Measurement of Ozone Emission and Particle Removal Rates from Portable Air Purifiers

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Air purifiers are designed to improve the quality of indoor air by removing suspended particulate matter, dust, and other air contaminants known to cause adverse health effects. They clean the air by a variety of methods including physical filtration, chemical scrubbing, and plasma-induced ionization of air impurities. One in three U.S. households in 2006 had a portable air purifier *(1)*.

The key parameter characterizing an air purifier is its clean air delivery rate, CADR,

$$\mathrm{CADR} = \gamma F \tag{1}$$

where F is the air flow rate through the purifier, which is typically measured in m^3/h, and γ is the probability of capture for a given contaminant. The latter ranges from $\gamma = 0$ for a plain fan that does not remove any contaminants to $\gamma = 1$ for a purifier that removes all contaminants from the air. A given air purifier is characterized by different values of γ, and hence CADR, for different contaminants. For example, HEPA (high efficiency particulate air) filters remove particulate matter with $\gamma > 0.99$, while having almost no effect on molecular contaminants.

Certain commercially available air purifiers emit ozone (O_3), a colorless molecule with a pungent, irritating odor. Ozone is generated either intentionally or as an unwanted by-product of air ionization. This presents a serious concern because exposure to ozone, even at low concentrations *(2),* is known to have detrimental health effects on humans including elevated mortality, exacerbation of asthma symptoms, and permanent lung damage in children.

Ambient ozone concentrations are continuously monitored in every major city; simple examples of such measurements were previously described in this *Journal (3, 4)*. The mixing ratio of ozone is 0.020–0.040 ppm (parts per million) in clean outdoor air, but can be well in excess of 0.100 ppm in heavily urbanized areas. The U.S. Environmental Protection Agency treats ozone as one of its criteria air pollutants, and it has established a National Ambient Air Quality Standard (NAAQS, U.S. Code of Federal Regulations, Title 40, Part 50) aimed at protecting the public from ozone exposure. The currently established 8-hour and 1-hour exposure limits for ozone are 0.080 ppm and 0.120 ppm, respectively.

Recent measurements demonstrated that certain air purifiers can produce indoor ozone concentrations that significantly exceed the NAAQS health-protective levels *(5–7)*. In response to these alarming observations, California has restricted sales of air purifiers producing more than 0.050 ppm of ozone in the exhaust air. Starting in 2008, all manufacturers of air purifiers intended for public use will have to demonstrate that their appliances comply with this new regulation.

The quantity of ozone emitted by an air purifier can be characterized by its ozone emission rate, E_{ozone}, which is typically measured in mg O_3 per hour (mg/h). Once emitted, ozone undergoes loss as a result of heterogeneous chemical decomposition on indoor surfaces, as shown schematically in eq 2, and physical removal by ventilation *(8)*.

$$O_3 \xrightarrow{\text{surface}} {}^{3}\!/_{2}\, O_2 \tag{2}$$

Competition between the emission of ozone from the air purifier and loss of ozone via decomposition on surfaces leads to a steady state *(5),*

$$\begin{aligned} \left[O_3\right]_{\mathrm{ss}} &= \frac{E_{\mathrm{ozone}}\,\tau}{k\,V} \\ k &= 118\ \frac{\left(\mathrm{mg/h}\right)\mathrm{min}}{\mathrm{ppm\ m^3}} \end{aligned} \tag{3}$$

where $[O_3]_{\mathrm{ss}}$ is the ozone mixing ratio at steady state, V is the room volume, τ is the lifetime of ozone, typically ~20 minutes *(8),* and k is a conversion factor for the units specified in eq 3 calculated at 1 atm and 298 K. Equation 3 can be used to estimate the steady-state mixing ratio of ozone produced by an air purifier once its ozone emission rate is known.

In an effort to better educate the public about air quality and indoor ozone chemistry, we have designed a laboratory protocol for testing portable air purifiers. The students use photometry and light scattering techniques to measure CADR and E_{ozone} for several kinds of portable air purifiers. The experiment is appropriate for students at a variety of levels, and the lab was offered to several groups of high school science teachers as a part of a summer teacher training program in environmental chemistry organized by the authors. This lab was also offered to undergraduate, graduate, and high school students, with appropriate adjustments to adapt it for students spanning this wide range of experience.

