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INDOOR AIR POLLUTION IN OFFICE BUILDINGS IN MEGA-CITIES

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by

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ABSTRACT

The amount of outdoor air (OA) intake and filter efficiency for a building heating, ventilation, and air conditioning system (HVAC) system are two major factors influencing indoor air pollution. Previous studies show that limiting OA flow and using high efficiency filters are effective strategies to control indoor $PM_{2.5}$ and ozone concentrations in office buildings in big cities such as Los Angeles and Beijing. However, most previous studies focused on identical filter efficiencies for outdoor air and recirculation air and often used outdoor air flow rate much lower than recommended values in standards. The objective of this study is to investigate impacts of flow rates and, filter efficiencies of outdoor and recirculation air on concentration of $PM_{2.5}$ and ozone in buildings in different mega-cities. Based on pollutant mass balance for a medium office building model, parametric analysis was conducted to examine indoor pollutant concentrations. Indoor $PM_{2.5}$ concentrations were estimated with a wide range of outdoor concentrations and OA intake. The results show that indoor concentrations of $PM_{2.5}$ and ozone are reduced with decreasing OA flow rate. Using air handling unit (AHU) filter + OA filter reduces 28.3% more indoor $PM_{2.5}$ than using AHU filter only, whereas it makes marginal difference for ozone removal. MERV 16 filter is effective in most cities under most OA flow rates. For polluted mega-cities, MERV 8 and 11 filter should be considered with specific OA flow rates to limit the impact of outdoor pollution on indoor concentrations.

Keywords: indoor air pollution, PM2.5, ozone, filter efficiency, office building

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Chapter 1

Introduction

Several studies have shown that people spend about 90% of their lives indoors (Chen and Zhao, 2011; EPA, 1996; Jenkins et al., 1992; Klepeis et al., 2001; Robinson and Nelson, 1995). In mega-cities, many people spend a considerable amount of time in office buildings (Ren et al., 2017). The indoor concentrations of critical pollutants can exceed recommended levels of National Ambient Air Quality Standard (NAAQS) (Cooper et al., 2015; Shi et al., 2016; US EPA, 2013, 2014). $PM_{2.5}$ is fine particulate matter less than 2.5 micrometer. It is inhalable and can induce respiratory diseases (Wang and Christopher, 2003). Indoor $PM_{2.5}$ levels in some office buildings can reach around 100 $\mu g/m^3$ while the limitation is 35 $\mu g/m^3$ (Liu et al., 2004). However, low efficiency MERV 2 filter is frequently used in real buildings, which does not often satisfy the filter requirement in ASHRAE 62.1-2013. Ground level ozone can trigger symptoms like coughing, shortness of breath and pain on deep inspiration (Lippmann, 1989). Indoor ozone concentration sometimes can be over 100 ppb, much higher than the limitation of 70 ppb (Weschler et al., 1989).

To reduce indoor exposure to pollutants, many studies were conducted to investigate source of pollutants. For office buildings, although there are indoor sources, outdoor air is the main source of indoor $PM_{2.5}$ (Morawska et al., 2017), which is generally generated from coal combustions (Zheng et al., 2005). Ozone is a product in chemical reactions between oxides of NO_x and VOC (Li et al., 2013). In some previous studies, ozone from outdoor air was considered as the only source of indoor ozone (Ben-David and Waring, 2016).

The influencing factors for indoor pollution has been explored and some strategies have been developed. For $PM_{2.5}$, Martins and Carrilho da Graça (2017) found that the use of natural ventilation could lead to large increase of indoor $PM_{2.5}$ levels and more HVAC energy. In a study performed by Ben-David and Waring (2016), indoor $PM_{2.5}$ concentration was found to be influenced by using outdoor air economizer or not, being mechanical or natural ventilated. Additionally, filter efficiency could greatly reduce indoor $PM_{2.5}$ concentration. To obtain lower indoor $PM_{2.5}$ level and lower energy consumption, Ren et al. (2017) developed a strategy using minimum outdoor air flow rate with higher level filters compared to existing systems in Chinese office buildings.

For ozone, Weschler et al. (1989) measured indoor and outdoor concentrations at office buildings and concluded that opening windows in late evening and early morning could prevent large amount of ozone entering rooms and save energy simultaneously in buildings with natural ventilation systems. In buildings with mechanical ventilation systems, carbon filtration was effective in outdoor ozone removal. Hyttinen et al. (2006) carried out a study on ozone removal. The results showed that increase of dust load on filters could result in more ozone reduction. Higher relative humidity could also cause higher ozone removal in supply airflow.

However, many studies employed identical filter efficiencies for both outdoor air and recirculation air to simplify the calculations (Martins and Carrilho da Graça, 2017; Ng et al., 2012; Riley et al., 2002) so that the impact of nonidentical filters was not clear. Some outdoor air (OA) flow rates were set much lower than the values in standards (Ren et al., 2017; Wargocki et al., 2000), with which the mechanical ventilation system could not provide acceptable indoor air quality for most people in offices. Consequently, the effect of using different filter for outdoor air and recirculation air combined with various OA flow rates on indoor pollutant concentration needs to be examined.

To fill these research gaps, the objectives of this study are (1) investigate the impact of outdoor air flow rate on indoor pollutant concentrations; (2) compare two filter configurations: AHU filter only and AHU filter + OA filter, and discuss the influence on indoor air pollution; and (3) find recommendation of filter or filter combination under different OA intake for different cities.

Chapter 2

Methodology

2.1 Building model

The building used in this study was reference building, medium office, developed by Department of Energy (DOE). The construction period was new construction after 2004. This building had three floors and each floor contained one core zone and four perimeter zones (See Figure 1). Table 1 shows detailed information of the zones on each floor.

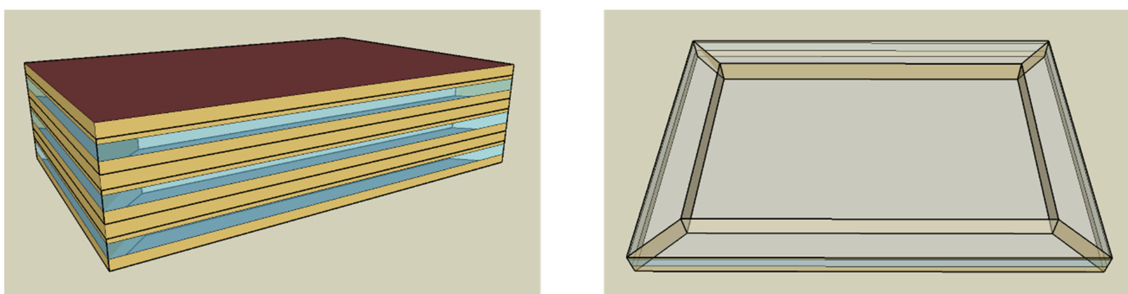

Figure 1. DOE reference building model, medium office

Table 1. Zone summary of each floor

Zone	Area (m^2)	Floor-to-Ceiling Height (m)	Exterior Wall Area (m^2)	Window Area (m^2)
Core	984	2.74	0	0
Perimeter 1	207	2.74	137	65
Perimeter 2	131	2.74	91	44
Perimeter 3	207	2.74	137	65
Perimeter 4	131	2.74	91	44

The HVAC system of this building was multi-zone VAV system. There was one packaged air handling unit on each floor, with a direct expansion coil, a gas heating coil and a variable volume supply fan. In each zone, there was an electric reheating coil.

Two mega-cities were considered in this study: Los Angeles and Beijing. For the building in Los Angeles, Typical Meteorological Year (TMY) weather data was used. Chinese Standard Weather Data (CSWD) was used for building in Beijing. Table 2 summarizes these two cities (Ashrae, 2006; Deru et al., 2011). The average flow rates of outdoor air, recirculation air and infiltration air during occupied time were outputted from EnergyPlus simulation and applied to the mass balance model below.

