

Indoor Air Quality Implications of Portable Ion Generators

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ABSTRACT

Ion generators are enormously popular air cleaners, despite the fact that scientific research and consumer advocate evaluation suggest caution in their use. Most ionizers generate ozone and have relatively low clean air delivery rates (CADRs). In this investigation, we present a review of scientific and popular literature that spans several decades of research on these devices. Despite some studies that show ion generators can improve perceptions of indoor air quality, reduce the incidence of sick building syndrome (SBS) symptoms, improve learning and productivity, and diminish clinical symptoms, there are also many studies that suggest or demonstrate no significant improvement in improving SBS symptoms. Several studies also measure CADR or parameters that can be used to calculate CADR. Although, reported CADRs varied widely, very few ion generators will significantly reduce indoor particle concentrations in typical indoor environments. Although the ion generators with the highest CADRs can reduce particle concentrations, these devices are typically intended for commercial application and are still not as effective as portable HEPA filters. Published ozone emission results from 16 ion generators suggest that most ionizers generate as much ozone as laser printers or dry-toner photocopiers with no ozone scrubbers. Thus, the ozone levels produced by many ionizing air cleaners are high enough to represent a health concern. In addition to being a respiratory irritant, ozone-initiated reactions can also form ultrafine particles. To investigate this phenomenon, we conducted screening experiments to measure the ultrafine particle formation when ion generators are operated in the presence of an air freshener. Preliminary results suggest that ion generators can act as particle generators, particularly for particles smaller than $0.1 \mu\text{m}$. These results beg the question of whether ion generators should ever be used in indoor environments.

INTRODUCTION

As more Americans realize 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.¹ One technology that has become increasingly popular is portable ion generators. Also called ionizers, ionic air cleaners, and portable electrostatic precipitators, these devices work by charging incoming particles with a corona and removing them to 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 to building surfaces. Most ionizing air cleaners also generate ozone, a respiratory irritant and oxidizing agent that can react with other airborne contaminants to produce fine particles and other byproducts²⁻⁵. The goals of this paper are to summarize the literature on ion generators and perceived air quality, particle removal, and ozone emission rates as well as present some screening experiments that explore particle generation from ion generators in the presence of a solid air freshener.

LITERATURE REVIEW

Ion generators have a long history of being associated with improvements in perceived air quality⁶. Our search found eight studies that conducted research with human subjects on a variety of symptoms associated with sick building syndrome (SBS) symptoms and these studies are summarized in Table 1. Table 1 lists the sample size, symptoms that were considered, as well as the results for each study. A test done with a placebo was a study that included an air cleaner that appeared to be operating but that was not, and a baseline test indicates a test on the same (or a similar population) with no air cleaner. It should be noted that almost all of the articles listed in Table 1 were conducted on 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	Symptom frequency and/or severity	Comments
Fishman (1981) ⁷	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) ⁸	108	thermal comfort rating, the alert-drowsy, fresh-stuffy scales, reported incidence of headache	significant improvement	baseline placebo
Laws (1982) ⁹	74	headache, nausea, dizziness incidence perceived alertness, freshness, sensation of comfort and pleasantness	improvement significant improvement	placebo
Hawkins and Morris (1984) ¹⁰	79	complaints of lethargy	significant improvement	baseline placebo
Wyon (1992) ¹¹	28	dry throat, dry lips, dry skin, brittle nails, dry eyes	significant improvement	baseline placebo
Shaughnessy <i>et al.</i> (1994) ¹²	10	mean order scores, mean nasal irritation, mean eye irritation, overall air acceptability	improvement	baseline
Rosen and Richardson (1999) ¹³	93	non-attendance due to sickness	improvement	baseline
Richardson <i>et al.</i> (2001) ¹⁴	7	dust and dirt, draught, stuffy bad air, dry air	improvement	baseline

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 improvement⁸⁻¹¹ in the listed symptoms in the presence of an ion generator and five studies^{7,9,12-14} show no significant improvement. 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 sick building syndrome symptoms 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^{1,12,15}. It is more independent of the measurement environment than CRF or ACF.

Table 2 lists sample size, experimental parameters, and CADR for 10 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^{12,15,18, 21,23} to over 500 m³/hr¹⁶ 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^{1,12,15, 24}.

