Master Graduation Thesis

Active & Passive Control Strategies of Indoor PM2.5 Concentration in High-rise Office Buildings

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1 Introduction

1.1 General

According to World Health Organization (WHO) statistics, every year air pollutions (both indoor and outdoor) cause more than 2 million premature deaths, among which more than a half is borne by the populations of developing countries [1]. Within the European Union, 420,000 premature deaths were caused due to air pollution in 2010, among which particulate matter, ground-level ozone and nitrogen dioxide were the fatal pollutants [2].

Air pollutants are defined as those substances in the air with concentration level high enough to have detrimental impact on the environment or human health [3]. Among all the threats to human health, indoor air pollution is ranked top five by EPA [4].

In urban regions, especially metropolis with heavy traffic and population loads, outdoor air is often much more polluted than indoor air. As a result, the ventilation of buildings supplying outside air into rooms plays a significant role in indoor air quality control. It is far from sufficient to rely on individual indoor purifiers alone while the outside supply air is not conditioned and controlled since filtering devices always perform better in tightly-sealed rooms than in open space . Therefore, the filtration performance of the HVAC system in mechanical ventilation buildings are dominant in determining the indoor air quality [5].

1.2 Indoor air contaminants

Contemporary buildings are designed and constructed more and more air-tightly out of energy saving, thermal and acoustical comfort, and other considerations. Given the fact of less natural ventilation, another raised issue is “Sick Building Syndrome” (SBS), in which situations occupants report health problems. Apart from fine particles, other certain airborne contaminants also contribute dramatically to the indoor air quality.

Nitrogen oxide (NOX)

Nitrogen oxide is directly emitted by industry, vehicles, shipping and household. Throat and eye irritation, respiratory infection and shortness of breath could be the results of excess NOX. In addition, Nitrogen oxides could react with others producing Ozone [2].

Sulphur dioxide (SO_2)

Sulphur dioxide is produced during fuel burning, emitted by industry, vehicles, shipping and households. It can do harm to breathing and respiratory system even with short-term exposure. High concentration level of SO_2 will also lead to the formation of other sulfur oxides (SO_x) [6].

Carbon monoxide (CO)

Carbon monoxide is often emitted from combustion processes. Unlike Sulphur dioxide or Ammonia, Carbon monoxide is odorless and colorless, so it is difficult to detect its existence. Headaches, dizziness and nausea may be caused by CO [3]. Furthermore, it can lead to death with high level concentration.

Ozone

As an air contaminant, ozone is generated in secondary pollution through chemical reactions of NOX and VOCs under high temperature. Extreme high level of ozone occurs mainly during summer. The correlation between indoor and outdoor concentrations is quite low, indicating that the pollution level of ozone in ambient environment has little influence on the indoor concentration [7]. Therefore, the contaminant level is determined by indoor generation.

VOC (Volatile organic compounds)

Regarded as the causative factor of “Sick Building Syndrome”, VOCs are the compounds emitted by solvents in industry, vehicles, and other activities. The concentration level of indoor VOCs may be up to 10 times higher than in the ambient environment, since building materials, interior furnitures and human activities could all off-gas VOCs into the air [8]. Furnishings, wall coverings, and digital devices are the largest sources of indoor VOCs. Various health risks are associated with VOCs, such as allergic, immune and respiratory problems [9]. Different from the species mentioned above, VOCs problem is particular to indoor air quality rather than a macroscopical atmospherical issue. Therefore, a little attention will be paid to it when accounting for specific indoor purification technologies.

Particulate matter (PM)

There is already abundant information concerning outdoor PM, including concentration level, distribution principles, health effects to human beings, standards and guidelines, and so on. However, research of indoor PM is far from well-established, especially for $PM_{2.5}$, which has been emerging more and more seriously in recent years in some developing countries. Therefore, indoor PM2.5 control is selected as the subject of this thesis.

1.3 Research objectives

The intention behind this thesis is to find a feasible approach to improve the indoor air quality in high-rise office buildings where people may spend a long time in daily life.

It is well known that particulate matter 2.5 pollution is becoming an intractable issue in China. The impact is not only on the ambient environment leading to more and more haze days, but also on the built environment, which arouses even more concern. So a newly built office building in Shanghai is taken as a the analyzed case.

As most high-rise office buildings utilize mechanical ventilation systems, the emerging task is how to filter the heavily polluted air through air handling process and ensure supplied fresh air that meets the standard of indoor particulate matter 2.5 guideline. As the thesis title indicates, this research mainly focus on how to develop a systematic control strategy from the point of building design to reduce indoor PM2.5 and create a qualified working environment in office buildings.