Table 2. Weather data in Los Angeles and Beijing

City	Climate Zone	Maximum T_{db} (°C)		Wind direction (°)	
		Winter	Summer	Winter	Summer
Los Angeles	3C	6.6	25.5	80	250
Beijing	4	-10.8	30.5	340	180

2.2 Mass balance model

A mass balance model was used to calculate indoor concentration of $PM_{2.5}$ and ozone. Figure 2 (a) shows the basic configuration of the model and (b) indicates another scenario using one AHU filter and one OA filter. Four assumptions were made based on previous studies: 1) the air in the space was well-mixed so that temperature, pressure, pollutant concentrations were uniform at any points (Breen et al., 2013; Macintosh et al., 2008; Thornburg et al., 2001); 2) the volume of exhaust air was equal to the sum of outdoor air and infiltration air volume (Rackes and Waring, 2013); 3) penetration factors for outdoor pollution entering room kept constant (Azimi et al., 2014; Stephens and Siegel, 2013); 4) deposition rate for pollutants depositing on indoor surfaces were fixed (Ren et al., 2017; Zhao et al., 2007).

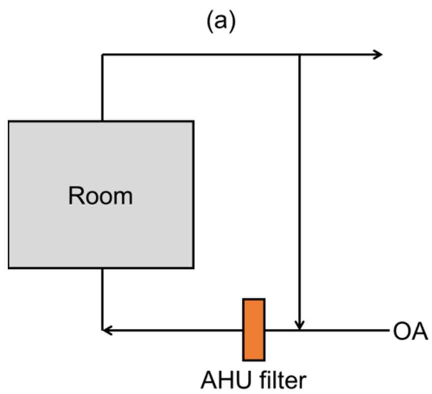

Figure 2. Configuration of pollutant mass balance model

$$\frac{dC}{dt} = S - LC \tag{1}$$

$$S = C_{out}\lambda_v(1-\eta_r) + C_{out}p\lambda_i \tag{2}$$

$$L = \lambda_r\eta_r + \lambda_v + \lambda_i + \beta \tag{3}$$

The change of indoor pollutant concentration over time is a function of source term and loss term, as shown in equation (1). Equation (2) explains source term (S), which includes outdoor pollutants sent in mechanical ventilation air and transported from infiltration. Equation (3) explains loss term (L), including pollutants removed by AHU filter, exhausted to the outdoor environment and deposited on indoor surfaces.

C_{out} is hourly measured outdoor $PM_{2.5}$ and ozone concentration collected by United States Environmental Protection Agency (EPA) and Beijing Municipal Environmental Monitoring Center. $\lambda_v, \lambda_i, \lambda_r$ are air exchange rates (AER) of ventilation, infiltration, and recirculation respectively, calculated from air flows mentioned in section 2.1. η_v, η_r are filter efficiencies of outdoor air and recirculation air, respectively. The filter efficiency of $PM_{2.5}$ is based on ASHRAE 62.1-2013 and Minimum Efficiency Reporting Value (MERV) in ASHRAE 52.2-2012. Three values are considered in calculation: 30% (MERV 8), 65% (MERV 11) and 95% (MERV 16). Filter efficiencies of ozone are collected from previous literature and three different values representing different filter status are used: 5% (new), 10% (used) and 25% (sooty) (Bekö et al., 2006; Hyttinen et al., 2006, 2003; Lin and Chen, 2014). The penetration factors p for $PM_{2.5}$ and ozone are 0.8 and 0.9 respectively, selected from studies conducted by Ben-David and Waring (2016), Li et al. (2017), Liu and Nazaroff (2001) and Ng et al. (2012). The deposition rates β are 0.5 h^{-1} for $PM_{2.5}$ and 4 h^{-1} for ozone (Ng et al., 2012).

When pollutants in ventilation air and recirculation air are removed by different filters, the filter scenario should be changed, as shown in Figure 2 (b). Consequently, the source term in this scenario needs to be altered from equation (2) to equation (4). To perform parametric analysis, steady-state indoor pollutant concentrations in two filter scenarios were solved according to equation (5).

$$S = C_{out}\lambda_v(1-\eta_v)(1-\eta_r) + C_{out}p\lambda_i \quad (4)$$

$$C = \frac{S}{L} \quad (5)$$

2.3 Parametric analysis

Using the building model associated with mass balance model, parametric analysis was conducted to examine the impact of OA flow rate and the impact of filters on indoor $PM_{2.5}$ and ozone concentration. Aside from the filter position and filter efficiencies discussed above, four OA flow rates are selected: 8.5, 17, 25.5 and 34 L/s/pers (Ben-David and Waring, 2017; Hedrick et al., 2015; Wargocki et al., 2000). The average and maximum outdoor concentration of $PM_{2.5}$ and ozone in Beijing are used. Table 3 shows all the variables.

Table 3. Simulation variables

Variables	**$PM_{2.5}$**	**Ozone**
Filter position	AHU filter only, AHU filter + OA filter	
Outdoor air flow rate	8.5, 17, 25.5 and 34 L/s/pers	
Concentration	86.2 and 667 μg/m^3	29 and 170 ppb
Filter efficiency	30%, 65%, 95%	5%, 10%, 25%

After investigating the impact of OA flow rate and the impact of filters, calculations were performed to understand combined effect of OA flow rate and filters on indoor $PM_{2.5}$ concentration. OA flow rate ranging from 0 to 34 L/s/pers and outdoor $PM_{2.5}$ concentration from 0 to 700 μg/m^3 were employed in the simulation. Thirteen cases were calculated, including one baseline case using MERV 2 filter in AHU, which is usually installed in real buildings (Macintosh et al., 2008; Stephens et al., 2010) but much lower than the MERV rating requirement of 8 in ASHRAE 62.1-2013, three cases using MERV 8, MERV 11, MERV 16 filter in AHU, and nine cases using MERV 8, MERV 11, or MERV 16 filter in AHU and OA duct. When calculations in all thirteen cases were completed, selection of filters to remove $PM_{2.5}$ could be concluded for both Los Angeles and Beijing.

Chapter 3

Results and Discussion

All the calculations were carried out for Beijing and Los Angeles. The air exchange rates in these two cities were similar and followed the AER results in the study carried out by Ben-David and Waring (2017): ventilation AER increasing with designed OA flow rate, recirculation AER decreasing and infiltration AER being almost constant. With same OA flow rate induced indoor, the building in Beijing had higher infiltration and recirculation air exchange rates (See Table A1 and Table A2). The main reason was more wind directly blown in building and higher load in Beijing. However, the results of indoor $PM_{2.5}$ and ozone concentrations in both cities did not differ a lot, with relative errors less than 6.5%. In Beijing, higher infiltration caused more pollutant source while more pollutants were removed in recirculation, which almost offset the increase in source term. To indicate and discuss the impact of OA flow rate, filters and the combined effect, only the plots for cases in Beijing are shown below.

3.1 Impact of OA flow rate

3.1.1 Indoor $PM_{2.5}$ concentration

Figures 3 (a) - (b) show the impact of OA flow rate on indoor $PM_{2.5}$ concentration with only AHU filter when the outdoor concentrations are 86.2 and 667 μg/m^3 respectively. Each box represents the distribution of indoor concentrations with different filter efficiencies. The top means the concentration associating the lowest filter efficiencies while the bottom means the concentration with the highest filter efficiencies. Figures 3 (c) – (d) show the cases with AHU filter + OA filter.

