Comprehensive Evaluation on the Removal Performance of Air Cleaners for Indoor Air Pollution

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Abstract. Portable air cleaners (PACs) are widely used as the most effective strategies to improve indoor environment. However, with the indoor air components have become more complicated, the current studies focusing on the removal performance for composite pollutants have been inadequate. Therefore, it is necessary to evaluate the comprehensive removal performance of PACs by mixture that is mainly existed in indoor air. In this study, the initial clean air delivery rates (CADRs) of several best-selling sorption-based air cleaners in Chinese market were calculated with a mixing model. The results indicated that the PACs displayed a reliable performance in improving indoor air quality, especially in terms of particulate matter purification. Furthermore, the removal performance of volatile organic compounds (VOCs) by air cleaners was found to be negatively correlated with molecular weight and polarity of pollutant, and the PACs removal performance for most VOCs was improved by reducing the concentration of particulate matter in indoor air.

1. Introduction

In several studies it has been shown that indoor air pollution (IAP) becomes increasingly serious with the development of indoor materials and anthropogenic activities in recent years. It has been estimated that more than 4.3 million deaths annually worldwide due to IAP [1]. Three basic methods are being used to improve indoor air quality: contaminant source control, dilution by ventilation, and air purification. However, for one thing, it is difficult to eliminate contaminants through source control, which needs to joint collaboration in manufacturing, enforcement and legislation, since the pollutants mainly generated by synthetic decoration materials are difficult to be handled [2]. For another, ventilation is frequently limited due to the higher air tightness of modern buildings and the severe atmospheric pollution [3]. Therefore, air purification technology becomes essential for improving indoor environment. Portable air cleaners (PACs) have been widely used as the most effective strategies for the improvement of indoor air quality. Most of air cleaners in the market have been claimed to retain an excellent effective on removal of contaminants, especially sorption-based type cleaners, which usually include an activated carbon (AC) filter and a high efficiency particulate air (HEPA) filter, have occupied 97.6% of the market share in China and exhibited better performance in removing particulate matter and volatile organic compounds [4-5]. However, the evaluations of PACs removal performance have been focused on measuring clean air delivery rates (CADRs) for particulate and gaseous pollutants, respectively. The components of indoor air, which mainly include particulate
matter and volatile organic compounds, are prevalent existed in the form of mixed state Therefore, it is necessary to evaluate the effectiveness of air cleaners on removal performance by mixture that is mainly existed in indoor environment.

The effectiveness of commercial sorption-based PACs on comprehensive removal performance for particulate matter and volatile organic compounds in indoor air was evaluated by measuring CADRs in 30m³ environmental chamber through a mixing model in this study. The decay trend of individual contaminant during test and the effect of particulate matter on removal performance for VOCs were further discussed.

2. Materials and Methods

2.1. Tested air cleaners

In recent years, PACs have developed rapidly in China, and various brands can be selected by consumers in the market. Representative sorption-based portable air cleaners were chosen to evaluate overall removal capacity according to the investigation of their brands, filter forms, purchase prices and sales records in 2018 from the major online shopping websites of China. Table 1 presents the information about the air cleaners used in this study. It should be further noted that PAC-A and PAC-B are domestic brands, while PAC-C and PAC-D are imported air cleaners.

| PAC Code | Model       | Type of Filter                                                                 | Cleaner Size W × D × H (mm) | purchase price (RMB) | Power Consumption (W) | Normal Applied Area (m²) |
|----------|-------------|--------------------------------------------------------------------------------|-----------------------------|----------------------|-----------------------|--------------------------|
| PAC-A    | M3          | Cylindrical composite filter (HEPA filter + activated carbon filter)           | 260 × 260 × 735             | 899                  | 66                    | 51-60                    |
| PAC-B    | KJ400F-NAJ  | Pleated composite filter (fine granular activated carbon interlayer sandwiched between HEPA filters) | 432 × 268 × 628             | 1798                 | 48                    | 31-40                    |
| PAC-C    | KJ421F-N01  | Pre-filter + pleated HEPA filter + porous activated carbon filter              | 395 × 230 × 620             | 2248                 | 55                    | 41-50                    |
| PAC-D    | F-VXJ90C    | Humidification Pre-filter + pleated HEPA filter + porous activated carbon filter | 398 × 275 × 636             | 3056                 | 88                    | 62                      |