Many ion generators also generate ozone as a byproduct of their operation. Although, ozone emission is occasionally marketed as being a positive attribute because ozone can remove odorous compounds and very high levels of ozone can act as a disinfectant, ozone emission is generally considered a negative feature because it is a respiratory irritant and can have serious health effects, even at low concentrations²⁵⁻²⁷. Table 3 lists ozone emission rates from 5 studies for 23 ion generators that include personal units that are intended to be worn around the neck, slightly larger 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 range from 56 µg/hr for the smallest portable unit to 4.04 mg/hr for the largest portable unit. The largest emission rates are similar to those from an uncontrolled laser printer or dry-toner photocopier with no ozone scrubber. Emissions are 1-3 orders of magnitude lower than dedicated ozone generators^{23,24,31}. However, when put in the context of a typical indoor environment, these emissions are still enough to cause a concern about human exposure, particularly for sensitive individuals²⁶.

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) ^{16 b,c}	3	21.5	ETS	piezoelectric	119
		69.9		microbalance monitor	130
		333		(0.01 - 3.0 μm)	533 ^d
Offermann <i>et al.</i> (1985) ^{15 e}	2	37.5	environmental tobacco smoke (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 0.5 - 3.0 μm dust 2 - 3 μm fungal spores 4 - 5 μm fungal spores 10 - 12 μm pollen	not reported	22 - 90 0 - 15
Grabarczyk (2001) ^{17 b,c,g}	1	50	ambient dust	optical particle counter (0.3 - 2.5 μm)	<146- 174 ^g
Niu <i>et al.</i> (2001a) ^{18 f}	5	6.4	0.3 - 3.0 μm incense smoke	light-scattering monitor (PM ₁₀ concentration)	6.7
					9.0
					57.4
					64.3
					96.6
Grinshpun <i>et al.</i> (2004) ^{19 h}	1	24.3	NaCl	optical particle counter, aerodynamic particle sizers (0.5 - 2 μm)	25-38
		2.6	latex spheres		
		0.026	ETS bacteria		
Lee <i>et al.</i> (2004) ^{20 f}	2	24.3	smoke	impactor	30-60 150
Grinshpun <i>et al.</i> (2005) ^{21 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) ^{22 h,i}	2	34.2	dust	optical particle counter, dust monitor	120
					173
Yu (2005) ^{23 j,k}	5	14	incense KCl	optical particle counter (0.1-1 μm)	19-79 30-65
				aerodynamic particle sizer (0.5 -5 μm)	3-37 52-111
					5-29

^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 $\lambda < 0.1/\text{hr}$

^f $\lambda < 0.03/\text{hr}$ (i.e. negligible)

^g Removal by ventilation is included in the CADR and thus it is an upper bound on the CADR.

^h Air exchange rate not reported

ⁱ The authors refer to the tested device as a “plasma air cleaner”, which appears to be the same as the other ion generators tested as part of this research most of the other portable ion generators described here.

^j $\lambda = 0.3 - 1 \text{ hr}$

^k Data for incense challenge aerosol also reported in Mullen *et al.* (2005)²⁴

Table 3. Ozone emission rates for portable ion generators.

Source	Sample Size	Description	Ozone Emission Rate (mg/hr)
Phillips <i>et al.</i> (1999) ²⁸	2	personal	0.102
		personal	0.144
Niu <i>et al.</i> (2001a, 2001b) ^{18, 29}	5	portable	0.056
		portable	0.065
		portable	0.174
		portable	0.255
		portable	2.757
Tung <i>et al.</i> (2005) ³⁰	3	portable	1.47 ± 0.19
		portable	0.95 ± 0.07
		portable	13.42 ± 1.38
Yu <i>et al.</i> (2005), Mullen <i>et al.</i> (2005) ^{23,24}	5	portable	2.42 ± 0.52
		portable	2.86 ± 0.15
		portable	0.74 ± 0.15
		portable	4.04 ± 0.16
		portable	3.92 ± 0.14
Britigan <i>et al.</i> (2006) ³¹	8	portable	2.2
		personal	0.3
		automobile	0.74
		automobile	0.40
		automobile	0.48
		small portable	0.17-0.24
		small portable	0.16
		personal	0.50

A particular concern about ozone emission is the potential for reactions with unsaturated compounds that can lead to multi-functional oxygenated gases, e.g. aldehydes, and ultrafine particles. 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 potential in the indoor environment^{2-5, 32,33}. These studies have characterized byproduct and ultrafine 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, and little is known about the potential for ion generators to form ultrafine particles. 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 (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.