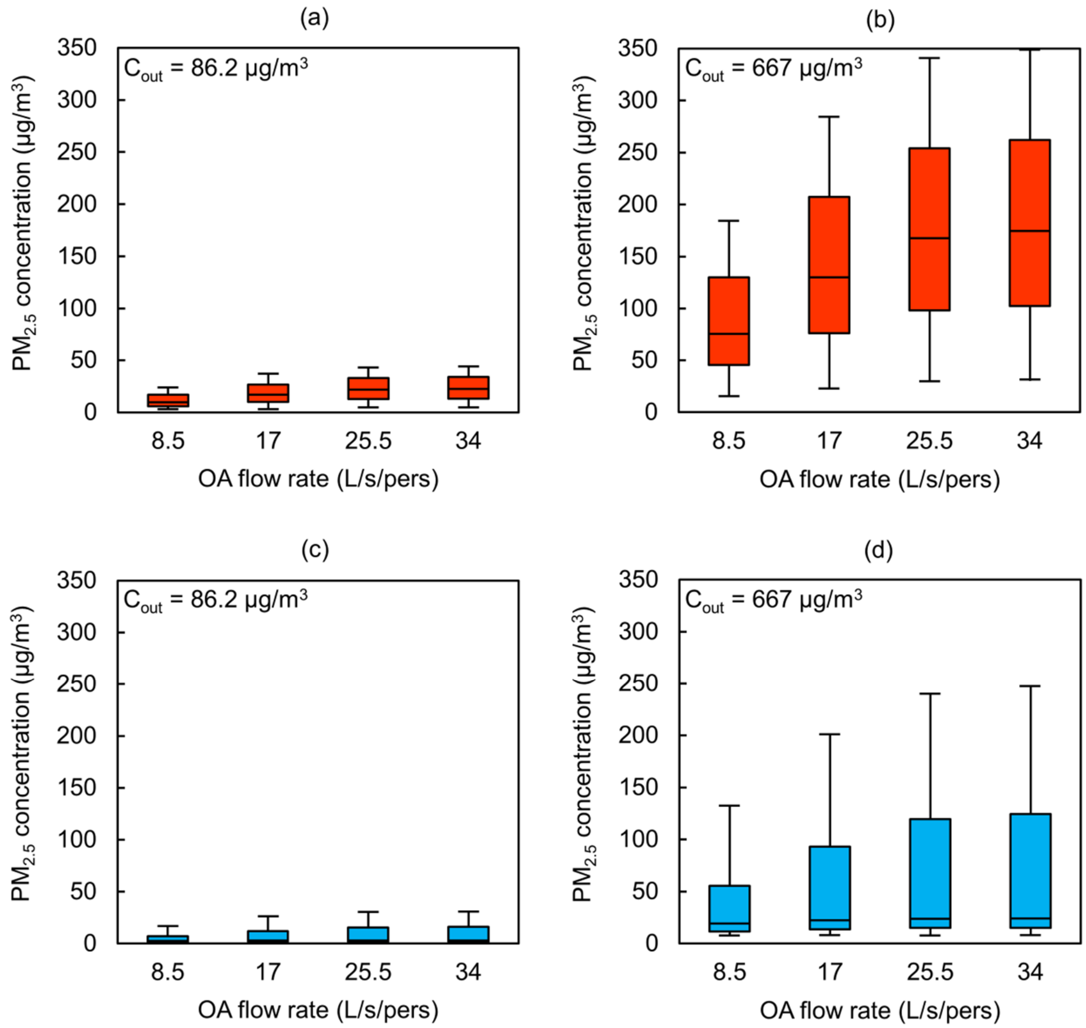

Figure 3. $PM_{2.5}$ concentration vs. OA flow rate: (a) AHU filter only, C_{out} = 86.2 μg/m^3; (b) AHU filter only, C_{out} = 667 μg/m^3 (c) AHU filter + OA filter, C_{out} = 86.2 μg/m^3; (d) AHU filter + OA filter, C_{out} = 667 μg/m^3.

Generally, the indoor $PM_{2.5}$ level can be reduced at least by 47.6% compared to the outdoor environment when one filter is used. Ben-David and Waring (2016) also reported that indoor $PM_{2.5}$ concentration using MERV 8 filter was 50% lower than the outdoor concentration in Los Angeles. In system using two filters, the percentage is 63.0%. The range of each whisker box is wide because of the filter efficiencies ranging from 30% to 95%. When OA flow rate is 34 L/s/pers and outdoor concentration is 667 μg/m^3, maximum indoor concentration is 319.3 μg/m^3 higher the minimum value in one-filter system, indicating the importance of selecting OA flow rate and filter efficiencies and combination for extremely polluted outdoor environment. Indoor concentration always rises with increased OA flow rate. For system with only AHU filter, the increase of average concentration when increasing OA flow rate from 8.5 to 34 L/s/pers can be 12.0 and 93.0 μg/m^3 of 86.2 and 667 μg/m^3 outdoor conditions, respectively. In system using AHU filter + OA filter, the increase is about 64% smaller, 4.3 μg/m^3 is for 86.2 μg/m^3 outdoor concentration and 33.0 μg/m^3 is for 667 μg/m^3 outdoor concentration. The increasing percentages in two filter configurations are over 84%. Using lower OA flow rate is an effective way to control $PM_{2.5}$ in office building, also concluded by Quang et al. (2013) and Ren et al. (2017), especially when outdoor $PM_{2.5}$ concentration is higher. In addition, the impact of OA flow rate is stronger when only AHU filter is installed in the system.

3.1.2 Indoor ozone concentration

In terms of ozone, figure 4 shows the distribution of indoor ozone concentration versus different OA flow rates with outdoor concentrations of 29 and 170 ppb. (a) – (b) represent the cases with one filter and (c) – (d) represent those with two filters. The indoor ozone concentration is reduced by at least 73.1% in one-filter system and 74.5% in two-filter system, compared to outdoor level. The ozone concentration was also reduce by over 70% in study done by Ben-David and Waring (2016).The range of each whisker box is narrower than that of $PM_{2.5}$ due to the filter efficiencies from 5% to 25%. In circumstance of 34 L/s/pers OA flow rate supplied in one-filter system and 170 ppb outdoor concentration, the maximum indoor concentration is 45.8 ppb, which is 9.6 ppb higher than the minimum value. Therefore, even new filter which has lowest efficiency of 5% and OA flow rate as high as 34 L/s/pers can satisfy the indoor ozone requirement of 70 ppb in cities like Beijing. In the system with AHU filter only, when outdoor air flow rate is changed from 8.5 to 34 L/s/pers, average ozone indoor concentration rises by 4.2 and 24.5 ppb in two outdoor conditions. When AHU filter is installed with OA filter, this rise is about 14% lower, around 3.6 and 21.2 ppb. Weschler et al. (1989) also pointed out that it was useful to control indoor ozone concentration by reducing ventilation rate during the time when outdoor ozone concentration was high. Similar to that of $PM_{2.5}$, the impact of OA flow rate on indoor ozone concentration is more obvious when outdoor ozone concentration is higher. The percentages of increase in these systems are more than 141%. However, this effect does not change a lot whether the system has only AHU filter or AHU filter + OA filter. Decreasing OA flow rate makes indoor concentration change within 10 ppb in normal condition, according to Figure 4 (a) and Figure 4 (c). It is also a useful strategy when outdoor concentration is very high, but not necessary based on concentration limit of 70 ppb.

