Building Energy and Environmental Systems Laboratory (BEESL)
Department of Mechanical and Aerospace Engineering
College of Engineering and Computer Science
Syracuse University

Healthy People in Healthy Indoor Environments
INDOOR AIR 2022
June 12th to 16th
Kuopio FINLAND

Performance of in-duct bipolar ionization devices on pollutant removal and potential byproduct formation in indoor environments

Jialei Shen[1], Zhenlei Liu[1], Daniel Love[2], Mary Dekold[2], Beverly Guo[1], Michael J. Birnkrant[2], Peter J. McKinney[2], Bing Dong[1] and Jianshun Zhang[1,3]

[1] Syracuse University
[2] Carrier Global Corporation
[3] Nanjing University

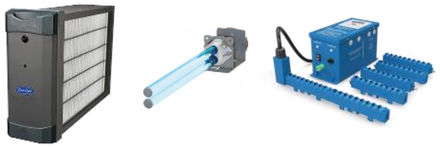
Background

IAQ and air cleaning technologies

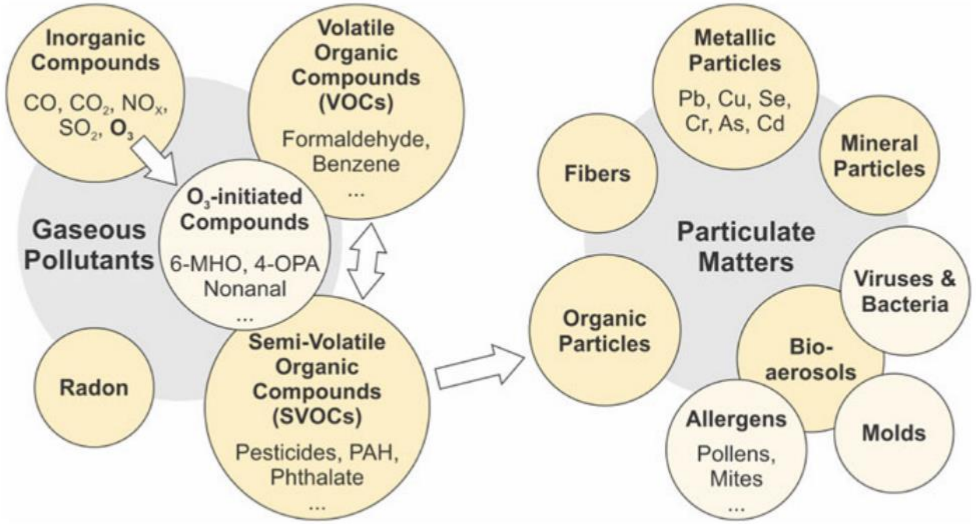
Indoor air quality (IAQ) is vital to human health, comfort, productivity, and wellbeing.

Air cleaning technologies:
- Filtration
- Sorption
- Ionization
- Oxidation
- UVGI
- …

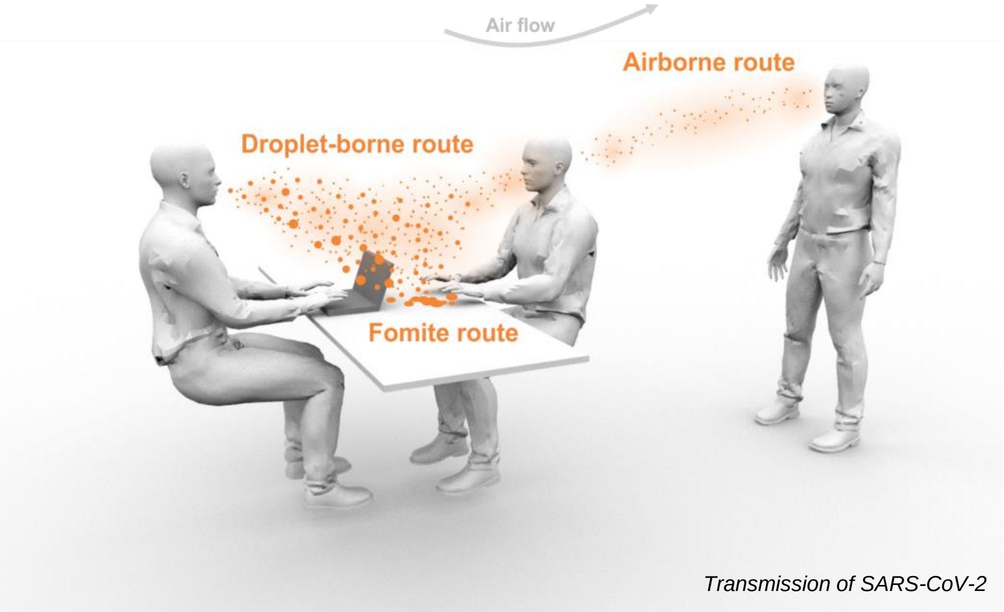
Portable unit



Induct unit



(Zhang et al., 2022)