This brings up several specific issues. The influences of building components considering both active and passive factors on indoor PM2.5 control are examined. The sub-questions include:

- What determines the indoor PM2.5 concentration level?
- What is the relationship between indoor and outdoor PM2.5 level?
- What approaches can help to ameliorate indoor particles?
- What kind of purifiers can remove airborne fine particles effectively?
- Is it essential to use a central filter or an individual indoor purifier?
- What is the filtration demand and requirement for purification systems?
- What sort of strategies of building design have a direct impact on indoor PM2.5 level?
- Which parameter is the most dominant one?
- What could be done to improve the indoor air quality concerning fine particles?

1.4 Research approaches

To propose appropriate control strategies for indoor air pollution, especially fine particulate matter, an analysis of contaminants in the indoor environment is necessary in the first place. This includes the causes of particle generation, distribution characteristics with a function of location, season or daily hour, primary and other influence factors, severity of pollution level, sources and sinks, and so on. This part will be presented in Chapter 2.

Secondly, some potential indoor air purification tools would be introduced in Chapter 3 and 4. In Chapter 3 the status quo of commonly applied air purification technologies will be illustrated containing respective purification mechanism, applicable contaminant species, features, superiorities and deficiencies. As most of these technologies are designed for gaseous contaminants rather than particles, only a few will be extended in the following content.

Apart from the traditional purification technologies based on either physical or chemical processes as presented in Chapter 3, another innovative purification tool, plant-based biofiltration is explored in Chapter 4. Other than those mature and widely applied technologies, botanic biofitration has not been well-developed yet and is being studied step by step. So the basic purification principles, typical products and potential applications in indoor office environments are proposed.

Next, a practical view is chosen focusing on the analyzed case. Considering the local climate, pollution level, population density, design code and other conditions, a specific control solution is given after numerical calculation on the scale of the built environment. This includes an elaboration of the necessities of centralized HVAC filters, individual indoor filters, HEPA filters and interior greenery.

Last but not least, it is vital to understand which parameter plays the determinant role in deciding indoor PM2.5 concentration from the point of building design. For high-rise office buildings the two main considerations are mechanical ventilation and unintended air infiltration. Thus the case is simulated based on different scenarios with the software CONTAM in Chapter 6. A further discussion and is made following the simulation data and comparison results on the scale of the building design. The adjustable parameters include the air leakage coefficient of the building envelope, interior control temperature, air supply and air return rate, respectively suggesting the influence of infiltration rate through envelope, air exchange rate through mechanical ventilation, pressure mode decided by both air supply and return rate, and temperature difference between interior space and the ambient. It is quantitatively examined through a sensitivity analysis to reveal which factor dominates in indoor PM2.5 mass concentration level. The indoor filtration demands in each scenario are also calculated to explore the efficiency rate requirements for indoor purification technologies induced in Chapter 3 and 4.

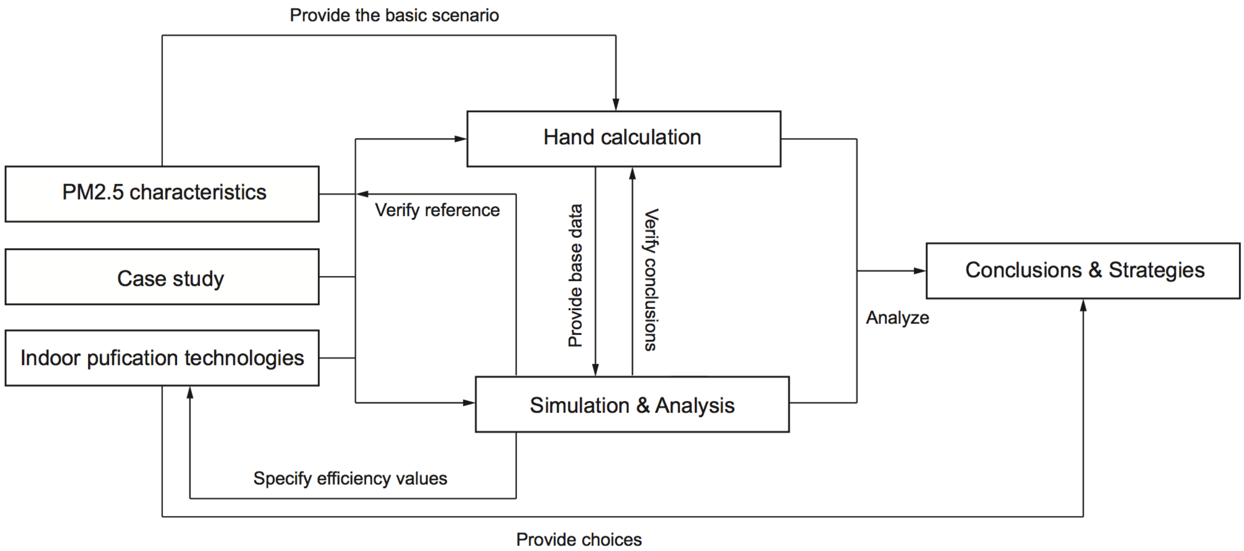


Figure 1. Workflow of the research thesis.