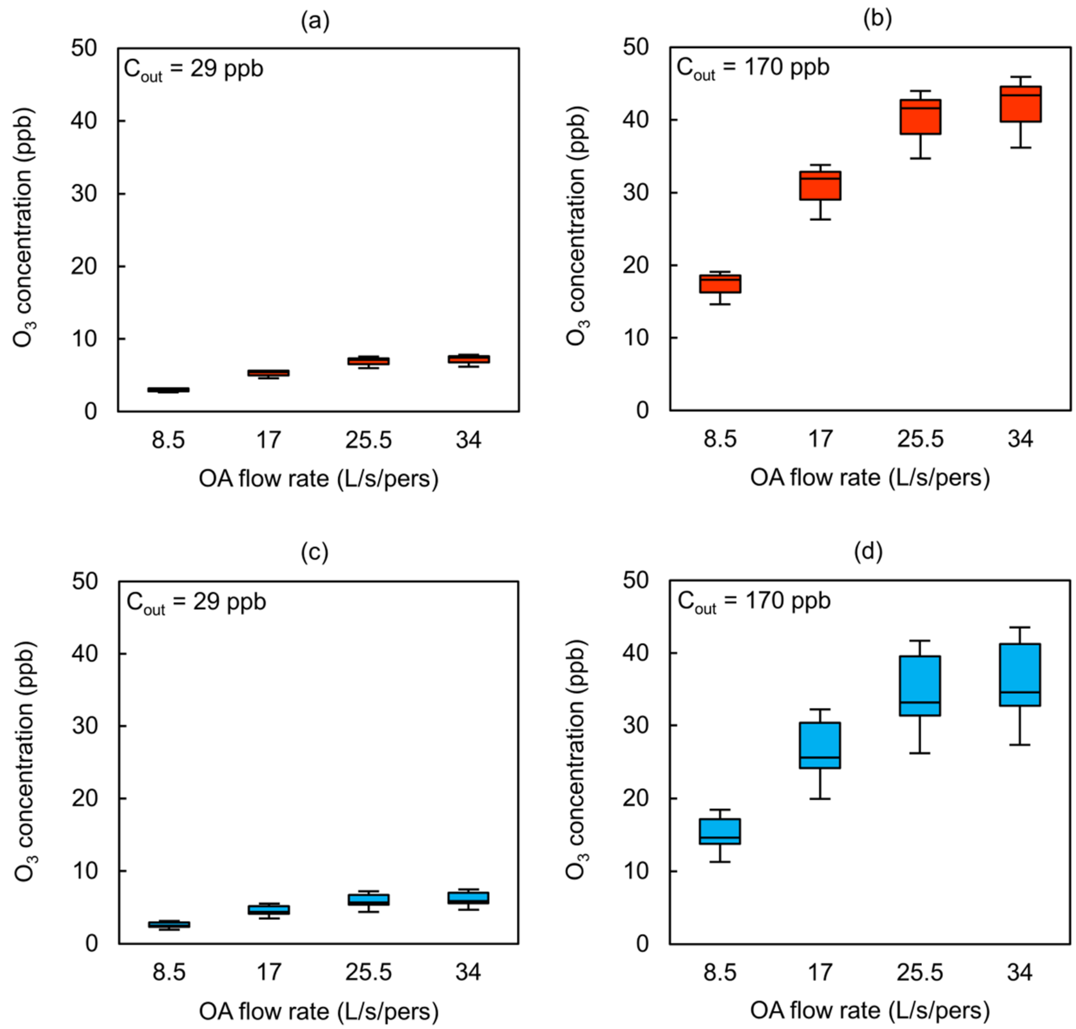

Figure 4. Indoor ozone concentration vs. OA flow rate: (a) AHU filter only, C_{out} = 29 ppb; (b) AHU filter only, C_{out} = 170 ppb (c) AHU filter + OA filter, C_{out} = 29 ppb; (d) AHU filter + OA filter, C_{out} = 170 ppb.

3.2 Impact of filters

3.2.1 Indoor $PM_{2.5}$ concentration

Figure 5 shows the impact of filter on indoor $PM_{2.5}$ concentration in system with only AHU filter under outdoor concentration of 86.2 and 667 μg/m^3. The distribution of each box is caused by different OA flow rates. The maximum value means concentration with 34 L/s/pers OA induced while the minimum one means concentration with 8.5 L/s/pers OA flow rate. Changing MERV rating from 8 to 16 (efficiency from 30% to 95%) can reduce indoor $PM_{2.5}$ concentration by at least 91.3 % when same amount of outdoor air is supplied. Ben-David and Waring (2016) also reported similar reduction of 90.6 % in PM2.5 indoor concentration by rising MERV rating from 8 to 16.

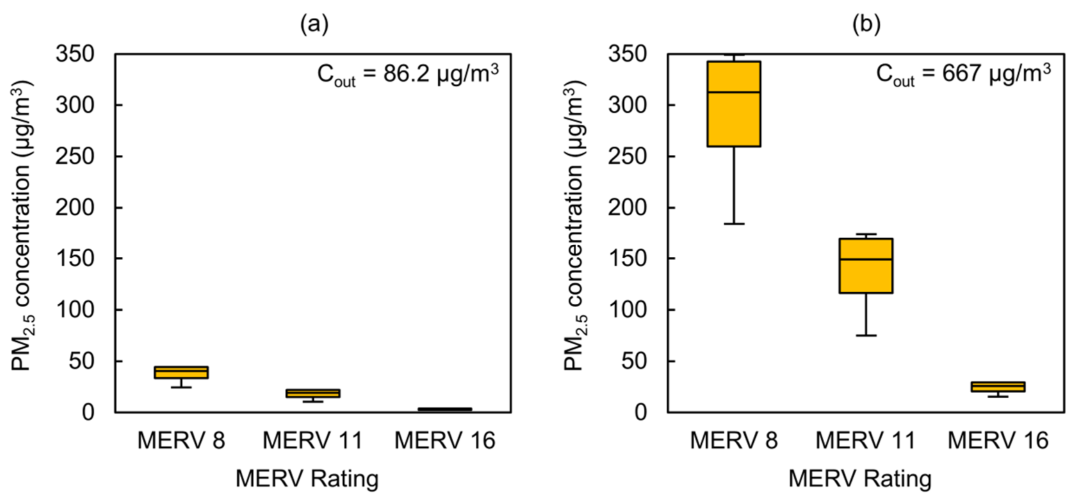

Figure 5. Indoor $PM_{2.5}$ concentration vs. MERV Rating, AHU filter only: (a) C_{out} = 86.2 μg/m^3; (b) C_{out} = 667 μg/m^3.

When AHU filter + OA filter are used in the system, the impact of AHU filter and OA filter on indoor $PM_{2.5}$ concentration is shown in contour plots in Figure 6 (a) – (b) are cases with OA supply of 8.5 L/s/pers and (c) – (d) are those with OA supply of 34 L/s/pers. Rising AHU filter + OA filter efficiencies from 30% + 30% to 95% + 95% (MERV 8 + MERV 8 to MERV 16 + MERV 16) decreases indoor concentration by over 94.5% with same OA flow rate. To make comparison between two filter configurations, the worst cases in each are discussed: 30% efficiency (MERV 8) for AHU filter only, 30% + 30% (MERV 8 + MERV 8) for AHU filter + OA filter. When OA flow rate is 8.5 L/s/pers, the indoor concentrations in Figure 6 (a) and (b) are 17.1 and 132.5 μg/m^3 for 86.2 and 667 μg/m^3 outdoor concentrations, which are 28.3% lower than those concentrations in Figure 5 (bottoms of MERV 8 distribution: 23.9 and 184.8 μg/m^3). When OA flow rate is 34L/s/pers, the concentrations in Figure 6 (c) – (d) are 31.9 and 246.8 μg/m^3, 29.4% lower than the values in Figure 5 (tops of MERV 8 distribution: 45.2 and 349.6 μg/m^3). Using two filters in the system can effectively decrease indoor $PM_{2.5}$ concentration than using only one filter.