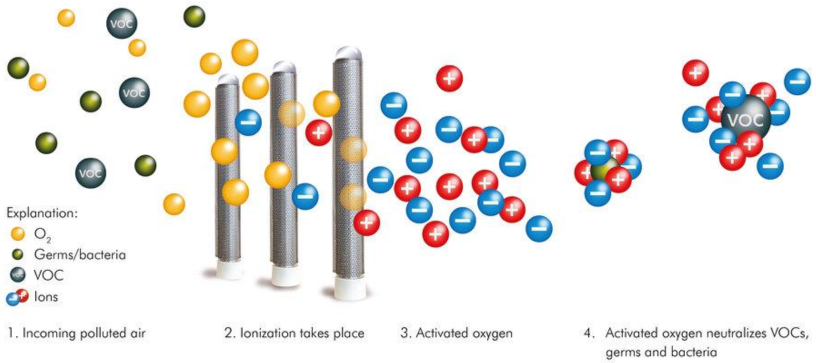
Transmission of SARS-CoV-2

Zhang, J., Shen, J., Gao, Z., 2022. Managing IAQ at Multiple Scales: From Urban to Personal Microenvironments. Handbook of Indoor Air Quality 2022:1–42.

Background

In-duct needlepoint bipolar ionization technology

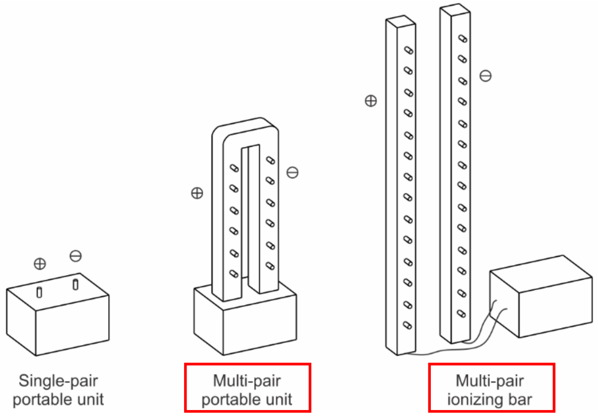
Air ions:
- attachment to particles → charge particles
- contact with a surface
- recombination with other ions
- reaction with gaseous molecules



(Airiusfans, 2022)

Commercially available needlepoint bipolar ionization devices:
- Generation of positive and negative air ions
- Charging particles for removal
- Inactivation of pathogen-laden particles
- Low ionization voltage (< 12V) to minimize the release of ozone and other byproducts

Typical configurations of induct bipolar ionizers:
- Single-pair portable unit
- Multi-pair portable unit
- Multi-pair ionizing bar



Commercially available induct needlepoint bipolar ionizers

Trane Technologies, A Taxonomy of Air-Cleaning Technologies Featuring Bipolar Ionization, 2021.
Airiusfans. Ionization/plasma air purification technology improve indoor air quality. Airiusfans.com. 2022.

Methodology

Operation conditions

Tested bipolar ionization configurations:

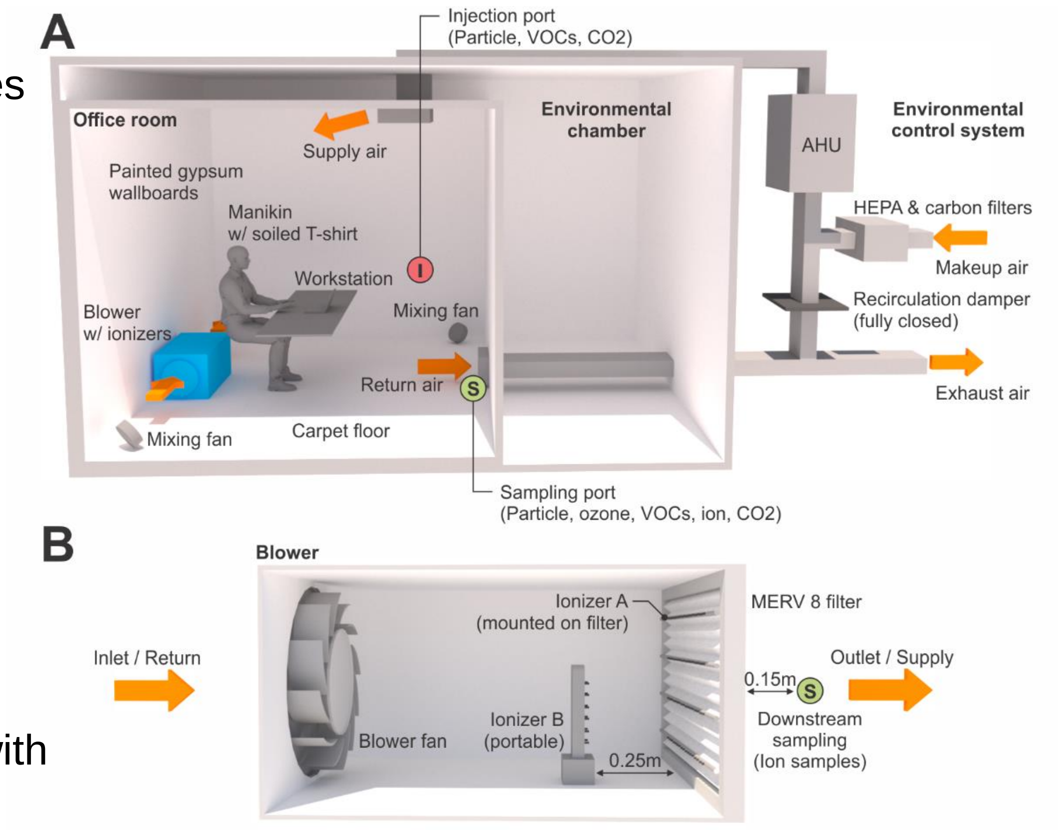
- Configuration A (Ionizer A): Ionizing bar (4 bars), 34 pairs of +/- poles → mounted on a MERV 8 filter
- Configuration B (Ionizer B): Multi-pair portable unit, 6 pairs of +/- poles