The chamber, which was cleaned with water (*i.e.*, no cleanser) and allowed to dry overnight before Tests 1 and 3, 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 ultrafine 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 approximately one-day period. During each test, continuous measurements of ozone and ultrafine 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 ultrafine 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 and Discussion

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 (79.2 – 82 °F), 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 temperatures⁴.

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 in Austin, Texas, where the testing was performed. 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 were a different brand of air cleaners than in Test 1 and 2, accounting for the differences in ozone emission rates evident from the steady-state concentrations. 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.

Steady-state ultrafine particle concentrations. Figure 1 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.

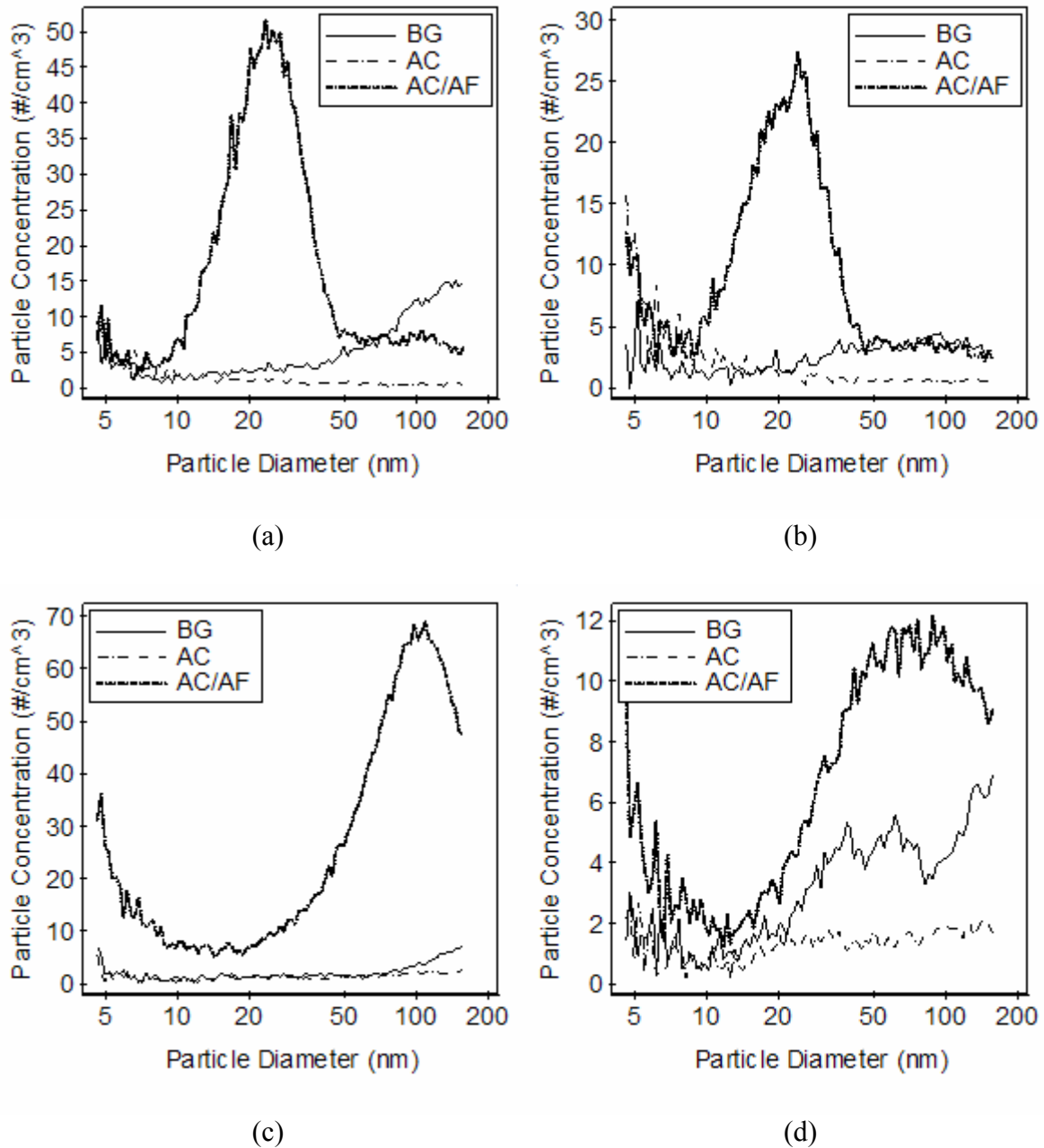
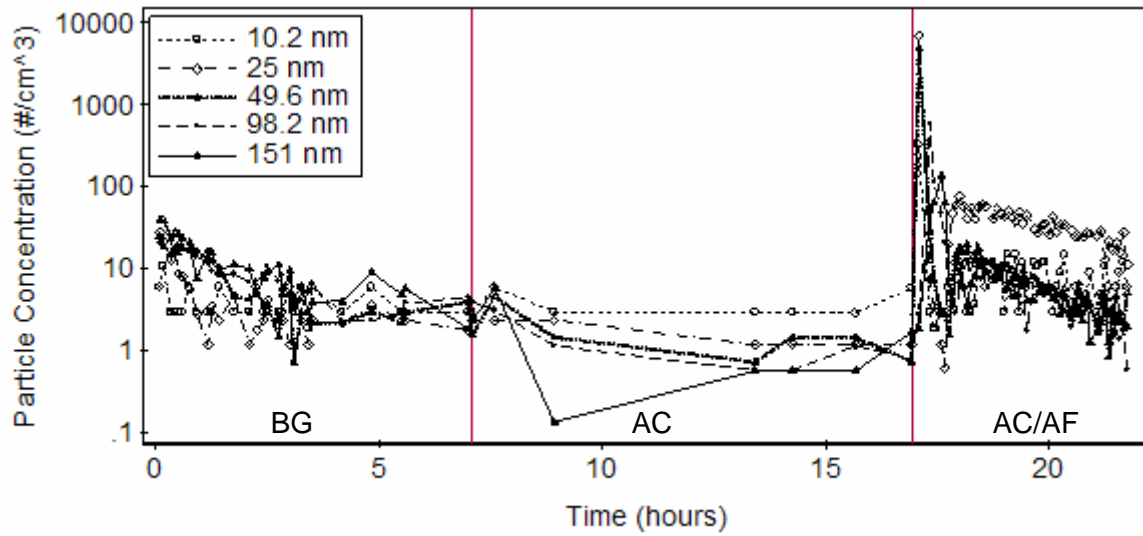
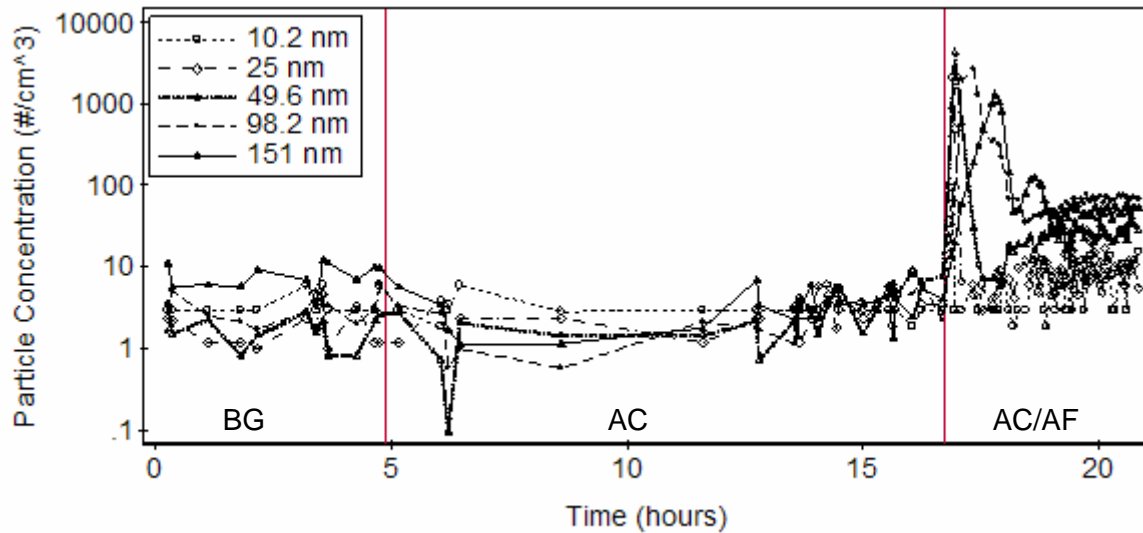


Figure 1. Steady-state particle concentrations of the BG, AC, and AC/AF chamber air for ultrafine particle growth during (a) Test 1, (b) Test 2, (c) Test 3, and (d) Test 4.