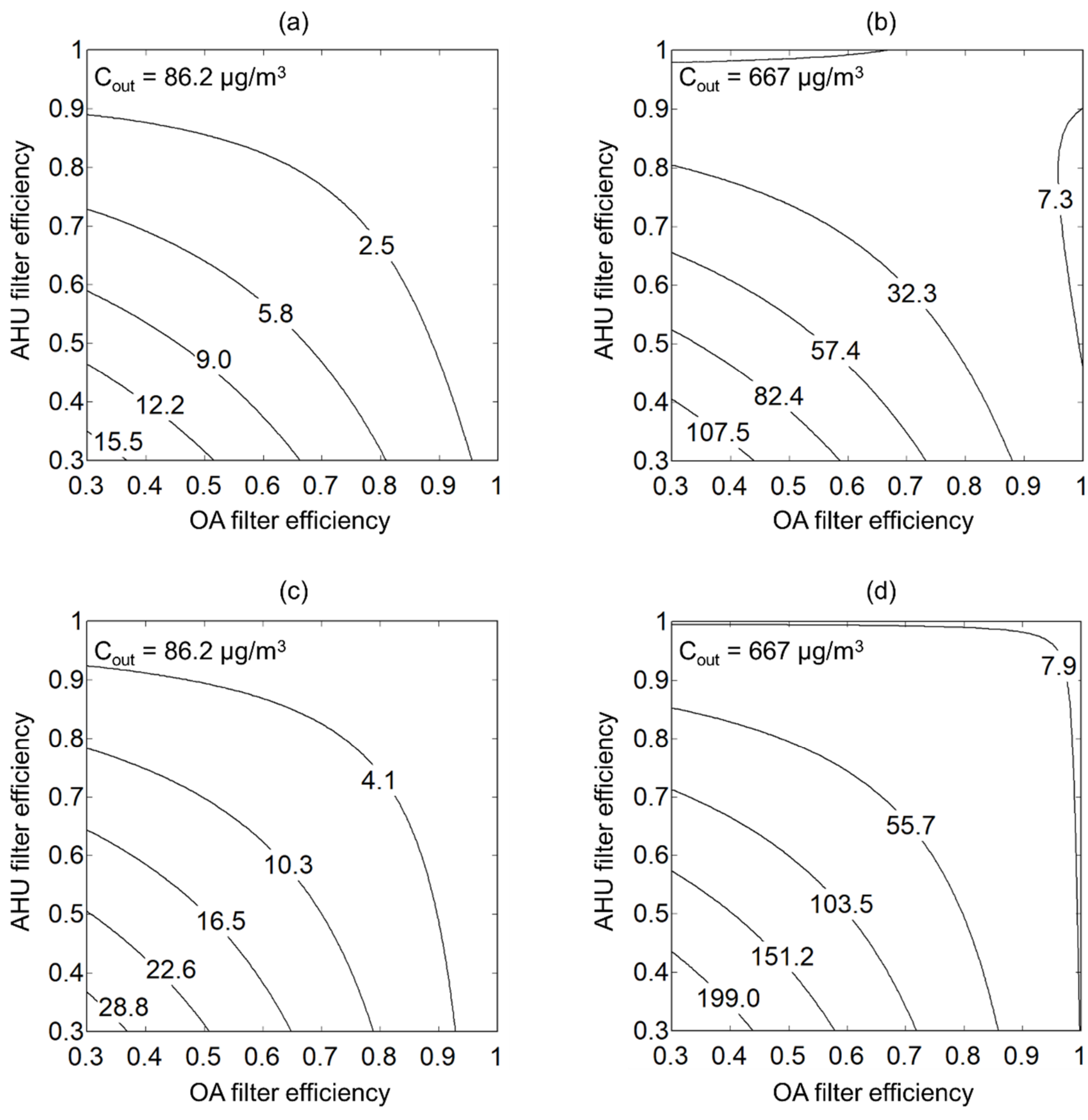

Figure 6. Indoor $PM_{2.5}$ concentration vs. filter efficiency, AHU filter + OA filter: (a) OA flow rate = 8.5 L/s/pers, C_{out} = 86.2 μg/m^3; (b) OA flow rate = 8.5 L/s/pers, C_{out} = 667 μg/m^3; (c) OA flow rate = 34 L/s/pers, C_{out} = 86.2 μg/m^3; (c) OA flow rate = 34 L/s/pers, C_{out} = 667 μg/m^3.

Table 4 shows detailed comparisons between two filter configurations with same AHU filter under 86.2 μg/m^3 outdoor $PM_{2.5}$ concentration and 8.5 L/s/pers OA flow rate. The reduction indicates the percentage of indoor concentration in two-filter system lower than that in one-filter system in each row. With higher MERV rating of AHU filter, the reduction percentage of indoor concentration made by increasing MERV rating of OA filter is much smaller. Reduction percentages using MERV 8 in AHU are 28.3 – 89.5% while the percentages using MERV 16 in AHU are 16.2 – 51.3%. This phenomenon shows the higher predominance of AHU filter than OA filter. The main reason is that AHU filter removes pollutants from both recirculation air and fresh air from outdoor environment but OA filter only processes the latter one.

Table 4. Comparisons of reduction in $PM_{2.5}$: C_{out} = 86.2 μg/m^3, OA flow rate = 8.5 L/s/pers

MERV rating (AHU filter)	**MERV rating (AHU, OA filter)**	**C_{in} (μg/m^3) (AHU filter)**	**C_{in} (μg/m^3) (AHU filter + OA filter)**	**Reduction (%)**
	8, 8	23.9	17.1	28.3
8	8, 11	23.9	9.3	61.3
	8, 16	23.9	2.5	89.5
	11, 8	9.8	7.2	26.7
11	11, 11	9.8	4.1	57.9
	11, 16	9.8	1.5	84.7
	16, 8	1.9	1.6	16.2
16	16, 11	1.9	1.3	35.1
	16, 16	1.9	0.9	51.3

Table 5 shows the same kind of comparisons in condition of 34 L/s/pers OA supply. The general trend of reduction is similar to that in Table 4. The magnitude is higher for each percentage because of more pollutants induced into the building and removed by OA filter. The indoor concentration reductions made by employing two filters in cases of 667 μg/m^3 have large magnitude and same percentages, so the tables are not shown in this paper. In general, combination of two filters is an effective way to lower indoor $PM_{2.5}$ concentration. AHU filter is more important than OA filter, taking filtration of recirculation and outdoor air. When large amount of outdoor air is supplied, there should be more focus on OA filter.

Table 5. Comparisons of reduction in $PM_{2.5}$: C_{out} = 86.2 μg/m^3, OA flow rate = 34 L/s/pers

MERV rating (AHU filter)	**MERV rating (AHU, OA filter)**	**Cin (μg/m^3) (AHU filter)**	**Cin (μg/m^3) (AHU filter + OA filter)**	**Reduction (%)**
8	8, 8	45.2	31.9	29.4
	8, 11	45.2	16.4	63.7
	8, 16	45.2	3.1	93.1
11	11, 8	22.6	16.1	28.8
	11, 11	22.6	8.5	62.5
	11, 16	22.6	2.0	91.3
16	16, 8	3.9	3.0	23.3
	16, 11	3.9	1.9	50.6
	16, 16	3.9	1.0	73.9

These are also shown in filter equivalence by finding the equivalent AHU filter which makes same indoor concentration with AHU filter + OA filter (see Table 6). When OA flow rate is 8.5 L/s/pers, by comparing cases with their reverse pairs (for example, MERV 8 AHU filter + MERV 11 OA filter versus MERV 11 AHU filter + MERV 8 OA filter), it can be observed that higher efficiencies are obtained with higher efficiency filters in AHU. Placing high efficiency filter in AHU makes more $PM_{2.5}$ removal than placing it in OA duct. When OA flow rate is 34 L/s/pers, the equivalent AHU filter efficiencies increase slightly and the equivalent MERV ratings rise when low efficiency filters are used. Therefore, higher OA flow rate can enhance the benefit of filter combination, especially for low efficiency filters.

Table 6. $PM_{2.5}$ filter equivalence

η_{AHU} (%)	η_{OA} (%)	MERV rating (AHU, OA filter)	8.5 L/s/pers		34 L/s/pers	
			Equivalent η_{AHU} (%)	Equivalent MERV rating	Equivalent η_{AHU} (%)	Equivalent MERV rating
30	9	8, 2	34.0	8	36.1	9
65	9	11, 2	67.6	11	68.1	11
30	30	8, 8	44.6	9	50.4	10
30	65	8, 11	66.7	11	74.8	11
30	95	8, 16	92.5	14/15	96.3	16
65	30	11, 8	73.8	11	75.3	11
65	65	11, 11	85.6	13	87.6	13
65	95	11, 16	97.0	16	98.2	16
95	30	16, 8	96.4	16	96.5	16
95	65	16, 11	98.1	16	98.2	16
95	95	16, 16	99.6	16	99.8	16

3.2.2 Indoor ozone concentration

With higher filter efficiencies, indoor ozone concentrations are decreased in both filter configurations, but not as much as those of $PM_{2.5}$. Figure 7 shows the indoor ozone concentration versus filter efficiency when only AHU filter is installed under outdoor concentration of 29 and 170 ppb, similar in form with Figure 5. Figure 8 shows the impact of AHU filter and OA filter on indoor ozone concentration, similar to Figure 6. In system with only AHU filter, when the filter efficiency increases from 5% to 25%, indoor concentration decreases by at least 21.1% for each OA flow rate. In system with AHU filter and OA filter, making higher combination of AHU filter + OA filter efficiencies from 5% + 5% to 25% + 25% (two new filters to two sooty filters) decreases indoor concentration by more than 37.3% with same OA flow rate.

