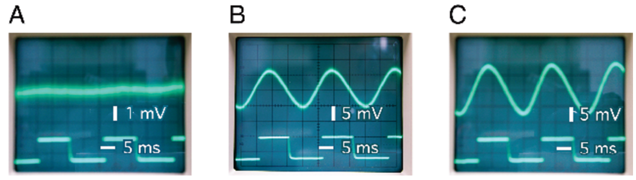

Figure 3. PA signals of some gas samples: (A) N_2, (B) CH_4, and (C) HFC-152a. The modulation frequency is 48 Hz.

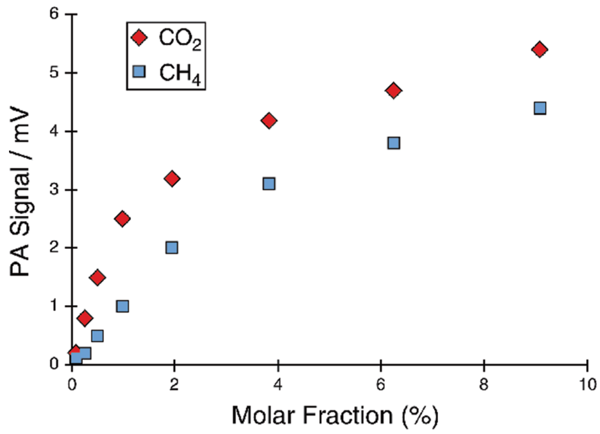

Figure 4. Concentration dependence of PA signal for CH_4 and CO_2 diluted with N_2. The modulation frequency is 50 Hz.

System Performance

The PA signal appears as a sine-like wave on the monitor of the oscilloscope (Figure 2). The simultaneous display of both the PA and reference signal illustrates that the modulation of the IR source determines the frequency and intensity of the PA signal. The intensity of PA signal decreases as the modulation frequency increases.

This system demonstrates the significant difference in IR absorption between GHGs and non-IR-absorbing gases. The PA signals of gases N_2 (Neriki, 99.99%), CH_4 (Neriki, 99%), and HFC-152a (1,1-CF_2HCH_3; from a can of air duster) are shown in Figure 3. Strong PA signals appear for GHG-like CO_2, H_2O, CH_4, and HFC-152a, but no distinctive signals appear for non-IR-absorbing gases such as N_2, O_2, and Ar.

The PA signal for CH_4 and CO_2 can be detected down to a concentration of 0.1%. The signal increases nearly linearly at low concentrations, but the rate of increase slows down at concentrations above 2% for CH_4 and 0.5% for CO_2 (Figure 4). This slowdown is due to the saturation of IR absorption; the cell transmission is approaching zero at the IR frequencies where molecules absorb strongly. The PA signal of H_2O is detectable at concentrations above 0.2%.

Discussion

The PA system has been tested three times in extracurricular classes of 2–3 h concerning global warming with ~20 students. Because of the reasonably low cost of the experimental setup, a separate system was provided to each group of 5–6 students. We found that the operating principle of the nondispersive PA method is easily understandable for high-school students. With support from a teaching assistant, the students were able to carry out the experiments using this system. According to the questionnaire, most students stated that the PA experiments were interesting and stimulated their interest in the greenhouse effect.

Through the following observations, students can confirm that the signal on the oscilloscope screen is due to the PA effect caused by the IR absorption: (1) The period of the signal wave is exactly the same as that of the light modulation and (2) when exchanging the IR light source with a visible light source, such as LED and fluorescent tube, the signal disappears.

This system can be applied to qualitative comparison of IR absorption intensity, but it requires attention to whether the sample concentration is suitable for this purpose. As shown in Figure 4, the PA signal tends to show saturation in the region of high concentration.

Although this PA system is a nondispersive type, it provides information about the wavelength range of major absorption bands of a gas, which can be done by observing the intensity change caused by inserting a filter having a strong absorption band in front of the incident window of the sample cell or by changing the material of the incident window. Depending on the absorption wavelength range of the filter (or incident window), the intensity of the PA signal changes. The IR absorptivity of a gas in the absorption range of the filter does not contribute to its PA signal. Therefore, a large intensity change means that the major IR absorption of the gas is located in the absorption range. For example, a sapphire plate can be used as a filter that cuts IR radiation in the wavelength range longer than 5.6 μm. The major absorption of CO_2 (4.2−4.5 μm) is out of the absorption range of a sapphire, whereas that of HFC-152a (6.7−12.5 μm) is in the absorption range *(12)*. Therefore, HFC-152a shows a much larger intensity decrease than CO_2 when inserting a sapphire filter.

The PA signal can be, of course, detected as sound by connecting the output of the microphone to an audio system. The IR absorptivity of gases is reflected in the loudness of the sound, which is effective as a lab demonstration for students.

Conclusion

A low-cost PA system has been developed to provide high-school students with a hands-on learning activity about IR absorption of gases. The PA experiments give reproducible results, which helps students understand that the IR absorptivity of the atmosphere is determined by its minor components, GHGs.

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Note Added after Print Publication

The given name of author Masayoshi Nishiyama was incorrectly identified in the original article published in the January 12, 2010 (Vol. 87, Issue 2) print issue. The corrected electronic version was published on the Web on February 11, 2010, and an Addition and Correction appears in the March 9, 2010 issue (Vol. 87, Issue 4).

Supporting Information Available

Instructor notes; details of the PA system; experimental procedures; samples of PA experiments; student directions. This material is available via the Internet at http://pubs.acs.org.

