

Title: Do Ion Generators Have A Role In Sustainable Indoor Environments?

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Do Ion Generators Have A Role In Sustainable Indoor Environments?

ABSTRACT

American consumers have started to recognize the value of improved indoor air quality. Consequently, many Americans have purchased portable air cleaners, including devices that remove particles by generating ions. Portable ion generators are appealing because they are quiet and use considerably less energy than HEPA filters and other air cleaners. However, these devices often do not remove enough particles to be effective, do generate enough ozone (a byproduct of their operation) to be of concern, and can generate ozone reaction products including secondary organic aerosols. This paper summarizes our recent research as well as the work of others. We demonstrate that portable ion generators have low clean air delivery rates (CADRs) for 5 nm - 10 μm particles, generate levels of ozone in typical indoor environments that may lead to adverse health effects, and can act as particle generators. Results strongly suggest that ion generators do not have a role in sustainable indoor environments.

INTRODUCTION

As more Americans recognize the importance of indoor air quality, there is increased interest in air cleaning devices. Currently, three in ten American homes use some sort of air cleaning device (Shaughnessy and Sextro, 2006). One heavily-marketed technology that has become increasingly popular is portable ion generators. Survey data suggest approximately 8% of all Californians have at least one ion-generating air cleaner in their home (Piazza *et al.* 2007). Also called ionizers, ionic air cleaners, and portable electrostatic precipitators, these devices work by charging incoming particles with a corona and removing them on oppositely charged electrodes. Many ion generators do not employ a fan to move air, and thus offer nearly silent operation. Others do not include charged plates and instead remove the charged particles on building surfaces. Most ionizing air cleaners also generate ozone, a respiratory irritant and oxidizing agent that can react with other airborne contaminants to produce ultrafine and fine particles and other byproducts (Weschler and Shields, 1999; Wainman *et al.*, 2000; Sarwar *et al.*, 2003; Hubbard *et al.*, 2005). In this paper we summarize the literature on ion generators and perceived air quality, particle removal, and ozone emission rates, as well as present results from screening experiments that explore particle generation from ion generators in the presence of a solid air freshener. The central research question evaluated in this paper is whether ion generators have a role in maintaining a sustainable indoor environment.

LITERATURE REVIEW

Ion generators have a long history of being associated with improvements in perceived air quality (Sun, 1980). Our search found eight studies involving human subjects and a variety of symptoms associated with sick building syndrome (SBS). These studies are summarized in Table 1. The sample size, symptoms that were considered, as well as the results for each study are listed in Table 1. A study conducted with a placebo was an experimental design that included some tests where an air cleaner that appeared to be operating but that was not, and a baseline test indicates a design that included some tests on the same (or a similar) population with no air cleaner present. It should be noted that many of the articles listed in Table 1 were conducted with larger ion generators intended for commercial use, rather than portable units intended for residential use.

TABLE 1
Summary of ion generator impacts on perceived air quality

| Reference | Subject sample size | Symptoms evaluated in study | Impact of ion generator on symptom frequency and/or severity¹ | Use of placebo and/or baseline² |
|----------------------------------|----------------------------|--|---|---|
| Fishman (1981) | 8 | open/oppressive, pleasant/unpleasant, dry/moist, fresh/stuffy, hot/cold, comfortable/uncomfortable, soothing/irritating, invigorating/dozy, calming/exciting, pleasing/annoying, good/bad, dry skin/moist skin, dry eye/moist eye, clear nose/congested nose | no effect | placebo |
| Hawkins (1981) | 108 | thermal comfort rating, the alert-drowsy, fresh-stuffy scales, reported incidence of headache | significant improvement | baseline and placebo |
| Laws (1982) | 74 | headache, nausea, dizziness incidence perceived alertness, freshness, sensation of comfort and pleasantness | improvement significant improvement | placebo |
| Hawkins and Morris (1984) | 79 | complaints of lethargy | significant improvement | baseline and placebo |
| Wyon (1992) | 28 | dry throat, dry lips, dry skin, brittle nails, dry eyes | significant improvement | baseline and placebo |
| Shaughnessy <i>et al.</i> (1994) | 10 | mean order scores, mean nasal irritation, mean eye irritation, overall air acceptability | improvement | baseline |
| Rosen and Richardson (1999) | 93 | non-attendance due to sickness | improvement | baseline |
| Richardson <i>et al.</i> (2001) | 7 | dust and dirt, draught, stuffy bad air, dry air | improvement | baseline |

¹Significant improvement indicates statistical significance as defined by each study author. Improvement and No effect indicate no statistical significance.

²Placebo indicates that symptoms were also evaluated in the presence of a “dummy” air cleaner that appeared to be working and Baseline indicates that symptoms were compared to a population in a similar or the same environment with no ion generator present.