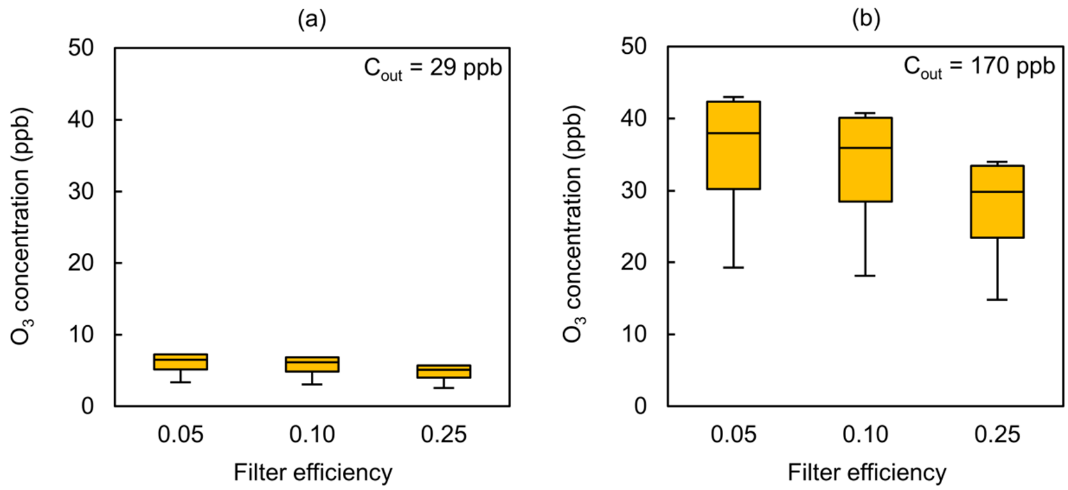

Figure 7. Indoor ozone concentration vs. filter efficiency, AHU filter only: (a) C_{out} = 29 ppb; (b) C_{out} = 170 ppb.

The comparison also focuses on the worst cases in each filter configuration: 5% efficiency for AHU filter only, 5% + 5% for AHU filter + OA filter. When outdoor air flow rate is 8.5 L/s/pers, the indoor concentrations in Figure 8 (a) – (b) are 3.1 and 18.3 ppb for 29 and 170 ppb outdoor concentrations, respectively, which are only 4.8% lower than those concentrations in Figure 7 (bottoms of 0.05 box: 3.3 and 19.2 ppb). When the outdoor air intake is 34 L/s/pers, this percentage is 4.9%, comparing values in bottom left corners in Figure 8 (c) – (d) (7.4 and 43.5 ppb) and top values of 0.05 box in Figure 7 (7.8 and 45.8 ppb). It is evident that using AHU filter + OA filter does not have much effect on decreasing indoor ozone concentration than using AHU filter only. The combination of filters is not necessary in process of controlling ozone level in office buildings.

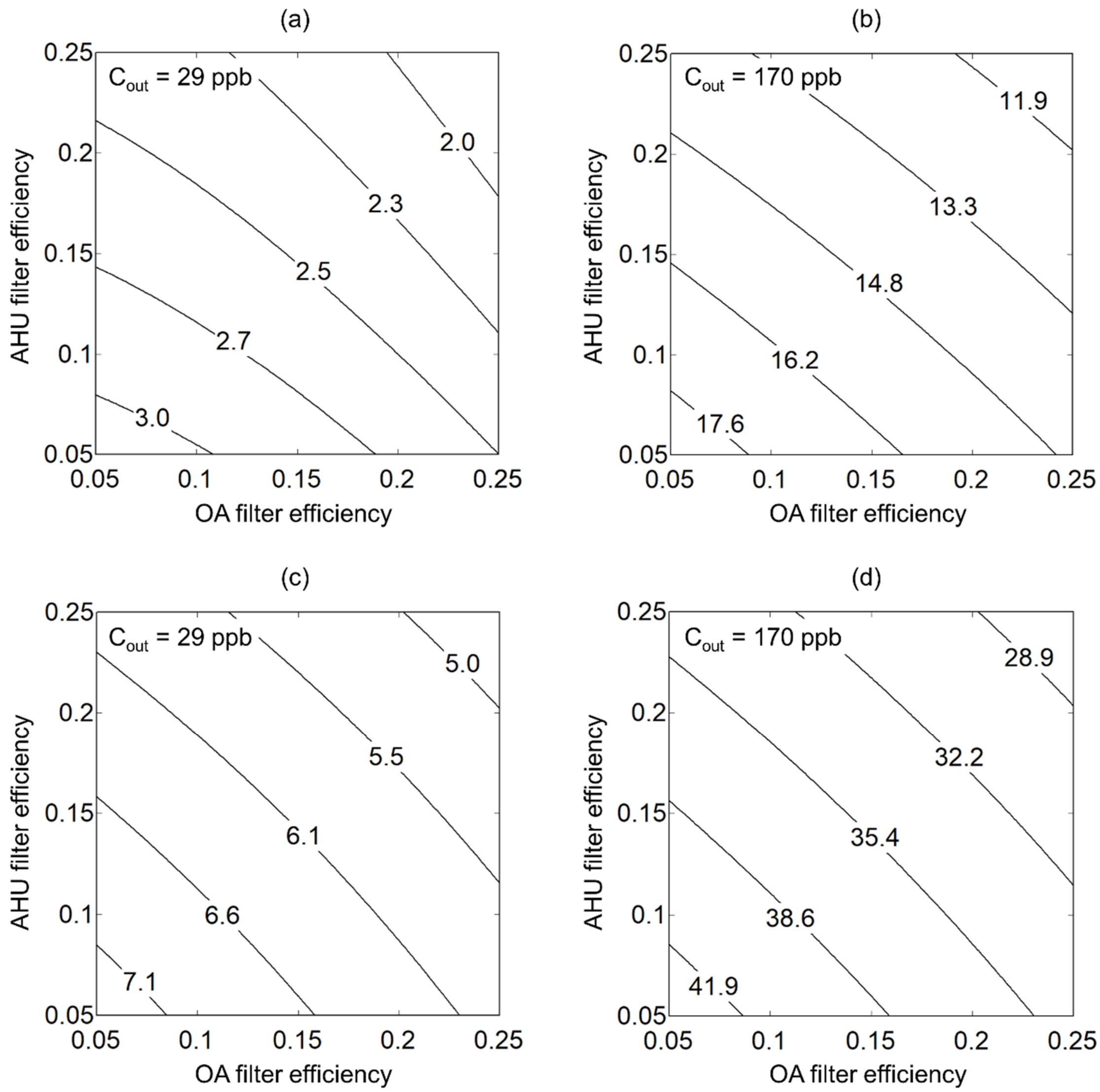

Figure 8. Indoor ozone concentration vs. filter efficiency, AHU filter + OA filter: (a) OA flow rate = 8.5 L/s/pers, C_{out} = 29 ppb; (b) OA flow rate = 8.5 L/s/pers, C_{out} = 170 ppb; (c) OA flow rate = 34 L/s/pers, C_{out} = 29 ppb; (c) OA flow rate = 34 L/s/pers, C_{out} = 170 ppb.