Tested duct (to simulate a realistic AHU):

- A blower system placed in the chamber (a metal box/duct with a controllable blower fan at the inlet)
- A MERV 8 filter installed at the outlet (with the I-A mounted at the upstream side)
- I-B installed 0.25m upstream of the filter
- Q = 505 m3/h during the tests

Full-scale environmental chamber with real-scenario office settings:

- Full-scale stainless-steel chamber in BEESL
- A full-scale single office built inside the chamber (3.5 × 3.0 × 2.7 m)
- Carpet, painted gypsum wallboard, table, partitions, heated manikin with soiled T-shirt
- Airflow rates: airtightness 0.01 ACH; low airflow Q = 24.0 m3/h (minimal value by ASHRAE), high airflow Q = 55.6 m3/h
- Two mixing fans



Methodology

Operation conditions

Particle injection:
- 8-jets nebulizer
- Purified clean air + salt solution
- Nominal injection airflow rate = 18 L/min
- Maintaining the steady-state PM2.5 below 100 – 200 μg/m3 (close to the worst-case indoor concentration)

VOC (formaldehyde and toluene) injection:
- Dynacalibrator (VICI Metronics, Inc.)
- Formaldehyde and toluene permeation tubes used
- Target background level of 39.3 μg/m3 for HCHO and 189.6 μg/m3 for toluene

Heated manikin with soiled T-shirt (skin oil):
- A freshly cleaned T-shirt worn by a volunteer overnight prior the test day
- Manikin maintained at 33.9 degC
- Summer clothes (T-shirt + long trousers), 0.43 clo

Methodology

Measurements

Monitors:

- Particles: APS,
- Ozone: 2B Tech Ozone monitor,
- VOCs: DNPH and Sorbent samples (HPLC and GCMS), PTRMS for background VOC level (w/ injection)
- CO2: Gas Monitor and HOBO CO2 logger
- Negative ion: Air ion counter

Sampling location:

Exhaust of the room (return air)