The studies listed in Table 1 provide mixed evidence for the impact of ion generators on perceived air quality. Four studies show a statistically significant improvement in the listed symptoms in the presence of an ion generator (Hawkins, 1981; Laws, 1982; Hawkins and Morris, 1984; Wyon, 1982), and five studies show no statistically significant improvement (Fishman, 1980; Laws, 1982; Shaughnessy *et al.*, 1994; Rosen and Richardson, 1999; Richardson *et al.*, 2001). Sample sizes tend to be larger (on average) for the studies that show an improvement. However, at least one of the studies that showed a significant improvement was repeated with a different population in a different environment, and no such improvement was found. Thus, firm conclusions about the efficacy of ion generators for ameliorating the symptoms of sick building syndrome are not possible given the collective results of previous studies.

Most modern ion generating air cleaners are purchased for their ability to remove particles from air. There are several metrics that have been used to describe particle removal effectiveness of ion generators and other air cleaners, including efficiency, concentration reduction factor (CRF), air cleaning factor (ACF), and clean air delivery rate (CADR). CADR is the best available metric because it takes into account both flow rate through the air cleaner and the particle removal efficiency (Offermann *et al.*, 1984, Shaughnessy *et al.*, 1994; Shaughnessy and Sextro, 2006). It is also much less dependent on the measurement environment than CRF or ACF.

Table 2 lists sample size, experimental parameters, and CADR for 11 studies. A range of CADR values indicates the range over all challenge aerosols tested. CADR values in italics indicate studies that did not report CADR, but provided enough information for it to be calculated based on other reported data. CADR values range from less than 10 m³/hr in several studies to over 500 m³/hr for a large commercial unit that created a “shower of ions”. The data in Table 2 indicate that most ion generators do not have very high CADRs, especially when compared with other available air cleaning technologies, such as HEPA filters which typically have CADR values that range from 250 – 670 m³/hr (Offermann *et al.*, 1984, Shaughnessy *et al.*, 1994; Mullen *et al.*, 2005; Ward *et al.*, 2005; Shaughnessy and Sextro, 2006; Waring *et al.*, 2007). Most ion generators have insufficient CADRs to be considered effective air cleaners in typical indoor environments (Shaughnessy and Sextro, 2006). One exception to this pattern of general low CADR is the portable ESP tested by Waring *et al.* (2007), as this unit has a fan that moves 850 m³/hr of air, a flow rate an order of magnitude higher than most of the ion generators.

Many ion generators also generate ozone as a byproduct of their operation. Ozone emission is occasionally marketed as being a positive attribute because extremely high concentrations of ozone can act as a disinfectant or deodorizer. However, such use of ozone can generate irritating or hazardous byproducts (Poppendieck *et al.*, 2007) and ozone emission is generally considered a negative feature because it is a respiratory irritant that can have serious health effects, even at low concentrations (Gent *et al.*, 2003; Bell *et al.*, 2004; Bell *et al.*, 2006; Triche *et al.*, 2006). Furthermore, ozone can react to produce ultrafine and fine particles and gas-phase byproducts that may represent a larger risk than from the direct ozone exposure (Weschler, 2006). Table 3 lists ozone emission rates from seven studies for 26 ion generators including personal units that are intended to be worn around the neck, small portable units that are intended for small rooms such as bathrooms or automobiles, and portable units that are intended to clean the air in an entire room. Emission rates for portable units range from 56 µg/hr to 4.3 mg/hr. The largest emission rates are similar to those from an uncontrolled laser printer or dry-toner photocopier with no ozone scrubber (Tuomi *et al.*, 2000). Emissions are one to three orders of magnitude lower than dedicated ozone generators (Mullen *et al.*, 2005; Yu *et al.*, 2005; Britigan *et al.*, 2006). It should be noted, however, that all of these devices can meet relevant ozone emission standards (typically 50 ppb), but this is reflective of the fact that the current Underwriters Laboratory (UL) Standard 867 Section 37 (UL, 2000) ozone emission test method is easily manipulated by varying air exchange, adding reactive material to the test chamber, using chamber surfaces with high ozone reactivity, using a large chamber, and changing air flow patterns within the space. Thus results from this test should not be considered to be reflective of ozone emission safety. Furthermore, the significance of the 50 ppb standard is extremely suspect given that the 50 ppb value seems to have little, if any, justification (Federal Register, 1972) and more recent research suggests that much lower levels may be more appropriate (Gent *et al.*, 2003; Bell *et al.*, 2004; Bell *et al.*, 2006; Triche *et al.*, 2006).