Hazards

Efficient ozone generators ($E_{\mathrm{ozone}} > 10$ mg/h) should not be operated outside of the sealed Teflon chamber. If a strong ozone smell is detected, all ozone generating appliances should be immediately turned off, and students should leave the room until the ozone concentration decreases.

Unusual Materials

The following items are not common for a chemistry laboratory: Teflon film for fabricating a suitable chamber (Professional Plastics; type FEP-200A); an ozone photometer with 0.001 ppm sensitivity for ozone concentration measurements (Ebara-Jitsugyo; model EG-2001); an aerosol particle coun-

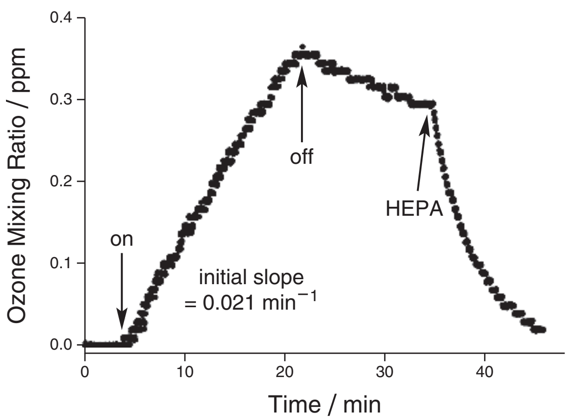

Figure 1. Sample measurement of ozone emission rate for model SI637 ionization air purifier. on: air purifier is turned on; off: it is turned off; HEPA: a HEPA filter is turned on to accelerate ozone removal.

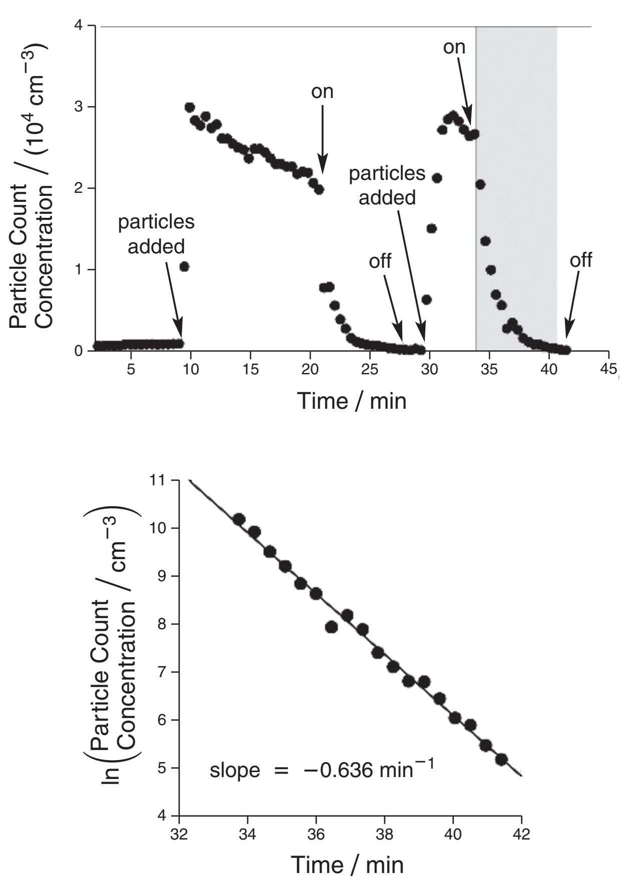

Figure 2. Sample CADR measurements for SI637 ionization air purifier. (top) Particles are introduced and allowed to mix in the chamber for a certain period of time. The particle concentration drops exponentially during the time the air purifier is on. The bottom panel shows a sample fit of the shaded portion of the data on a log–linear scale.

ter (Particle Measuring Systems, model Lasair 1510). Ozone emitting air purifiers can be purchased in many stores; a list of models known to emit ozone is available from the California Air Resource Board Web site *(9)*.