Procedure

Decay ("pull-down") tests

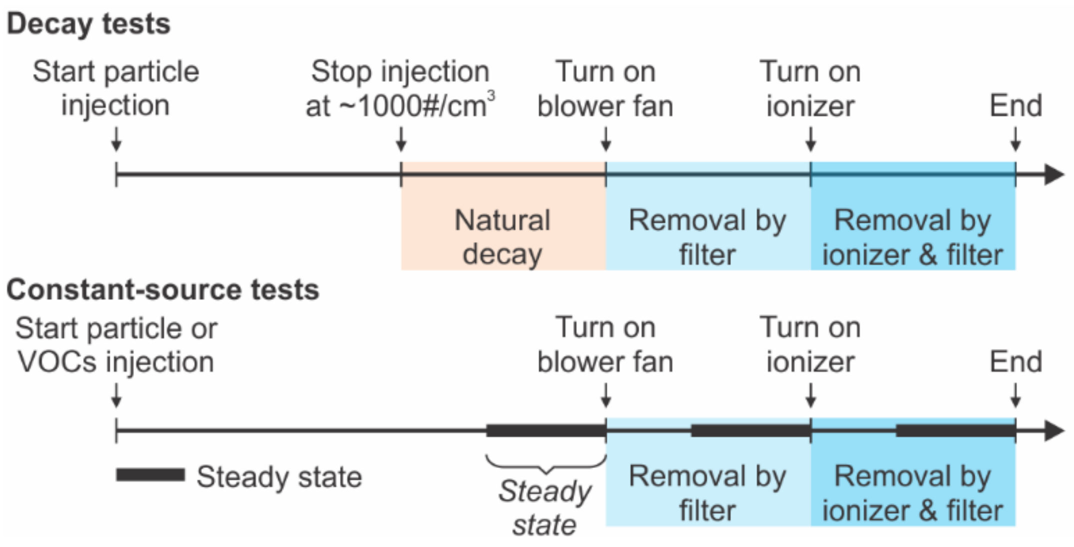
Constant-source tests

Test method	Test ID	Test condition	Airflow condition	Injected pollutants	Test date
Decay test	Test 1	Natural decay	Infiltration[a]	Particles	Dec 1st, 2021
	Test 2	Blower w/ MERV 8 filter	Infiltration	Particles	Nov 29th, 2021
	Test 3	Ionizer A & filter	Infiltration	Particles	Nov 28th, 2021
	Test 4	Ionizer B & filter	Infiltration	Particles	Nov 30th, 2021
	Test 5	Ionizer B (w/t filter)	Infiltration	Particles	Dec 10th, 2021
Constant-source test	Test 6	Ionizer A & filter	Low airflow[b]	Particles	Oct 28th, 2021
	Test 7	Ionizer A & filter	Low airflow	Particles	Nov 24th, 2021
	Test 8	Ionizer A & filter	High airflow[c]	Particles	Feb 14th, 2022
	Test 9	Ionizer A & filter	High airflow	Particles	Feb 14th, 2022
	Test 10	Ionizer A & filter	Low airflow	VOCs	Nov 23rd, 2021

[a] Infiltration: Environmental system was fully closed. There was only natural infiltration existing in the room, $\lambda_{inf} = 0.01h^{-1}$ (0.3 m^3/h).

[b] Low airflow: Q = 24.0 m^3/h.

[c] High airflow: Q = 55.6 m^3/h.



Methodology

Data analysis

Single-zone model

$$\lambda C_{in} = \lambda C_{out} - k_{dep} C_{in} + \frac{E}{V}$$

Decay tests

$$C_t = C_0 \cdot e^{-\lambda t}$$

$$\lambda = k_n + k_{AC} = (\lambda_{inf} + k_{dep}) + k_{filter} + k_{ionizer}$$

$$\lambda = \lambda_{inf} + \lambda_Q = \lambda_{inf} + \frac{Q}{V}$$

Clean air delivery rate (CADR) and single-pass removal efficiency (SPRE)

$$CADR = k_{AC} \cdot V$$

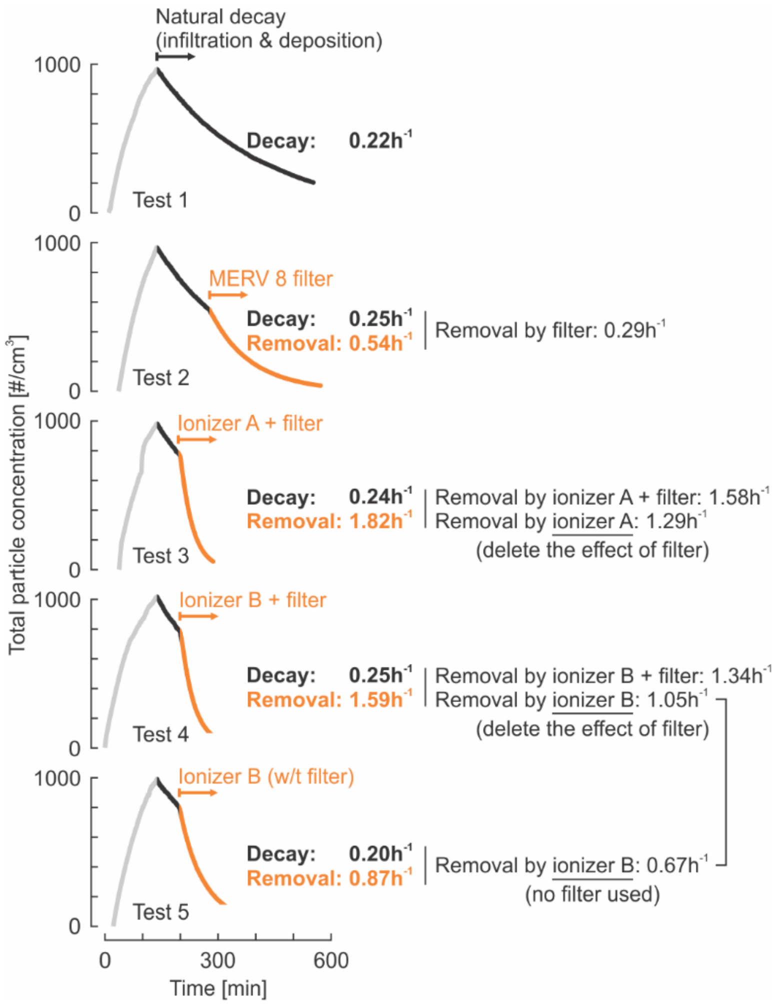
$$CADR = (Q + k_{dep} \cdot V) \cdot (\frac{C_1}{C_2} - 1)$$

$$SPRE = \frac{CADR}{Q_{AC}}$$

Results & Discussions

Particle removal performance

Decay tests



Tests	Test 1	Test 2	Test 3	Test 4	Test 5
Test conditions	Natural decay	Filter (MERV 8)	I-A + filter	I-B + filter	I-B (w/t filter)
Natural decay rate[a] [h^{-1}]	0.22	0.25	0.24	0.25	0.20
Removal rate [h^{-1}]	/	0.54 **0.29** (w/t decay)	1.82 **1.58** (w/t decay)	1.59 **1.34** (w/t decay)	0.87 **0.67** (w/t decay)
$CADR_{PM}$ [m^3/h]	/	15.7 **8.5** (w/t decay)	53.0 **46.0** (w/t decay)	46.3 **38.9** (w/t decay)	25.3 **19.4** (w/t decay)
$SPRE_{PM}$ [%]	/	3.1 **1.7** (w/t decay)	10.5 **9.1** (w/t decay)	9.2 **7.7** (w/t decay)	5.0 **3.8** (w/t decay)

[a] Natural decay rate (k_n): the combined effect of infiltration (λ_{inf}) and particle natural deposition (k_{dep}).