In order to assess these ozone emission rates in the context of a typical indoor environment, we used a one-box, well-mixed indoor mass balance and assumed a value of 0.53 for ozone penetration, which is the mean value for an idealized fiberglass-insulated wall (Liu and Nazaroff, 2001), 377 m³ for indoor volume (American Housing Survey, 2001), and varied the air exchange rate from 0.2 to 2 per hour. The ozone deposition loss rate was assumed to be 4/hr (Weschler, 2000). Figure 1 shows the equivalent increase in outdoor ozone concentration as a function of air

exchange rate for ozone emission rates that span the range of those listed in Table 3. For a typical residential air exchange rate of 0.5 per hour, the outdoor ozone concentration would need to increase by 4 to 21 ppb in order to achieve a steady-state indoor ozone concentration equivalent to that in the same home with an operating ion generator. The effect becomes even more dramatic for more energy efficient (tight) residential construction. Bell *et al.* (2004) found that a 10 ppb increase in the previous week's ambient (outdoor) ozone concentration was associated with a 0.52% increase in daily mortality, indicating the potential for an increase in health problems due to the increased ozone concentration that results from the use of these devices in indoor environments.

TABLE 2
Previous studies that measure ion generator clean air delivery rates

| Reference source | Sample size ^a | Experimental volume, V (m ³) | Challenge aerosol | Measurement instruments | CADR (m ³ /hr) |
|--|--------------------------|--|-------------------------------------|--|--|
| Repace <i>et al.</i> (1983) ^{b,c} | 3 | 21.5 | environmental tobacco smoke (ETS) | piezoelectric microbalance monitor (0.01 - 3.0 μm) | 119 |
| | | 69.9 | | | 130 |
| | | 333 | | | 533 ^d |
| Offermann <i>et al.</i> (1985) ^e | 2 | 37.5 | ETS | electrostatic classifier/ optical particle counter (0.01 - 3.0 μm) | 2 ± 2 |
| | | | | | 52 ± 2 |
| Shaughnessy <i>et al.</i> (1994) ^{12 f} | 2 | 24.9 | ETS | not reported | 22 – 90 0 - 15 |
| | | | 0.5 - 3.0 μm dust | | |
| | | | 2 - 3 μm fungal spores | | |
| | | | 4 - 5 μm fungal spores | | |
| Grabarczyk (2001) ^{b,c,g} | 1 | 50 | ambient dust | optical particle counter (0.3 - 2.5 μm) | <146- 174 ^g |
| | | | | | |
| Niu <i>et al.</i> (2001a) ^f | 5 | 6.4 | 0.3 – 3.0 μm incense smoke | light-scattering monitor (PM ₁₀ concentration) | 9.0 57.4 64.3 |
| Grinshpun <i>et al.</i> (2004) ^h | 1 | 24.3 | NaCl latex spheres ETS, bacteria | optical particle counter, aerodynamic particle sizer (0.5 - 2 μm) | 25-38 |
| | | 2.6 | | | |
| | | 0.026 | | | |
| Lee <i>et al.</i> (2004) ^f | 2 | 24.3 | smoke | impactor | 30-60 150 |
| | | | | | |
| Grinshpun <i>et al.</i> (2005) ^h | 5 ^j | 2.6 | NaCl latex spheres bacteria | optical particle counter (0.3 - 3 μm) | 1 |
| | | | | | 5 |
| | | | | | 7 |
| | | | | | 11 |
| | | | | | 65.5 |
| Xu <i>et al.</i> (2005) ^{h,i} | 2 | 34.2 | dust | optical particle counter, dust monitor | 120 173 |
| | | | | | |
| Yu (2005) ^{j,k} | 5 | 14.5 | incense KCl | optical particle counter (0.1-1 μm) aerodynamic particle sizer (0.5 -5 μm) | 19-79 30-65 3-37 52-111 5-29 |
| | | | | | |
| | | | | | |
| | | | | | |
| Waring <i>et al.</i> (2007) ^{j,l,m} | 3 | 14.5 | incense | scanning mobility particle sizer (0.02-0.5 μm) | 120- 455 ^l 16-76 |
| | | | | | |

^a Number of ion generators tested ^b Tested in real indoor environment, rather than in a laboratory chamber ^c Air exchange by natural ventilation
^d Large CADR comes from commercial system with six heads that creates "ion shower" and is thus very different from other units described here.
^e $\lambda < 0.1/\text{hr}$ $\lambda < 0.03/\text{hr}$ (i.e., negligible)
^f Removal by ventilation is included in the CADR and thus it is an upper bound on the air cleaner CADR. Air exchange rate not reported
^g The authors refer to the tested device as a "plasma air cleaner", which appears to be the same most of the other portable ion generators here.
^h $\lambda = 0.3 - 1 \text{ hr}^{-1}$ Data for incense challenge aerosol also reported in Mullen *et al.* (2005)
ⁱ Testing includes a portable electrostatic precipitator (highest CADR values) which has a fan.