Sample Results

Ozone Emission Rates

In this part of the experiment, students measure E_{ozone} from selected air purifiers. The air purifier is placed in a Teflon chamber of known volume, and the chamber is sealed. An ozone photometer is used to monitor the ozone mixing ratio in the chamber in real time. When the air purifier is turned on, the ozone mixing ratio starts to increase. The initial rate of increase is approximately linear and can be converted into the ozone emission rate using eq 4 *(5)*:

$$E_{\text{ozone}} = kV_{\text{chamber}} \frac{\mathrm{d}[\mathrm{O_3}]}{\mathrm{d}t} \qquad (4)$$

A sample measurement for an ionization air purifier manufactured by Sharper Image (model SI637), performed at 60% relative humidity, is shown in Figure 1. As expected, ozone concentration increases linearly when the air purifier is turned on. The rate of increase translates into an E_{ozone} of ~1.5 mg/h, which is typical for this model *(5, 7)*. When the air purifier is turned off, the ozone mixing ratio slowly decays due to the slow decomposition of ozone on the walls and other surfaces inside the chamber. Turning on a HEPA filter with an activated charcoal pre-filter accelerates the removal of ozone in preparation for the next measurement cycle. This experiment is repeated several times for reproducibility. Several air purifiers can be tested and compared after several hours of work. Each group of students can work with a different set of air purifiers, so that many models can be compared at the end of the course. An example of a set of air purifiers might be an ionization air purifier, an ozone-generator, a refrigerator air purifier, and a personal air purifier.

CADR for Particulate Matter

In this part of the lab, students examine the effectiveness of a selected air purifier with respect to removing micrometer-sized aerosol particles. The air purifier is similarly placed in a sealed Teflon chamber. A small quantity of aerosol particles (typically, 10^4 particles per cm^3) is injected through one of the chamber ports. The total number concentration of particles is then measured as a function of time.

Typical results for sodium chloride aerosol particles removed by the SI637 ionization air purifier are shown in Figure 2. The top panel shows a plot of particle number concentration versus time covering two particle injection–removal cycles. When particles are added to the chamber, a large increase in the particle concentration is observed, followed by a slow decrease due to particle deposition to the walls and other surfaces inside the chamber. Turning on the air purifier leads to a rapid exponential decrease in the particle number concentration. The addition and removal of particles is repeated several times for reproducibility; two cycles are shown in Figure 2. The bottom panel of Figure 2 shows a typical fit of the decaying section of the plot on a log–linear scale. Because the particle concentration obeys the first-order kinetics, the slope of this plot is equal to the effective particle removal rate constant, and can be converted into CADR using eq 5.

$$\text{CADR} = -\frac{\mathrm{d}\ln\left(\left[\text{particle}\right]\right)}{\mathrm{d}t} V_{\text{chamber}} \qquad (5)$$

Data shown in Figure 2 (a slope of −0.636 min^{-1} in a 600 L chamber) translate into CADR = 380 L/min or 23 m^3/h, which falls on the low end of typical air purifier performance *(1)*.

Educational Value

The scope and depth of the discussion of this experiment depends on the level of the students. With high school teachers and students, we normally discuss the chemical properties of ozone, its health effects, distinction between the upper atmospheric ozone in the ozone layer and ground-level ozone associated with air pollution, and specifics of indoor ozone chemistry. The students use their measured values of E_{ozone} to estimate how much ozone would build up as a result of using ozone-emitting air purifiers in rooms of different sizes. They also compare ventilation rates for typical rooms with their measured values of CADR and judge the overall effectiveness of the air purifiers in cleaning the room air.

Undergraduate students additionally discuss the analytical aspects of UV photometry and light scattering used in these experiments. Advanced undergraduate students and graduate students use their knowledge of kinetics to derive all the equations listed in the lab manual. They are also asked to calibrate the ozone photometer and particle counter used in the measurements.

In conclusion, we have presented a laboratory protocol that is suitable for students with a wide range of education and experience. Students are introduced to concepts in indoor air chemistry, air pollution, kinetics, and instrumental measurement of atmospheric trace species.

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Supplement

Instructions for the students

Notes for the instructor

Prelab and post lab questions