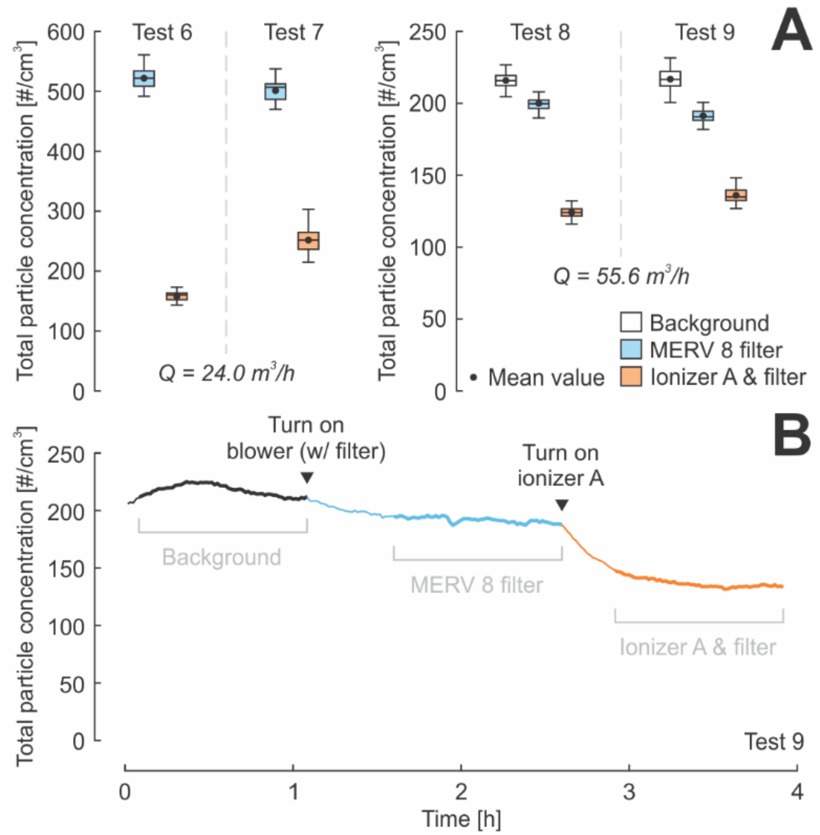
Airtightness: ACH = 0.01 /h

The combined use of ionizers (A and B) and MERV 8 filter showed an absolute increase on $SPRE_{PM}$ by about 6-7.4%

The ionizer B alone (i.e., without the MERV 8 filter) provided very limited particle removal efficiency (3.8%).

Particle removal performance

Constant-source tests



Test	Q [m³/h]	$k_{dep}\cdot V^a$ [m³/h]	Average total particle number level in each state [#/cm³]			CADR$_{PM}$^{b} [m³/h]			SPRE$_{PM}$^{b} [%]		
			Bkg	Blower on (w/ filter)	Ionizer A on	MERV 8 filter	Ionizer A & filter	Ionizer A^c	MERV 8 filter	Ionizer A & filter	Ionizer A
6	24.0	6.1	/	521.4	159.1	/	/	68.5	/	/	13.6
7	24.0	6.1	/	500.7	251.7	/	/	29.8	/	/	5.9
8	55.6	6.1	215.5	199.7	124.5	4.9	45.1	37.3	1.0	8.9	7.4
9	55.6	6.1	217.3	191.6	136.6	8.3	36.5	24.8	1.6	7.2	4.9
8^d	55.6	6.1	/	/	/	/	52.6^e	/	/	10.4^e	/