TABLE 3
Ozone emission rates for portable ion generators

| Source | Sample Size | Description | Ozone Emission Rate (mg/hr) |
|---|-------------|--------------|-----------------------------|
| Phillips <i>et al.</i> (1999) | 2 | personal | 0.102 |
| | | | 0.144 |
| Niu <i>et al.</i> (2001a, 2001b) | 5 | portable | 0.056 |
| | | | 0.065 |
| | | | 0.174 |
| | | | 0.255 |
| | | | 2.757 |
| Tung <i>et al.</i> (2005) | 3 | portable | 1.47 ± 0.19 |
| | | | 0.95 ± 0.07 |
| | | | 13.42 ± 1.38 |
| | | | 2.42 ± 0.52 |
| Yu. (2005) Mullen <i>et al.</i> (2005) | 5 | portable | 2.86 ± 0.15 |
| | | | 0.74 ± 0.15 |
| | | | 4.04 ± 0.16 |
| | | | 3.92 ± 0.14 |
| | | | |
| Britigan <i>et al.</i> (2006) | 8 | portable | 2.2 |
| | | 2 small | 0.17-0.24 |
| | | portable | 0.16 |
| | | 3 automobile | 0.74 |
| | | | 0.40 |
| | | | 0.48 |
| | | 2 personal | 0.50 |
| 0.30 | | | |
| Waring <i>et al.</i> (2007) | 3 | 2 portable | 4.3 ± 0.20 |
| | | | 3.3 ± 0.16 |
| | | portable ESP | 3.8 ± 0.19 |

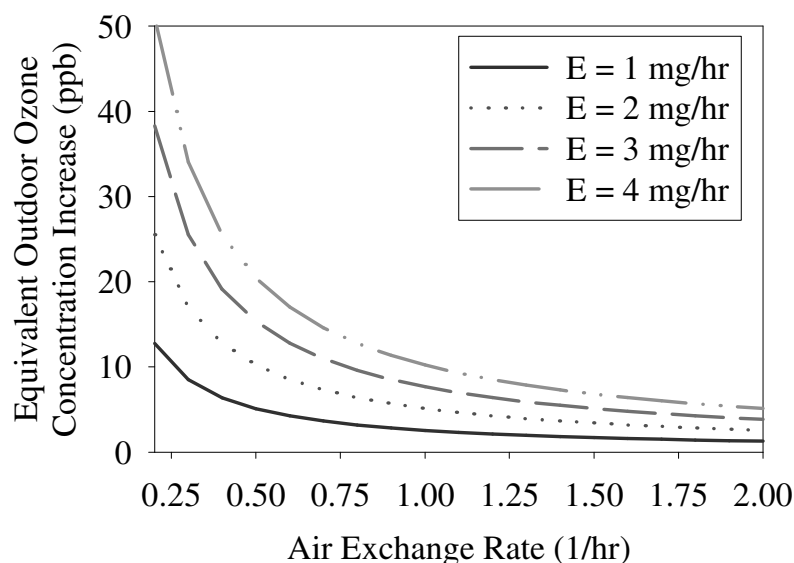


Figure 1: Impact of ozone emission defined in terms of equivalent increase in outdoor ozone concentration

An additional concern about ozone emissions is the potential for reactions with unsaturated compounds that can lead to multi-functional oxygenated gases, e.g. aldehydes, and ultrafine and fine particles. These reactions are an issue in sustainable indoor environments as it would be counterproductive to utilize an air cleaner that produces pollution. Common sources of unsaturated compounds include cleaning products, personal care products, and air fresheners. Secondary aerosol formation has been studied extensively in the outdoor environment, and several studies have characterized this phenomenon in the indoor environment (Weschler and Shields, 1999; Wainman *et al.*, 2000; Sarwar *et al.*, 2003; Sarwar *et al.*, 2004; Hubbard *et al.*, 2005). These studies have characterized byproduct and ultrafine and fine particle formation in laboratory chambers as well as residences and office buildings. Ozone from outdoors or from dedicated ozone generators has been the source of ozone for these studies. Recent research does suggest that ion generators can form particles in real indoor environments (Alshawa *et al.*, 2007). Our screening experiments to explore this phenomenon are described below.

METHODOLOGY

The goal of this investigation was to determine the change in steady-state ultrafine and fine (5 – 150 nm) particle concentrations that can be attributed to secondary organic aerosol (SOA) formation due to reactions between ozone produced by energized portable ionic air cleaners and unsaturated compounds produced by a solid air freshener. Four tests with different ionizing air cleaners were conducted in a 14.75 m³ stainless steel test chamber at the Center for Energy and Environmental Resources (CEER) at the University of Texas at Austin. Tests 1 and 2 were conducted with one popular brand (Brand A) of ionizing air cleaner and were repeat tests with two different units of the same model. Tests 3 and 4 were conducted with a different popular brand (Brand B) and were two different models, the second of which was operated with a UV lamp intended to neutralize bioaerosols. All four air cleaners used in the tests were new units and were cleaned according to the manufacturer's instructions before use. Previous testing has shown Brand A and Brand B ionizers to emit 2.5-3.1 mg/hr and 3.9-4.2 mg/hr of ozone, respectively.