Particle growth wave due to ozone/unsaturated compound reactions. The reduction in ozone and the increase in particle concentrations is evidence that ozone-initiated particle formation is occurring. Figure 2 shows the particle number concentrations in the chamber as a function of time for Tests 2 and 3.



(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.

Five particle sizes are shown on each of the plots, 10.2, 25, 49.6, 98.2, and 151 nm diameters. Note that the y-axes in both cases are presented on a logarithmic scale, and that the x-axes correspond with the test duration. For both cases shown, the BG concentrations are higher than the during the AC period when the air cleaners were energized, which corresponds to the results displayed in Figure 1. At the beginning of the AC/AF periods, the pine-scented air freshener was added to the chamber, and the particle growth is evident in the plots. In both cases, there were large particle bursts and increases of over 1000 particles/cm³ for some size ranges. Initially, the concentrations of the 49.6 nm diameter particles increased dramatically, followed in time by the

98.2 and 151 nm diameter particle sizes. This particle growth wave is likely due to coagulation and condensation effects, which are evidenced by the diminishing concentrations of 49.6 nm size particles and the increasing concentrations of 98.2 nm size particles. This particle growth wave is clearly noticeable, most especially on Figure 2b. Other researchers conducting ozone/terpene particle formation experiments have noted similar particle formation and growth wave patterns²⁻⁴.

Also, the dynamic particle number concentrations shown for Tests 2 and 3 reinforce the trends for the different brands discussed above. In Figure 2a, the 25 nm sized particles remain elevated above the other size ranges during the AC/AF period, which is in the size range most poorly removed by Brand A (*i.e.*, the 10 – 50 nm range). Also, in Figure 2b, the larger size particles are the most elevated during the AC/AF period, again in agreement with the findings for Brand B discussed above.

DISCUSSION AND CONCLUSIONS

Thus, 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 removal of 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 some air cleaners (Brand A) and in the entire tested range (5 – 150 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 done 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 for that do not explicitly account that the presence of terpenes (or any ozone-reactive surface or airborne agent) 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^{34,35}.

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 will be conducted in the near future 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 clean air delivery rates and thus are unlikely to be effective at particle removal in typical indoor environments. The ozone emitted by ion generators, while still considerably lower than dedicated ozone generators, is enough to be of concern for a human health perspective, 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.

ACKNOWLEDGMENTS

The International Society for Exposure Assessment and the American Chemistry Council provided funding for this work.