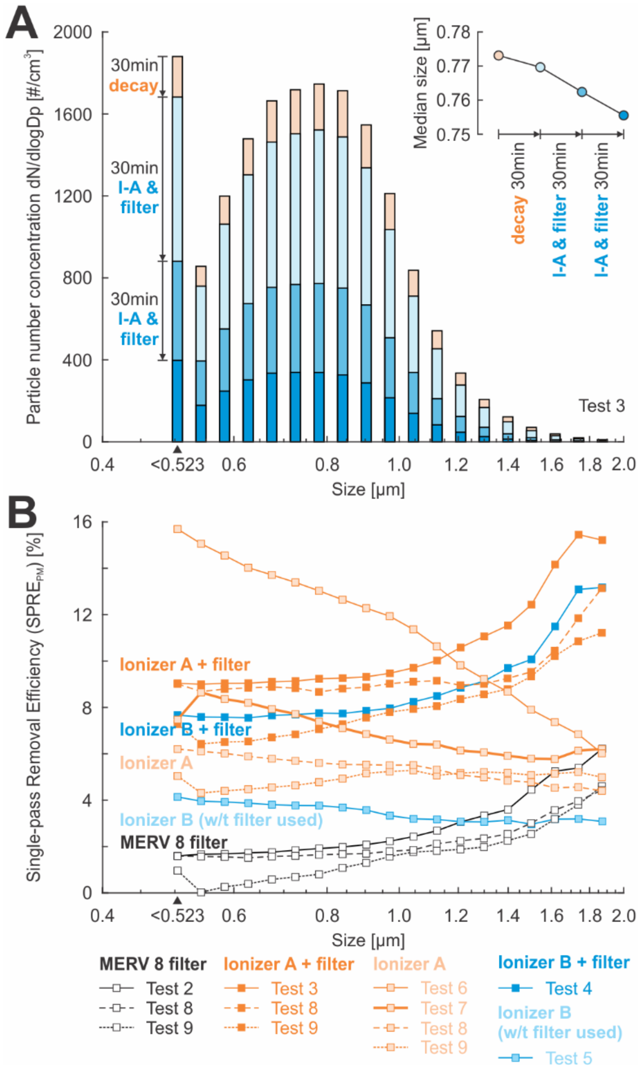
[a] Assuming a constant particle deposition rate k_{dep} = 0.21 h^{-1}. The estimated CADR$_{PM}$ and SPRE$_{PM}$ for the scenario with ionizer A and filter, and the scenario with ionizer A individually, may be underestimated as the actual particle deposition rate was likely higher when the ionizer was working.
[b] Particle removal due to natural deposition were ruled out.
[c] The CADR of ionizer was calculated through Eq. (6), instead of subtracting the CADR of filter from the CADR of ionizer and filter.
[d] A decay test was performed along with the constant-source test of Test 8. The overall decay rate estimated from the exponential regression was 3.86 h^{-1} (including natural deposition and dilution by fresh air supplied by the control system Q).
[e] Excluding natural deposition and dilution by fresh air supply.

	Filter	Filter + I-A	→ Individual I-A
SPRE$_{PM}$	1.0 – 1.6%	7.2 – 10.4%	→ 4.9 – 13.6%

Results & Discussions

Particle removal performance

Particle size distribution



Configurations	Test	Size-specific average SPRE$_{PM}$ [%]	
		0.5-1.0 μm	1.0-2.0 μm
MERV 8 filter	Test 2	1.9	4.1
	Test 8	0.8	2.6
	Test 9	1.6	2.9
	Mean±SD	1.4±0.6	3.2±0.8
Ionizer A/B + filter	Test 3	9.2	12.2
	Test 4	7.7	10.3
	Test 8	8.8	10.0
	Test 9	7.0	9.3
	Mean±SD	8.2±1.0	10.5±1.2

MERV 8 filter removed larger particle more efficiently

I-A and I-B alone removed smaller particles more readily

When integrated with the filter, ionization can improve the particle efficiency considerably for greater particles.

→ It is preferred to apply ionizers in the air duct integrated with the filter rather than using the ionizer independently

Results & Discussions

Byproduct formation – Air ions

Adverse effects on cardiovascular health were observed when people were exposed to 13×10^3 #/cm3 and 60×10^3 #/cm3 level of airborne negative ions in literature