Detailed comparisons between different filter configuration using same AHU filter are shown in Table 7 and Table 8, similar to Table 4 and Table 5, indicating the reduction under 29 ppb outdoor ozone concentration and 8.5, 34 L/s/pers OA flow rates. When higher efficiency filter is installed in AHU, the reduction percentage of indoor concentration caused by increasing efficiency of OA filter is almost same, around 5 – 24% for 8.5 L/s/pers and 5 – 25% for 34

L/s/pers. The reduction percentages of higher OA flow rate are slightly higher than those of low OA flow rate, same trend as the cases of $PM_{2.5}$. It is mainly caused by similarity in mass balance model of $PM_{2.5}$ and ozone, and by the narrow range of ozone filter efficiencies from 5% to 25%. Therefore, although AHU filter has a little more importance according to the mass balance model, the difference between influence of AHU filter and OA filter is diminished by low ozone filter efficiencies of 5 – 25%.

Table 7. Comparisons of reduction in ozone: C_{out} = 29 ppb, OA flow rate = 8.5 L/s/pers

η_{AHU} (%)	η_{AHU}, η_{OA} (%)	C_{in} (ppb) (AHU filter)	C_{in} (ppb) (AHU filter + OA filter)	Reduction (%)
5	5, 5	3.3	3.1	4.8
	5, 10	3.3	3.0	9.5
	5, 25	3.3	2.5	23.8
10	10, 5	3.1	2.9	4.7
	10, 10	3.1	2.8	9.5
	10, 25	3.1	2.3	23.7
25	25, 5	2.5	2.4	4.7
	25, 10	2.5	2.3	9.4
	25, 25	2.5	1.9	23.5

Table 8. Comparisons of reduction in ozone: C_{out} = 29 ppb, OA flow rate = 34 L/s/pers

η_{AHU} (%)	η_{AHU}, η_{OA} (%)	C_{in} (ppb) (AHU filter)	C_{in} (ppb) (AHU filter + OA filter)	Reduction (%)
5	5, 5	7.8	7.4	4.9
	5, 10	7.8	7.0	9.8
	5, 25	7.8	5.9	24.6
10	10, 5	7.4	7.0	4.9
	10, 10	7.4	6.7	9.8
	10, 25	7.4	5.6	24.6
25	25, 5	6.2	5.9	4.9
	25, 10	6.2	5.6	9.8
	25, 25	6.2	4.7	24.5

3.3 Combined effect of OA flow rate and filters on indoor $PM_{2.5}$ concentration

As is discussed in section 3.1.2 and 3.2.2, regular filters for ozone can control the indoor ozone concentration under 70 ppb with OA flow rate from 8.5 to 34 L/s/pers in both Los Angeles and Beijing. It is not necessary to analyze the combined effect of OA flow rate and filters on indoor ozone level. Blondeau et al. (2005) also reported indoor ozone concentration about 0-45% of the outdoor level. Only analysis of $PM_{2.5}$ has been carried out. In the baseline case using MERV 2 filter in AHU, the efficiency of 9% is used (ASHRAE 52.2-2012). Figure 9 shows the contour of indoor $PM_{2.5}$ concentration with different outdoor condition and OA intake. (a) is the plot of baseline case. (b) – (c) shows the cases with only AHU filter, representing MERV 8, MERV 11 and MERV 16 filter, respectively. (e) shows the indoor concentration with MERV 16 filter in OA duct and lowest efficiency filter (MERV 8) in AHU. (f) – (i) shows the cases using MERV 8 filter or MERV 11 filter in AHU or OA duct. The red line in each plot is indoor concentration of 35 $\mu g/m^3$ in NAAQS Table. Thus, every point under this line means this group of outdoor concentration and OA flow rate is available to control the indoor $PM_{2.5}$ concentration to satisfy the standard. For fixed filter or filters, higher OA flow rate makes narrower range of available outdoor concentration; for fixed OA flow rate, higher filter efficiency or efficiencies also makes more outdoor concentration available. This trend is the same as the indoor $PM_{2.5}$ control strategy discussed in study performed by (Ren et al., 2017), using minimum OA supply rate with higher level filters.

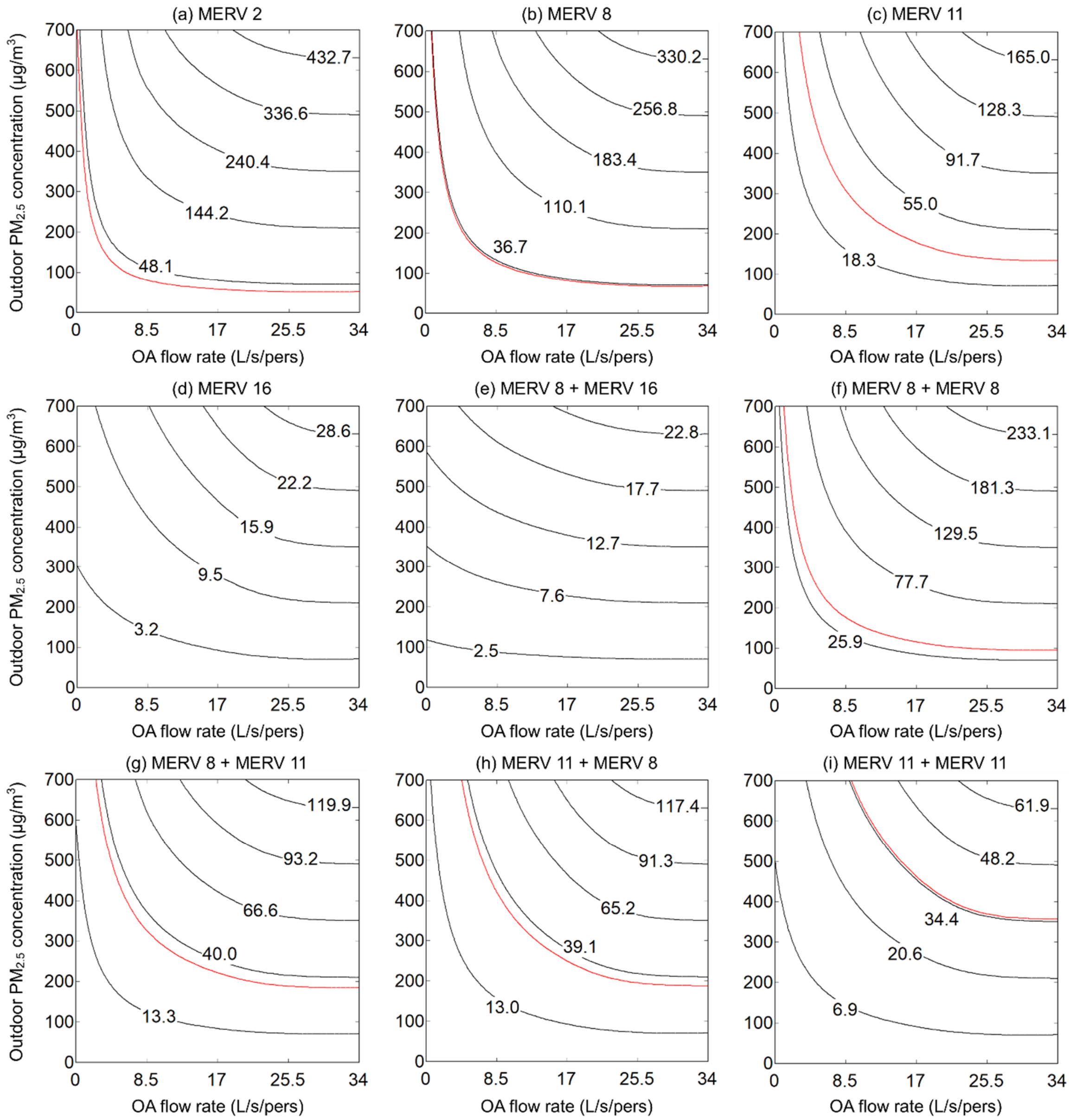

Figure 9. Combined effects of OA flow rate and filters on indoor $PM_{2.5}$ concentration under outdoor concentration from 0 to 700 μg/m^3: (a) MERV 2; (b) MERV 8; (c) MERV 11; (d) MERV 16; (e) MERV 8 + MERV 16; (f) MERV 8 + MERV 8; (g) MERV 8 + MERV 11; (h) MERV 11 + MERV 8; (i) MERV 11 + MERV 11.