2.2. Test Facilities

the experiment was conducted in 30m³ environmental chamber as shown in Figure 1. Several studies have found that the PACs contaminants removal capability was sufficient enough to resist the impact of temperature and humidity fluctuations in the real environment [6]. Considering the initial state stability of contaminants, the repeatability of the experiment, and the economy of the equipment, the temperature and relative humidity were maintained at 23 ± 2 °C and 45 ± 5%, respectively, by heating, ventilation, and air conditioning (HVAC) system. Fresh ambient air was pumped in through filtration system, so that the concentration of individual contaminant in the environmental chamber was less than the background concentration respectively. Superior airtightness was verified through CO₂ injected and monitored (air exchange rate was 0.0005 h⁻¹), good air mixing was shown through recirculation (mixing level was 83.9%), and excellent anti-adsorption of pollutants on the surface was demonstrated through the natural attenuation (the max value of pollutants was 0.0032 min⁻¹).
2.3. Model emission
The contaminants in the mixing model were generated by mixture system with particulates emission and compounds injection. Particulate matter was generated by burning standard cigarettes (EIGHT, Beijing Cigarette Factory, China) in the smoking machine (SPG-C, Suzhou Alos, China). At the same time, VOCs, including alkanes, aromatics, olefins, esters and carbonyls, were introduced into the chamber by evaporation of formaldehyde, acetaldehyde, acetone, toluene, n-butyl acetate, ethylbenzene, xylene, styrene and n-undecane by gas generator (SPG-F, Suzhou Alos, China). All organic solvents were chromatography grade of standard from O2Si except formaldehyde (1.0 mg·L⁻¹ solution standard, NIMTT, China).

2.4. Test Procedure
As the evaluations of PACs removal performance, the CADRs of the mixing model were measured through the total decay of the individual component subtracting the natural attenuation, and then multiplying the volume of the chamber and constant \( t \) (60 min·h⁻¹). The decay values were obtained by constants \( k \) that is the slope of the negative natural logarithm concentration (-ln (C), mg·m⁻³) over time (\( t \), min) through linearly fitting. Correlation coefficients \( R \) were not less than 0.99.

Before all procedures, the internal chamber surfaces were cleaned with deionized water. Air cleaner was placed in the center of the environmental chamber, adjusted the rated state to ensure it was operating normally, and the treated cleaner was then turned off. The HVAC system of environmental chamber was regulated so that the air properties were maintained at the set point (temperature: 23 ± 2 °C, relative humidity: 45 ± 5%). The filtration system was turned on until the background concentration of particles size above 0.3 μm, individual volatile organic compound and total volatile organic compounds was less than 2×10⁶ particles·m⁻³, 5×10⁻³ mg·m⁻³ and 5×10⁻² mg·m⁻³, respectively. The HVAC and filtration system of the chamber were turned off. Meanwhile, the stirring fan and circulating fan were started to improve the air mixing and left running for 10 min. 30 mg, discussed in detail in this paper, was emitted.

Figure 1. Demonstration of the 30m³ environmental chamber
in 1 hour for all compounds besides six standard cigarettes by mixture system, the mixture was stirred sufficiently in 10 min, and then the stirring fan was turned off. Concentrations of components in the mixture were measured after turning on the air cleaner to its normal status, the concentration of PM_{0.3-2.5}, formaldehyde, acetaldehyde, acetone, toluene, n-butyl acetate, ethylbenzene, xylene, styrene, and n-undecane was recorded every 2 minutes and 5 minutes, respectively, until it reached equilibrium.