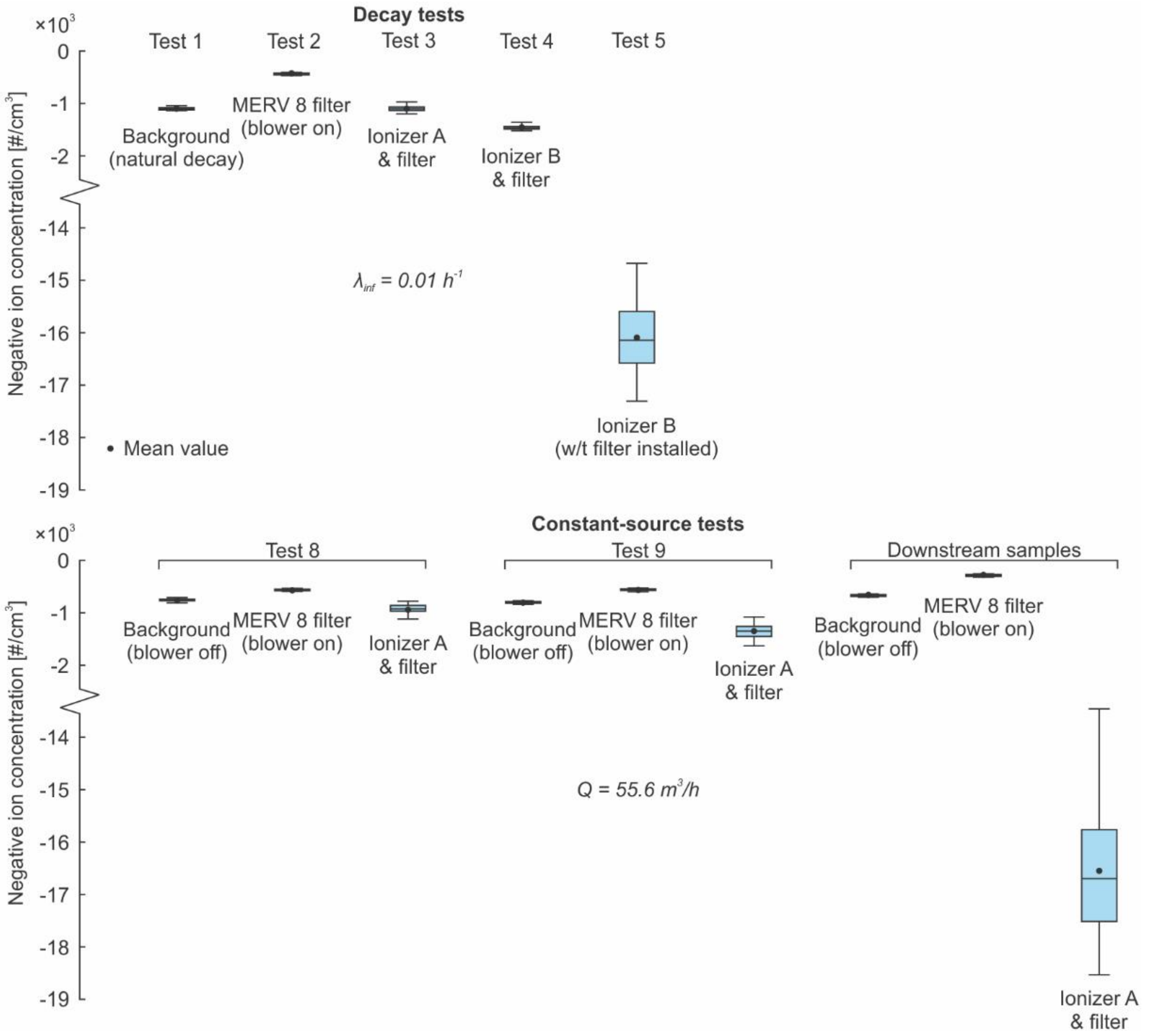
→ Maintaining the indoor air ion at a relatively healthy level

I-A released negative ions to indoor air at a rate between 5.1×10^{11} and 9.8×10^{11} #/h (with filter)

I-B generated negative ions at a rate of 5.4×10^{13} #/h (w/t filter) and 1.3×10^{12} #/h (w/ filter), indicating a significant reduction of 97.6% through the filter

→ Filter (at downstream) can remove most air ions (almost 100% drop of air ions through MERV 11-12 filters in literature)

Negative ions were decomposed very quickly in the fully mixed space



W. Liu, J. Huang, Y. Lin, C. Cai, Y. Zhao, Y. Teng, J. Mo, L. Xue, L. Liu, W. Xu, X. Guo, Y. Zhang, J. Zhang, Negative ions offset cardiorespiratory benefits of PM2.5 reduction from residential use of negative ion air purifiers, Indoor Air.

W. Dong, S. Liu, M. Chu, B. Zhao, D. Yang, C. Chen, M.R. Miller, M. Loh, J. Xu, R. Chi, X. Yang, X. Guo, F. Deng, Different cardiorespiratory effects of indoor air pollution intervention with ionization air purifier: Findings from a randomized, double-blind crossover study among school children in Beijing, Environ. Pollut. 254 (2019) 113054

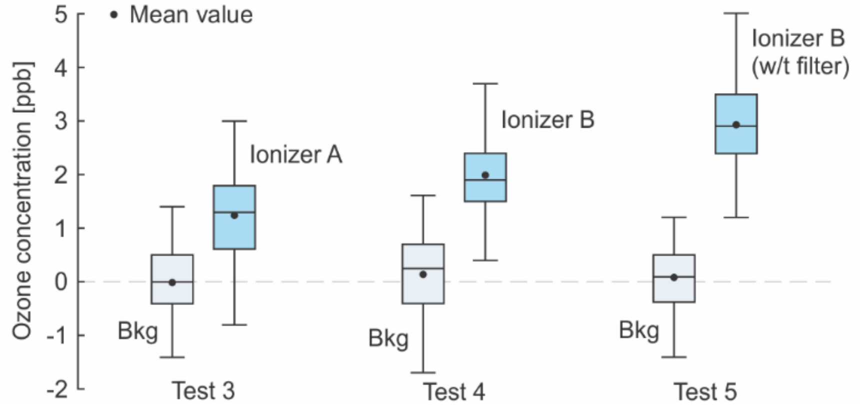
Results & Discussions

Byproduct formation – Ozone

Slight ozone increase/generation during decay tests (ACH = 0.01 /h)