2 Particulate Matter 2.5

In this chapter, the background of particulate matter 2.5 is briefly demonstrated in section 2.1 to 2.3, including the cause of formation, emission sources, health risk, particle features, local distribution, etc. The focus of this chapter is on the relationship between outdoor and indoor concentrations, as well as other factors contributing to the increase of indoor pollution level, which compose section 2.4. Based on these explorations, corresponding guidelines of control strategies from the point of building design are given in section 2.5.

2.1 Background

Particulate matter (PM), also referred as aerosol as a mixture, is microscopic solid or liquid particle matter suspended in the atmosphere with a wide range of sizes [10].

Particle matter could be removed from air through either wet or dry deposition. Wet deposition can be achieved by rain, fog, snow and other high humidity actions. That is why high relative humidity helps particles concentrate and deposit. Dry deposition refers to the process due to natural gravity, impaction, interception or diffusion [11]. This characteristic varies among particles (see Figure 2). Particles with various sizes follow distinctly different motion principles. For large particles, turbulent impaction is the main mode, since the diffusion velocity function is in a negative correlation with the increase of particle size. The deposition velocity for particles larger than 10 microns are usually higher than 1 cm per second, which leads to easy deposition on surfaces [12]. In contrast, small particles could be diffused rapidly, dominated by Brownian movement [13]. So it is much easier for fine particles to be transported by airflow for a long distance, called airborne particles. Generally speaking, it is difficult for airborne particles to fall on the ground directly, since they could be blown and resuspended again by slight air flow, while it is more likely to be attached on the hairs, oils and secretions of leaf surfaces [14].

PM2.5, one of the particulate matter defined as airborne particles with aerodynamic diameters of 2.5 micron or smaller, is also called fine particulate matter or fine particles (to be distinguished from coarse particles, often referred to as PM10). Despite of its small volume, PM2.5 containing large amounts of toxic contaminants could be retained in the atmosphere for a long time and transported further than coarse particles [15]. The constitution of PM2.5 varies according to different sizes, emission resources, formation processes, etc. Non-volatile carbon, heavy metals, water-soluble ions like sulfate, together with semi-volatile ammonium nitrate and other organics are found in PM2.5 [16-17].

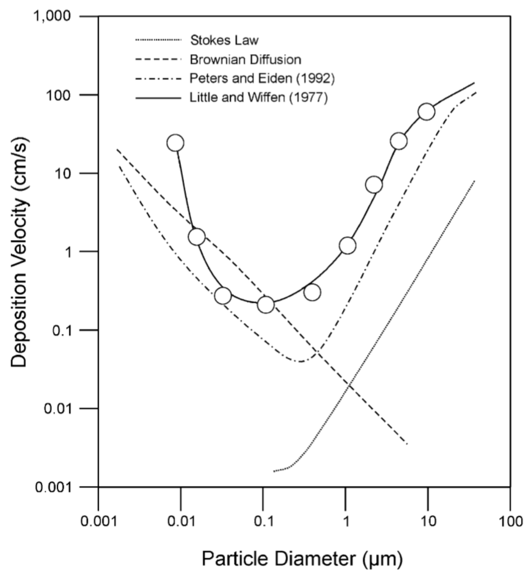


Figure 2. Relationship between particle diameter and deposition velocity. (Source: El-Shobokshy.)

2.2 Dangers of PM2.5

According to a global assessment of disease, 3,223,540 deaths were caused by ambient particulate matter pollution worldwide in 2010 alone [18]. The shocking data aroused public attention to the severity of consequence of fine particulate matter.

The impact of airborne particulate matter to human health has already been reported by lots of research [19]. Compared with coarse particles, fine particulate matter poses much greater risk to human health for the below reasons:

(1) Toxic substance such as transition heavy metals (e.g. cadmium, nickel, arsenic, mercury, etc.), gaseous contaminants, PAHs (polycyclic aromatic hydrocarbons), even virus and bacteria could easily attach on fine particles with smaller size of 1 micron rather than coarse ones [20].

(2) Particles larger than 10 micron would be blocked by nasal cavity; those between 5 to 10 micron could be obstructed by respiratory tract; While PM2.5 could pass through and deposit in the bronchus, pulmonary alveoli or even other organs through humors, and take long time to be eliminated [21].