The experimental chamber was cleaned with water (i.e., no cleanser) and allowed to dry overnight before Tests 1 and 3. Additionally, the chamber was passivated with an ozone generator or several ion generators overnight before each test. Sampling lines were installed approximately 1.5 m from the floor in the center of the chamber to measure ozone and particles, and any chamber openings were closed and taped. During each test, three mixing fans

were operated in the chamber to ensure that the air was well-mixed. The chamber air exchange rate during each of the tests was measured by releasing a discrete amount of CO₂ into the chamber and monitoring its decay with a continuous CO₂ analyzer (TSI Q-Trak).

The tests each took place over an approximate 24-hour period. During each test, continuous measurements of ozone and particle concentrations of the air in the chamber were taken. The ozone concentrations were measured every minute with a calibrated UV absorbance ozone analyzer (2B Technologies). The particle concentrations were measured with a TSI Scanning Mobility Particle Sizer (SMPS) with a nano-Differential Mobility Analyzer (DMA) and the airflow set to measure particles in the range of 4.61 – 157 nm over 99 particle size bins, with a scan-time of three minutes for Tests 1, 3, and 4, and five minutes for Test 2. The tube lengths were approximately 3 m (6 mm OD) for the ozone analyzer and 3.5 m (6 mm OD) for the SMPS. Each test had three distinct periods of testing: the Background (BG) period, the Air Cleaner (AC) period, and the Air Cleaner/Air Freshener (AC/AF) period. During the BG period, the air cleaner was not energized and there was not a terpene source present. During the AC period, the air cleaner was energized but there was also not a terpene source. During the AC/AF period, the air cleaner was energized and a new pine-scented solid air freshener was located approximately 1.5 m from the floor in the center of the chamber. Each period of the test was conducted for at least four hours to ensure that a steady-state condition was obtained.

For each of the four tests, the resulting steady-state particle concentrations during each period were compared. The steady-state concentrations were taken as the mean concentrations for the last 20 scans during each of the test periods for Tests 1, 3, and 4, and for the last 12 scans for Test 2 (since the scan time was five rather than three minutes). Due to the small sample size, the Behrens-Fisher t-test was used to evaluate if there were statistically significant changes ($P < 0.05$) in steady-state concentrations among the three periods. Integrated number concentrations were determined for each of the three periods by summing the number concentrations in each particle size bin of the SMPS.

RESULTS

The air exchange rates for Tests 1, 2, 3, and 4 were respectively 0.49, 0.54, 0.92, and 0.96 h⁻¹. For all four tests, the chamber air temperature was in the range of 26.2 – 27.8 °C, and the RH was in the range of 49 – 54%. It was important to conduct SOA formation experiments that compared the different ionizing air cleaners at relatively constant temperatures, as the amount of SOA formation has been shown to be directly influenced by the air temperature, with lower temperatures resulting in higher levels of particle formation due to the increase in gas-to-particle partitioning of ozone/unsaturated compound reaction products at lower temperatures (Wainman *et al.*, 2000; Sarwar *et al.*, 2003).