- I-A + filter: 0.39 mg/h
- I-B + filter: 0.63 mg/h
- I-B: 0.92 mg/h

No ozone generation detected during constant-source tests (realistic scenarios)



Ozone concentrations in decay test

Results & Discussions

VOC removal and formation

The variation of VOC concentrations before/after using ionizers were within the background fluctuation (PTRMS data)

No VOC removal or formation were detected

Compounds	Formula	VOC concentration at different test conditions [μg/m³] Bkg	Blower on (with filter) Set 1[b]	Blower on (with filter) Set 2	Blower on (with filter) Mean	Ionizer A on Set 1	Ionizer A on Set 2	Ionizer A on Mean	% change after using ionizer	Relative SD of reference bkg VOC levels[c] [%]
		t = 0h	t = 9h	t = 12h	/	t = 18h	t = 50h	/		
Formaldehyde[a]	CH2O	20.6	18.4	19.8	**19.1**	19.5	22.1	**20.8**	**+8.9%**	4.3%
Acetaldehyde	C2H4O	6.6	5.2	5.0	**5.1**	4.9	4.3	**4.6**	**-9.8%**	12.5%
Acetone	C3H6O	9.1	9.0	9.4	**9.2**	10.1	10.4	**10.3**	**+12.0%**	10.5%
Benzene	C6H6	1.8	1.8	1.7	**1.8**	1.8	1.8	**1.8**	**0.0%**	66.7%
Toluene[a]	C7H8	138.7	141.5	139.9	**140.7**	144.1	150.3	**147.2**	**+4.6%**	4.0%
Cyclotrisiloxane, hexamethyl-	C6H18O3Si3	3.8	3.1	3.2	**3.2**	3.2	3.6	**3.4**	**+6.2%**	25.0%
Hexanal	C6H12O	2.5	2.3	2.3	**2.3**	2.4	2.7	**2.6**	**+13.0%**	6.0%
Ethylbenzene	C8H10	n.d.	n.d.	n.d.	n.d.	1.1	1.2	**1.2**	+	n.d.
Cyclotetrasiloxane, octamethyl-	C8H24O4Si4	2.8	1.6	1.6	**1.6**	1.6	1.8	**1.7**	**+6.2%**	38.8%
Benzaldehyde	C7H6O	2.2	1.8	2.0	**1.9**	2.3	2.2	**2.2**	**+15.8%**	207.7%
2(5H)-Furanone, 3-methyl-	C5H6O2	2.2	1.8	n.d.	**1.8**	n.d.	n.d.	n.d.	-	n.d.
Phenol	C6H6O	1.0	0.8	0.9	**0.9**	0.9	0.9	**0.9**	**0.0%**	12.5%
Cyclopentasiloxane, decamethyl-	C10H30O5Si5	1.4	1.1	1.4	**1.3**	1.4	2.1	**1.7**	**+30.8%**	18.8%
Acetophenone	C8H8O	2.5	1.5	1.0	**1.2**	1.0	1.1	**1.1**	**-8.3%**	32.0%
Nonanal	C9H18O	1.3	1.1	1.1	**1.1**	1.5	1.8	**1.7**	**+54.5%**	47.8%
Naphthalene	C10H8	2.2	2.0	1.7	**1.9**	1.5	1.9	**1.7**	**-10.5%**	n.d.
Propanoic acid, 2-methyl-, 1-(1,1-dimethylethyl)-2-methyl-1,3-propanediyl ester	C16H30O4	4.1	5.3	5.6	**5.4**	5.7	5.4	**5.6**	**+3.7%**	27.6%
TVOC	/	202.8	198.3	196.6	**198.5**	203.0	213.6	**208.5**	**+5.0%**	/

[a] Injected compounds.
[b] Two duplicated samples were collected for each sampling set. The average of two duplicated samples was calculated and presented in the table.
[c] From Table 6.

Results & Discussions

Electric power (measured by a power line meter)

I-A: 0.4 W

I-B: 1.0 W

Typical power of portable air cleaners: 56 W (median)

→ Power / $CADR_{PM}$:

I-A: 0.006 – 0.016 W/(m3/h)
I-B: 0.033 – 0.052 W/(m3/h)
Typical portable air cleaners: 0.15 W/(m3/h)

→ Moderate particle removal efficiency, no significant byproduct formation, low energy use, (price of ionizer?)

B. Zhao, Y. Liu, C. Chen, Air purifiers: A supplementary measure to remove airborne SARS-CoV-2, Build. Environ. 177 (2020) 106918.

Conclusions

1. With the application of ionizer, the equivalent $SPRE_{PM}$ increased from 1.0-1.7% for the regular MERV 8 filter to 7.2-10.4% for the combined ionizer A/B and filter assembly

2. Most ions generated by the ionizer were trapped/captured by the filter

3. No significant ozone and VOC generated under realistic scenarios

4. No VOC removal

5. Cost and efficacy: Moderate particle removal efficiency, but low energy use

Acknowledgement

Syracuse University
Carrier Global Corporation

Thanks!

Jialei Shen
jshen20@syr.edu