In general, higher outdoor concentration works with lower OA flow rate to make required indoor concentration. In baseline case, most area is above the red line, so available combinations of outdoor condition and OA flow rate are limited. For Los Angeles, all OA flow rates are good enough in regular condition with 95th percentile outdoor concentration of 30 μg/m^3 while only OA flow rates less than 4 L/s/pers are available in extreme condition with maximum outdoor concentration of 185 μg/m^3. For buildings in Beijing, MERV 2 filter in AHU performs much worse because of the high maximum and 95th percentile outdoor concentration of 667 μg/m^3 and 278 μg/m^3 respectively. The available OA flow rates in regular condition should be less than 3 L/s/pers and nearly zero in extreme condition. Consequently, the use of MERV 2 filter in office buildings are not effective in highly polluted cities like Beijing, but it can be enough in most time for cities like Los Angeles.

When using higher MERV rating filter from MERV 8 to 16 in AHU, more groups of outdoor concentration and OA flow rate are available. MERV 8 filter is still not enough for Beijing and extreme condition in Los Angeles. MERV 11 filter makes 8.5 L/s/pers OA flow rate work in Los Angeles under maximum outdoor concentration but the OA intake should not be higher than 17 L/s/pers. It also satisfies 95% time in Beijing with 8.5 L/s/pers OA flow rate but is not available to be combined with OA flow rate higher than 4 L/s/pers for a whole year. When MERV 16 filter is used, as shown in Figure 9 (d), even the highest outdoor concentration and highest OA flow rate makes indoor level under 35 μg/m^3. Based on the results in section 3.2.1, MERV 16 AHU filter plus an OA filter can make indoor concentration lower than single MERV 16 filter in AHU. In system with MERV 16 filter installed as OA filter, even being combined with MERV 8 filter makes all the points in plot under 35 μg/m^3, shown in Figure 9 (e). Therefore, one MERV 16 filter in AHU or OA duct is enough in both Los Angeles and Beijing. Combining it with another filter is not necessary no matter which OA flow rate is selected from 0 to 34 L/s/pers.

When two MERV 8 filters are used, there is more availability than only one MERV 8 filter, but less than one MERV 11 filter. This combination performs poorly in Beijing while it is available in Los Angeles for regular condition and extreme polluted days with OA flow rate lower than 8.5 L/s/pers. Increasing OA filter MERV rating to 11, the combination works slightly better than one MERV 11 filter, especially under high OA flow rates. It allows the use of all OA flow rates in Los Angeles and 8.5 L/s/pers in Beijing. When reversing this combination into MERV 11 AHU filter + MERV 8 OA filter, it performs similar to the latter combination, with more availability for low OA flow rate condition. In Figure 9 (i), more than half of area is under the red line, which means two MERV 11 filters rise availability to control indoor $PM_{2.5}$ concentration effectively. In addition, this combination makes indoor concentration lower than 35 μg/m^3 under 8.5 L/s/pers in extremely polluted Beijing.

It is clear that one MERV 2 filter in AHU is enough for regular condition in Los Angeles. MERV 16 filter in AHU or OA duct, or in both is very useful in Beijing under high OA flow rates, but it is not necessary in regular condition. To make selection of filter or filter combination with MERV 8 or MERV 11 filter in two cities, details can be found in Table A3 to Table A6.

Chapter 4

Conclusion

By conducting steady-state calculations for medium office building based on pollutant mass balance model, this study investigated the impact of OA flow rate, and the impact of filters, including filter position and efficiency on indoor concentration of $PM_{2.5}$ and ozone. The analysis of combined effect of outdoor air and filters were performed for $PM_{2.5}$ in Los Angeles and Beijing under regular and extreme circumstances. Primary findings have been listed as follows:

(1) For $PM_{2.5}$, increasing OA flow rate from 8.5 to 34 L/s/pers makes average indoor concentration 84% higher and its influence is more obvious when only AHU filters is used; Combination of AHU filter and OA filter can remove at least 28.3% more $PM_{2.5}$ than single AHU filter; Installing high efficiency filter in AHU makes more reduction.

(2) For ozone, the increase of OA flow rate results in 141% higher average indoor concentration but the impact is almost same in two different filter configurations; Using two filters does not yield much improvement in ozone removal. All filter efficiencies can reduce indoor ozone level under the value in standard.

(3) One MERV 16 filter in AHU or OA duct is effective enough to control indoor $PM_{2.5}$ under OA flow rate ranging from 0 to 34 L/s/pers in Los Angeles and Beijing; Combination of MERV 16 filter and another filter is not necessary in most cities.

(4) If using MERV 8 or MERV 11 filter in the system, in Los Angeles, MERV 2 AHU filter can satisfy 95% of time. To consider extreme condition, MERV 11 AHU filter with 8.5 L/s/pers

OA flow rate can be selected; with OA intake from 17 to 34 L/s/pers, MERV 8 + MERV 11, or reversely should be selected; the combination or two MERV 11 filters are not necessary in highly polluted Los Angeles.

(5) For Beijing, to satisfy regular condition, at least one MERV 11 filter should be used with 8.5 L/s/pers OA flow rate; with OA flow rate of 17 – 34 L/s/pers, two MERV 11 filters should be installed. In extreme polluted condition, only two MERV 11 filters with 8.5 L/s/pers OA intake can satisfy the 35 $\mu g/m^3$ indoor concentration.

There are a few limitations in this study. Although the filter efficiencies have been selected for $PM_{2.5}$, a wide particle size distribution is not considered. Analysis of specific filters for specific particle size is not included. This study discusses particles in mass concentration, but does not perform calculations based on number concentration. Future studies should assess the impact of outdoor air and filters on particles with detailed size distribution and associated filter selections.

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Appendix A

Supporting Information

Table A1. Air exchange rates in Los Angeles

OA flow rate (L/s/pers)	Ventilation AER (h^{-1})	Infiltration AER (h^{-1})	Recirculation AER (h^{-1})
8.5	0.521	0.027	1.002
17	1.043	0.027	0.481
25.5	1.388	0.027	0.136
34	1.431	0.027	0.093

Table A2. Air exchange rates in Beijing

OA flow rate (L/s/pers)	Ventilation AER (h^{-1})	Infiltration AER (h^{-1})	Recirculation AER (h^{-1})
8.5	0.521	0.028	1.161
17	1.043	0.028	0.640
25.5	1.473	0.028	0.210
34	1.560	0.028	0.127

Table A3. $PM_{2.5}$ filter selection in Los Angeles in regular condition (no MERV 16 filter)

OA flow rate (L/s/pers)	MERV rating of AHU filter (+ OA filter)						
	2	8	11	8 + 8	8 + 11	11 + 8	11 + 11
8.5	✓	✓	✓	✓	✓	✓	✓
17	✓	✓	✓	✓	✓	✓	✓
25.5	✓	✓	✓	✓	✓	✓	✓
34	✓	✓	✓	✓	✓	✓	✓

Table A4. $PM_{2.5}$ filter selection in Los Angeles in extreme condition (no MERV 16 filter)

OA flow rate (L/s/pers)	MERV rating of AHU filter (+ OA filter)						
	2	8	11	8 + 8	8 + 11	11 + 8	11 + 11
8.5			✓		✓	✓	✓
17					✓	✓	✓
25.5					✓	✓	✓
34					✓	✓	✓

Table A5. $PM_{2.5}$ filter selection in Beijing in regular condition (no MERV 16 filter)

OA flow rate (L/s/pers)	**MERV rating of AHU filter (+ OA filter)**						
	2	**8**	**11**	**8 + 8**	**8 + 11**	**11 + 8**	**11 + 11**
8.5			✓		✓	✓	✓
17							✓
25.5							✓
34							✓

Table A6. $PM_{2.5}$ filter selection in Beijing in extreme condition (no MERV 16 filter)

OA flow rate (L/s/pers)	**MERV rating of AHU filter (+ OA filter)**						
	2	**8**	**11**	**8 + 8**	**8 + 11**	**11 + 8**	**11 + 11**
8.5							✓
17							
25.5							
34							