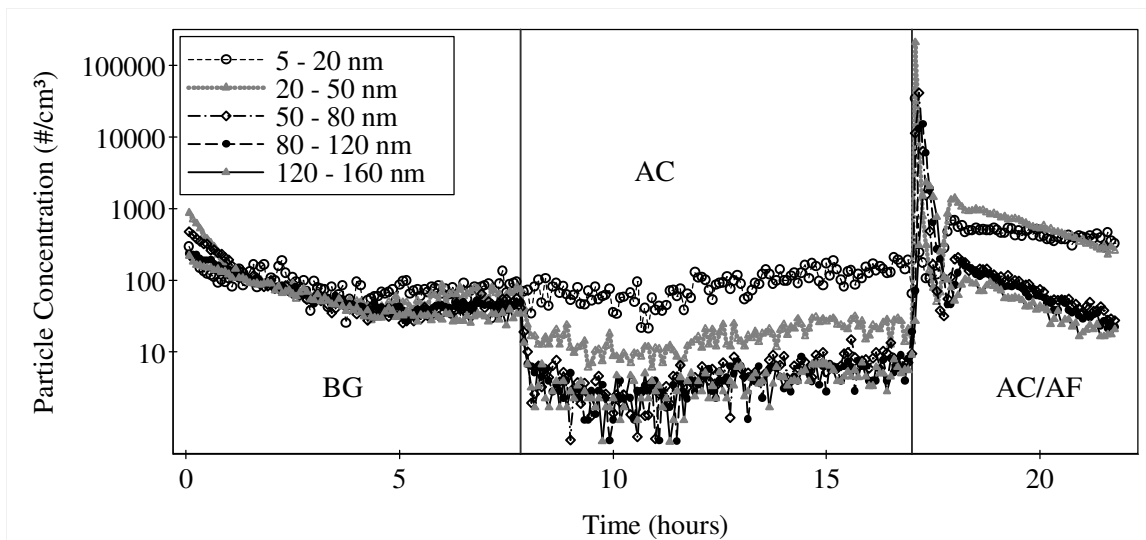
Steady-state ozone concentrations. For all four tests, during the BG period the ozone concentrations were approximately 8 – 27 ppb in the chamber. These levels represent typical indoor background levels of ozone (Weschler, 2000). For Tests 1 and 2, during the AC period when the air cleaner was energized the steady-state ozone concentrations in the chamber were approximately 120 ppb. For Tests 3 and 4 during the AC period, the steady-state ozone concentrations in the chamber were approximately 45 ppb. Tests 3 and 4 involved a different brand of air cleaners than in Test 1 and 2 and also had a much higher air exchange rate. For Tests 1 and 2 during the AC/AF period when the air freshener was added, the steady-state ozone concentrations were approximately 17 – 21 ppb. For Tests 3 and 4 during the AC/AF period, the steady-state ozone concentrations were approximately 9 – 13 ppb.

Particle growth wave due to ozone/unsaturated compound reactions. The reduction in ozone during the AC/AF period is evidence that ozone-initiated reactions are occurring. Figure 2 shows the particle number concentrations in the chamber as a function of time for Tests 2 and 3. Five particle size ranges are shown on each of the plots. Note that the y-axes in both cases are presented on a logarithmic scale, and that the x-axes correspond with the test duration. Tests 1 and 4 show similar patterns of particle growth. Initially, the concentrations of the 20 to 50 nm diameter particles increased dramatically, followed in time by the larger particle sizes. This particle growth wave is likely due to coagulation and condensation effects, which are evidenced by the diminishing concentrations of smaller size particles as the larger size particle concentrations increased. This particle growth wave is clearly noticeable, most especially on Figure 2b. Other researchers who have conducted ozone/terpene particle formation experiments have noted similar particle formation and growth wave patterns (Weschler and Shields, 1999; Wainman *et al.*, 2000; Sarwar *et al.*, 2003).

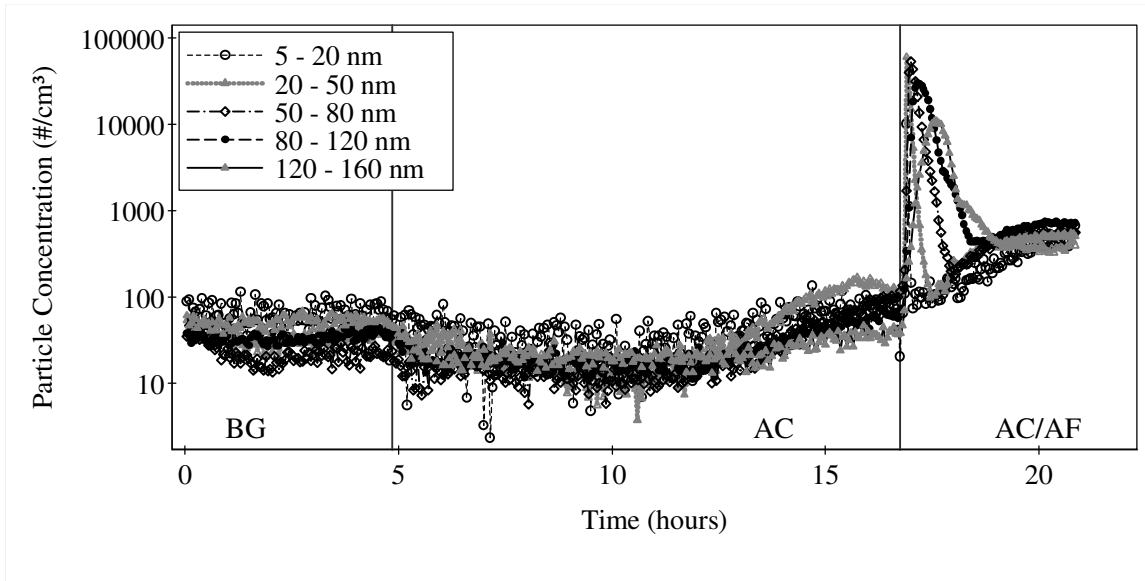
Steady-state ultrafine particle concentrations. Figure 3 shows the resulting steady-state ultrafine particle concentrations (4.61 – 157 nm) as a function of particle diameter measured during the BG, AC, and AC/AF periods for all four chamber tests.