2.5. Sampling and analytical methods

The sampling point of the mixing model containing two stainless steel parallel channels was designed with a distance of 0.5 m from the wall and a relative height of 1.5 m to avoid air turbulence. One channel was connected to the laser dust particle counter (LBT-D, Tiandi, China) through a diluter (DL-100, Nuoda, China) to measure the concentration of PM_{0.3-2.5} in the mixing model; the other one was connected to a stainless steel TD adsorption tube (Tenax TA, 60-80 mesh) and a DNPH-Silica cartridges (2, 4-Dinitrophenylhydrazine, 800 mg) through an ozone scrubber cartridges (Sep-Pak, Waters, USA), these devices were intended for measuring all VOCs in combination with the constant flow and steady temperature air sampler (Pro 1200, Minghua, China) for 5 min at 0.2 L·min^{-1}.

The carbonyls including formaldehyde, acetaldehyde and acetone were analyzed by liquid chromatography. The DNPH-Silica cartridge was eluted with acetonitrile to a 5 mL volumetric flask through a 0.45 μm filter. 10 μL aliquots of the extract were injected into HPLC (e2695, waters, USA) quipped with a UV detector and a C18 column (25 cm × 4.6 mm, 5 μm). The column temperature was set at 30 °C, and the UV wavelength was 360 nm. The mobile phase procedure at a flow rate of 1.0 mL·min^{-1} was carried out under 60% acetonitrile of water for 35 minutes. The others were analyzed by thermal desorber - gas chromatography. The TD adsorption tube was desorpted on the thermal desorber (TD100-xr, MARKES, UK) at 280 °C and 30 mL·min^{-1} of N_{2} for 5 min. The compounds from the desorption were collected at -10 °C in the cold trap. The cold trap was flash heated to 280 °C and maintained 3 min with transfer line at 250 °C. The compounds were transferred to gas chromatography (GC, 7890A, Agilent, USA) with AT-TVOC column (50 m × 30 μm, 1 μm) and flame ionization detection (FID). The FID was set at 250 °C and the inlet temperature was 250 °C. The detailed gradient of N_{2} as mobile phase at a flow rate of 1.0 mL·min^{-1} was as follows: the temperature was held for 1 min at 80 °C then increased at 5 °C·min^{-1} to 180 °C, and finally increased at 20 °C·min^{-1} to 250 °C, held for 10 min.

The concentrations of target compounds, which were detected by the methods, were in the concentration range of the calibration curves. The correlation coefficients of the standard curves were all meted \( R > 0.999 \). In the penetration test, less than 20% of compounds in the second sampling devices in series were found. Less than 20% of compounds were detected in the entire procedure blank. The quantitation limits were \( 1.12 \times 10^{-3} \text{mg·m}^{-3}, 1.72 \times 10^{-3} \text{mg·m}^{-3} \) and \( 1.88 \times 10^{-3} \text{mg·m}^{-3} \) for formaldehyde, acetaldehyde and acetone, respectively, and the others were \( 2.0 \times 10^{-3} \text{mg·m}^{-3} \) for toluene, n-butyl acetate, ethylbenzene, xylene, styrene and n-undecane (the sample volume was 1 L).