REFERENCES

1. Shaughnessy, R. J.; Sextro, R. G. *J. of Occ. Environ. Hygiene* **2006**, *3*, 169-181.
2. Weschler, C. J.; Shields, H. C. *Atmos. Environ.* **1999**, *33*, 2301-2312.
3. Wainman, T.; Zhang, J. F.; Weschler, C. J.; Liroy, P. J. *Environ. Health Persp.* **2000**, *108*, 1139-1145.
4. Sarwar, G.; Corsi, R.; Allen, D.; Weschler, C. *Atmos. Environ.* **2003**, *37*, 1365-1381.
5. Hubbard, H. F.; Coleman, B. K.; Sarwar, G.; Corsi, R. L. *Indoor Air* **2005**, *15*, 432-444.
6. Sun, M. *Science* **1980**, *210*, 31-32.
7. Fishman, D.S. *Heat. & Vent. Engin.* **1981**, *Oct.*, 13-15.
8. Hawkins, L.H. *J. of Environ. Psych.*, **1981**, *1*, 279-292.
9. Laws, C.A. *Heat. & Vent. Engin.* **1982**, *May*, 18-20.
10. Hawkins, H.L.; Morris, L. *Indoor Air: Proc. of the 3rd Int. Conf. on IAQ and Climate* **1984**, 197-200.
11. Wyon D. P. *Environ. Tech.* **1992**, *13*, 313-322.
12. Shaughnessy, R. J.; Levetin, E.; Blocker, J.; Sublette, K. L. *Indoor Air* **1994**, *4*, 179-188.
13. Rosen, K. G.; Richardson, G. *Sci. Tot. Environ.* **1999**, *234*, 87-93.
14. Richardson, G.; Harwood, D. J.; Eick, S. A.; Dobbs, F.; Rosen, K. G. *Sci. Tot. Environ.* **2001**, *269*, 145-155.
15. Offermann, F. J.; Sextro, R. G.; Fisk, W. J.; Grimsrud, D. T.; Nazaroff, W. W.; Nero, A. V.; Revzan, K. L.; Yater, J. *Atmos. Environ.* **1985**, *19*, 1761-1771.
16. Repace, J.L.; Seba, D.B.; Lowrey, A.H.; Gregory, T.W. *Clinical Ecology* **1983**, *2*, 90-94.
17. Grabarczyk, Z. *J. of Electrostatics* **2001**, *51*, 278-283.
18. Niu, J. L.; Tung, T. C. W.; Burnett, J. *J. of Electrostatics* **2001**, *51*, 20-24.
19. Grinshpun, S.A.; Adhikari, A.; Lee, B.U.; Trunov, M.; Mainelis, G.; Yermakov, M.; Reponen, T. *Air Pollution XII* **2004**, 689-704.
20. Lee, B. U.; Yermakov, M.; Grinshpun, S. A. *Atmos. Environ.* **2004**, *38*, 4815-4823.
21. Grinshpun, S. A.; Mainelis, G.; Trunov, M.; Adhikari, A.; Reponen, T.; Willeke, K. *Indoor Air* **2005**, *15*, 235-245.
22. Xu, J.; Zhang, H.; You, S. *Indoor Air 2005: Proc. of the 10th Int. Conf. on IAQ and Climate* **2005**, 2920-2924.
23. Yu, X. *MS Thesis, The University of Texas at Austin, Department of Civil, Architectural, and Environmental Engineering* **2005**.
24. Mullen, N.; Yu, X.; Zhao, P.; Corsi, R. L.; Siegel, J. A. *Indoor Air 2005: Proc. of the 10th Int. Conf. on IAQ and Climate* (**2005**), 2957-2961.

25. Gent, J. F.; Triche, E. W.; Holford, T. R.; Belanger, K.; Bracken, M. B.; Beckett, W. S.; Leaderer, B. P. *JAMA* **2003**, *290*, 1859-1867.
26. Bell, M. L.; McDermott, A.; Zeger, S. L.; Samet, J. M.; Dominici, F. *JAMA* **2004**, *292*, 2372-2378.
27. Bell, M. L.; Peng, R. D.; Dominici, F. *Environ. Health Persp.* **2006**, *114*, 532-536.
28. Phillips, T. J.; Bloudoff, D. P.; Jenkins, P. L.; Stroud, K. R. *J. of Exp. Anal* **1999**, *9*, 594-601.
29. Niu, J. L.; Tung, T. C. W.; Burnett, J. *Atmos. Environ.* **2001**, *35*, 2143-2151.
30. Tung, T. C. W.; Niu, J.; Burnett, J.; Hung, K. *Indoor Built Environ.* **2005**, *14*, 29-37.
31. Britigan, N.; Alshawa, A.; Nizkorodov, S. A. *JA&WMA* **2006**, *56*, 601-610.
32. Rohr, A. C.; Weschler, C. J.; Koutrakis, P.; Spengler, J. D. *Aerosol Sci. Tech.* **2003**, *37*, 65-78.
33. Sarwar, G.; Olson, D. A.; Corsi, R. L.; Weschler, C. J. *JA&WMA* **2004**, *54*, 367-377.
34. Rohr, A. C.; Wilkins, C. K.; Clausen, P. A.; Hammer, M.; Nielsen, G. D.; Wolkoff, P.; Spengler, J. D. *Inhal. Tox.* **2002**, *14*, 663-684.
35. Rohr, A. C.; Shore, S. A.; Spengler, J. D. *Inhal. Tox.* **2003**, *15*, 1191-1207.