During the BG period for Tests 1 and 2, the ultrafine particle concentrations are less than 15 particles/cm³ for the investigated range of particle sizes. The BG concentrations were lower during Test 2, reflective of lower ambient concentrations. For Tests 3 and 4, the BG concentrations were less than 10 particles/cm³. For all four tests, when the air cleaner was energized during the AC periods, the steady-state concentrations were often lower, particularly for particles greater than 20 nm in diameter. For Tests 1 and 2, the resulting steady-state concentrations during the AC/AF periods were significantly higher ($P < 0.05$) than concentrations during either the BG or AC periods for particles 10 – 50 nm in diameter. For Test 3, the steady-state concentrations during the AC/AF period were significantly higher ($P < 0.05$) than the BG or AC periods for all measured particle sizes, and for Test 4, for particles greater than 21 nm in diameter.

Thus, the use of ionic air cleaners in a chamber with a terpene source (the AC/AF period) yielded steady-state particle concentrations that, in many cases, were elevated above those measured during the BG period, implying that in some size ranges, ionic air cleaners may be net particle producers rather than removers in indoor environments. Moreover, the tests conducted with the different brands of air cleaners clearly exhibited different trends. The Brand A units removed enough large diameter particles that the particle formation did not cause an elevation above the BG steady-state levels, except in the 10 – 50 nm range for Test 1 and 10 – 40 nm for Test 2. The Brand B units, however, were much less effective at removing larger sizes of particles, though more effective in the 10 – 50 nm range, than the Brand A units.

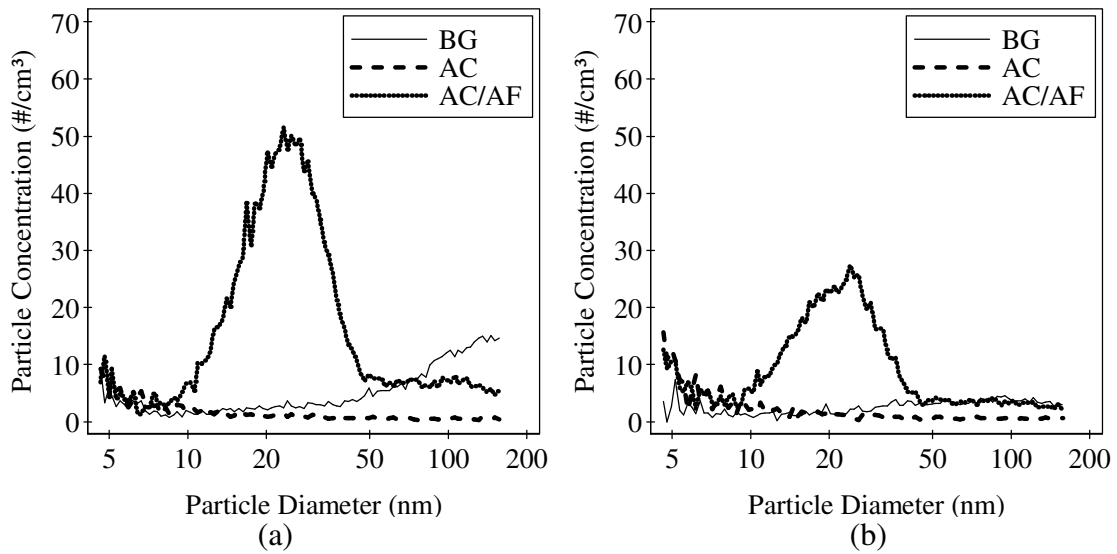


(a)



(b)

Figure 2. Particle number concentrations as a function time for (a) Test 2 and (b) Test 3. The BG, AC, and AC/AF periods are delineated on the plots.



(a)

(b)