3. Results and discussion

3.1. Measured CADRs of PACs

Table 2 summarizes the initial CADRs of the air cleaners (repeated test 6 times). Results indicate that the RSDs of the test were from 3.96% to 9.98%, suggesting the test method exhibits fairly good reproducibility, stability and reusability. A reliable performance in purifying both PM and VOCs was certificated by air cleaner, the CADRs ranges for PM and VOC were 273.1 m^{3}·h^{-1} to 344.6 m^{3}·h^{-1} and 7.8 m^{3}·h^{-1} to 134.2 m^{3}·h^{-1}, respectively, most of which exceeded the minimum requirement of GB/T 18801-2015 (20 m^{3}·h^{-1}). In addition, PAC-B, which had a pleated composite filter element with fine granular activated carbon interlayer sandwiched between HEPA filters, exhibited better removal performance at CADRs for the mixing model than others. This was consistent with previous work, which tested the four portable air cleaners of initial CADRs for formaldehyde [4]. It is further confirmed that finer particle size is advantageous for VOCs adsorption [7]. PAC-C and PAC-D had
similar filter structures, but the CADRs of PAC-D were generally smaller. The reason for the results seems that adsorption losses of activated carbon are compounded by the presence of moisture, which produced by humidification pre-filter. The test results in Table 3 illustrate that, with the increase of molecular weight of compounds containing a same functional group, the removal performance of sorption-based PACs for IAP showed a non-linear decay trend. The trend could be seen in the CADRs of carboxyls (formaldehyde, acetaldehyde and acetone) and aromatics (toluene, ethylbenzene and xylene), respectively. These were agreed with the observations that Xiao et al. calculated CADRs of air cleaners for benzene compounds [8]. Furthermore, CADRs for compounds with similar molecular weight, such as xylene, ethylbenzene and styrene, were increased with decreasing polarities (Table 3). Figure 2 presents the concentration decay curves of PAC-B for PM$_{0.3-2.5}$ and typical VOCs respectively during the dynamic period. For each air cleaner tested, similar concentration decay curves were obtained. The PM$_{0.3-2.5}$ purification of the PACs tended to be stable at 46 min, while it took 60 min for VOCs, and the decline trend of individual compound was not same.

Table 2. Summary of CADRs and relative standard deviations for individual VOC of tested air cleaners ($n=6$).

| Typical Components | Molecular Weight | Dipole Moment (D) | PAC-A CADR (m$^3$ h$^{-1}$) | PAC-A RSD (%) | PAC-B CADR (m$^3$ h$^{-1}$) | PAC-B RSD (%) | PAC-C CADR (m$^3$ h$^{-1}$) | PAC-C RSD (%) | PAC-D CADR (m$^3$ h$^{-1}$) | PAC-D RSD (%) |
|--------------------|------------------|------------------|--------------------------|--------------|--------------------------|--------------|--------------------------|--------------|--------------------------|--------------|
| PM$_{0.3-2.5}$     | -                | -                | 344.64                   | 6.69         | 294.65                   | 5.54         | 273.06                   | 8.05         | 315.75                   | 5.84         |
| Formaldehyde       | 30.03            | 2.33             | 79.71                    | 7.27         | 73.32                    | 9.22         | 45.24                    | 6.52         | 37.17                    | 9.77         |
| Acetaldehyde       | 44.05            | 2.75             | 52.71                    | 8.11         | 45.24                    | 9.22         | 14.43                    | 9.25         | 20.76                    | 8.07         |
| Acetone            | 58.08            | 2.88             | 21.51                    | 8.85         | 27.84                    | 9.20         | 34.92                    | 9.17         | 22.35                    | 8.08         |
| Toluene            | 92.14            | 0.38             | 48.66                    | 6.52         | 134.16                   | 9.52         | 84.87                    | 8.05         | 26.13                    | 7.13         |
| n-Butyl acetate    | 116.16           | 1.87             | 15.06                    | 9.90         | 34.92                    | 9.17         | 22.35                    | 8.08         | 26.13                    | 9.06         |
| Ethylbenzene       | 106.17           | 0.59             | 27.21                    | 6.79         | 68.67                    | 9.20         | 53.16                    | 9.98         | 39.69                    | 8.95         |
| Xylene             | 106.17           | 0.64             | 22.29                    | 9.87         | 55.41                    | 9.23         | 45.15                    | 5.10         | 32.61                    | 7.73         |
| Styrene            | 104.15           | 0.12             | 28.35                    | 4.80         | 81.09                    | 6.86         | 59.61                    | 3.96         | 51.84                    | 6.21         |
| n-Undecane         | 156.31           | 0.00             | 7.80                     | 9.53         | 36.48                    | 9.27         | 16.35                    | 9.71         | 13.56                    | 9.85         |
3.2. Measured CADRs of PACs

In order to investigate the difference between the comprehensive removal performance for the mixture and the individual removal performance for PM and VOCs of PACs in indoor air, and the effect of particulate matter on the air cleaners removal performance for VOCs, the CADRs of separation procedure was compared with that of the mixed model. The separation procedure consisting of two steps was designed. Under the same test conditions as the initial concentration, the emission procedure, the sampling and analytical methods of contaminants in the mixing model, the removal performance for typical VOCs was first evaluated, and then the PM$_{0.3-2.5}$ purification test was conducted. The tested sorption-based type cleaners own a similar structure, including a HEPA filter and an AC filter. Therefore, PAC-B was selected as a representative for research because it held more prominent CADRs than other air cleaners. Table 3 provides the statistical description of the CARDs of PAC-B through the mixing model and separation procedure ($n = 6$). It is clear that the CADRs for formaldehyde, acetaldehyde, acetone, n-butyl acetate, toluene, ethylbenzene, xylene and styrene obtained by the mixing model were significantly reduced ($p < 0.01$, t-test) in comparison with the CADRs obtained through the separation procedure, but the difference between the results for PM$_{0.3-2.5}$ and n-undecane (non-polarity) was not significant ($p > 0.05$). Hence, the effect of VOCs on PACs removal performance for particulate matter was not obvious, while the removal performance for VOCs was significantly affected by particulate matter except for non-polarity compounds. These results further indicate that the air cleaners were reliable in eliminating indoor air pollutants, but the presence of particulate matter could affect the removal performance for VOCs.

Table 3. Comparison of determination results of typical contaminants by the separation procedure and the mixing model ($n = 6$).

| Typical Components | Separation procedure | Mixing model | p-value |
|--------------------|----------------------|--------------|---------|
| PM$_{0.3-2.5}$     | 295.95 ± 13.03       | 294.65 ± 16.34 | 0.882   |

Figure 2. The decline curves of the concentrations of typical components in the mixing model.
| Compound       | Test Concentration | Control Concentration | p-value |
|---------------|-------------------|-----------------------|---------|
| Formaldehyde  | 168.90 ± 7.65     | 110.79 ± 8.95         | < 0.001 |
| Acetaldehyde  | 107.43 ± 5.87     | 73.32 ± 6.76          | < 0.001 |
| Acetone       | 33.60 ± 3.10      | 27.84 ± 2.56          | 0.005   |
| Toluene       | 194.01 ± 17.15    | 134.16 ± 12.78        | < 0.001 |
| n-Butyl acetate | 42.60 ± 3.56     | 34.92 ± 3.20          | 0.003   |
| Ethylbenzene  | 86.04 ± 2.48      | 68.67 ± 6.32          | < 0.001 |
| Xylene        | 72.63 ± 3.93      | 55.41 ± 5.12          | < 0.001 |
| Styrene       | 96.92 ± 5.24      | 81.09 ± 5.56          | < 0.001 |
| n-Undecane    | 37.92 ± 3.59      | 34.53 ± 3.39          | 0.123   |

### 4. Conclusion

This study evaluated the effectiveness of commercial sorption-based PACs on comprehensive removal performance for particulate matter and volatile organic compounds in indoor air by measuring CADRs in a 30m³ environmental chamber through a mixing model. The tested air cleaners displayed a reliable performance in improving indoor air quality, especially in removing particulate matter. The removal trends of volatile organic compounds by air cleaners were negatively correlated with molecular weight and polarity of pollutants. Lastly, in comparison with the test through separation procedure, this study demonstrates that the removal performance of the PACs for most volatile organic compounds was affected by particulate matter except for non-polarity compounds. Therefore, reducing the concentration of particulate matter in the indoor air can effectively improve the VOCs purification of air cleaner.

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