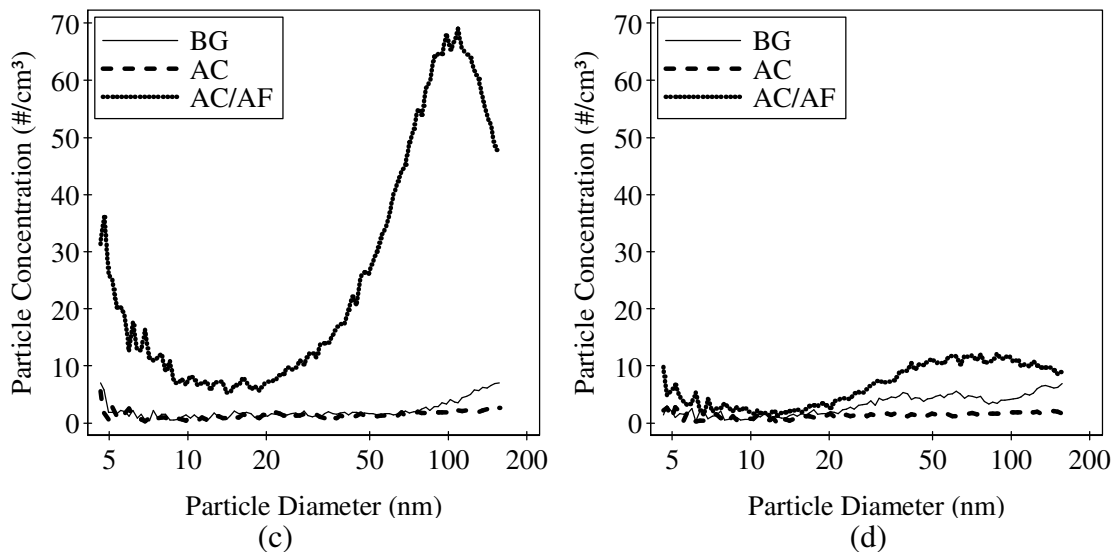


Figure 3. Steady-state particle concentrations of the BG, AC, and AC/AF chamber air for ultrafine particle growth during (a) Test 1, (b) Test 2, (c) Test 3, and (d) Test 4.

DISCUSSION AND CONCLUSIONS

The reactions between ozone emitted from ionizing air cleaners and indoor terpenes have been shown to yield elevated steady-state particle concentrations in a chamber setting. Moreover, the particle removal by the air cleaners is often not effective enough to counteract the particles generated by the ozone/terpene reactions. Thus, the use of an ozone generating air cleaner in the presence of a terpene source can potentially result in increased concentrations of ultrafine particles, particularly those 10 – 50 nm in diameter for the Brand A air cleaners and in the entire tested range of 5 – 160 nm for other air cleaners (Brand B).

The results from these tests have implications for the evaluation of the effectiveness, emission rates of ozone, and health effects regarding ionizing air cleaners. Clean air delivery rate (CADR) tests completed in the absence of a terpene source do not capture this particle generation phenomena and thus overstate the CADR of the ionic air cleaner in the presence of such a source. Furthermore, the entire CADR test methodology fails to account for an air cleaner acting as an emission source of particles because it does not control for air exchange rate, chamber volume, strength of terpene source, and ozone-surface reactions, among other variables. This is a bias and suggests that CADR values for ozone-emitting air cleaners in real indoor environments may be lower than would result from chamber testing. Additionally, ozone emission tests that do not explicitly account for the presence of terpenes or any ozone-reactive surface or airborne agent, such as the UL 867 test, potentially understate the ozone emissions of the device. Further, public health researchers have discovered that the health effects due to SOAs may be different and more deleterious than those from primary aerosols (Rohr *et al.*, 2002 & 2003).

One very important limitation regarding these investigations is that the application of these tests to real indoor environments is dependent on similar conditions to those in the test chamber, particularly similar ozone and terpene concentrations. Additional field tests are being conducted to evaluate these effects in real indoor settings.

The literature cited in this paper is inconclusive on the impact of ion generators on sick building syndrome symptoms, as there are some studies that indicate a positive effect and others that found no effect. However, ion generators, particularly smaller portable units, tend to have very small CADRs, and thus are unlikely to be effective at particle removal in typical indoor environments (Shaughnessy and Sextro, 2006). The ozone emitted by ion generators, while still considerably lower than dedicated ozone generators, is enough to be of concern for human health, although further research on indoor ozone exposures is warranted. The experiments described herein demonstrate the potential for ultrafine particle formation when ion generators are operated in the presence of a terpene source. In summary, this investigation suggests caution in the use of ion generating air cleaners in indoor environments.

On the central issue of this paper, it is clear that ion generators similar to those described herein have no role in a sustainable indoor environment. Ion generators tend to be quiet and consume considerably less energy than

effective air cleaners (i.e., HEPA filters). Despite these advantages, as well as the fact that most ion generators do remove some particles from the air, the negative consequences of ozone generation outweigh these benefits. The ozone itself, as well as the reaction products that result from ozone-initiated chemistry (Weschler, 2006), are of concern. Any air cleaner that can emit more pollution than it removes should not be considered to be sustainable. Furthermore, technologies such as portable HEPA filters do exist that are effective at particle removal and do not generate ozone or other harmful byproducts. A challenge is to create next generation portable air cleaners that are effective and safe, but consume little to no energy, are quiet, and have no harmful side effects.

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