(3) 90% of inhaled PM2.5 could penetrate into sensitive regions of the respiratory system such as lung and bloodstream, leading to various potential diseases [22]. The smaller the particles, the deeper they penetrate into the lungs.

It could be concluded that long-term exposure to high concentration of PM2.5 would to a great extent increase the occurrence of both respiratory and cardiovascular diseases. This has already been verified by sufficient epidemiological surveys [23-27]. A recent WHO report even links more potential diseases with long-term exposure to PM2.5, such as atherosclerosis, adverse birth outcomes, neurodevelopment and cognitive function, diabetes and other chronic diseases [28]. Particle number, size, shape, surface area, solubility and chemical composition all contribute to the health effects [29].

On the other hand, the negative impact of PM2.5 is also embodied on the global climate system. Together with other air components like carbon dioxide and ozone, fine particulate matter is a climate forcer that could destroy the near-surface energy budget balance of the earth by absorbing, scattering or reflecting solar radiation, which leads to poor atmospheric visibility [20]. Haze weather is a direct and typical production of decreased atmospheric environmental quality. Depending on different composition, the effect of particles on near-surface temperature of the earth is different, either warming or cooling the atmosphere [30].

2.3 Pollution level status

2.3.1 Origins and sources

The origins of airborne particles are quite complex. They can be either emitted directly by related sources or generated through chemical reactions involving nitrogen oxides, sulphur dioxide, ammonia, and volatile organic compounds. The sources of particulate matter can be either natural, such as sea salt, pollen, dust, volcanic ash and others, or anthropogenic. Human factors include fuel combustion, vehicle emission, cooking and smoking, etc. Therefore, the concentration of particulate matter close to ground is much more serious.

Different from coarse particles, fine particles, which consist of black and elemental carbon, metal oxides, nitrate, sulfate, primary and secondary organic compounds, ammonium and hydrogen ions, mainly come from combustion or chemical reactions [31]. Incomplete fuel combustion, regardless of fossil fuels for industries, gasolines for transportation, or coals for heating, is considered as the primary origin of PM2.5 [32].

2.3.2 Distribution characteristics in China

Among the 190 cities in China, only 25 are qualified which could meet the National Ambient Air Quality Standards of China. According to a great deal of previous research over the past decade, the distribution of PM2.5 in China characterizes the following features:

(1) Geographic variability

Distinct regional characteristics is the first point to be mentioned. Natural terrain and climate conditions, uneven extents of economic development, local industrial structures and various human behaviors all contribute to the discrepancy. As a whole, severity in cities are much higher than in countrysides, and better in coastal areas than in middle parts. The Heihe-Tengchong Line and Yangtze River are the two boundaries of high or low concentration areas, respectively on east-west and north-south directions [33]. The most polluted region appears around southern Hebei Province. Among the main population centralized regions, the northern conurbation space (including Beijing), the North China Plain area space, and the Yangtze river delta area space (revolving around Shanghai) are the PM2.5 severe regions, while the southeastern coastal areas are with much less concentrations and better air quality [34] (see Figure 3).

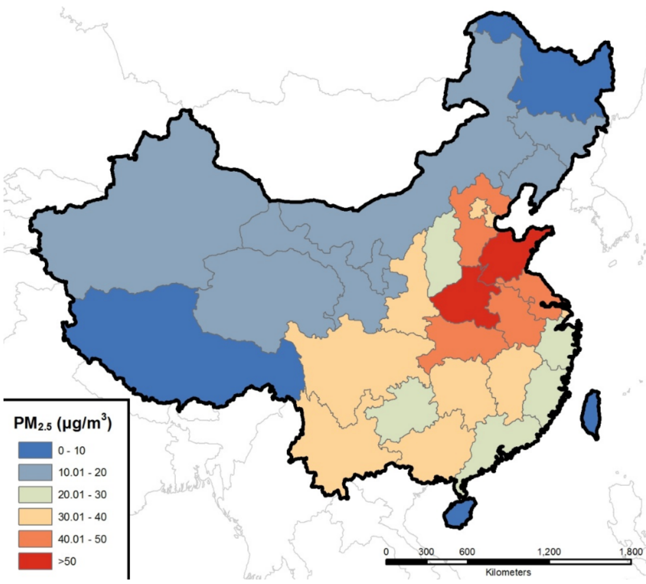


Figure 3. Average PM2.5 concentration distributions in China in 2007. (Source: Chinadialogue.)

(2) Seasonal variability

An obvious seasonal variation is observed. Generally, the highest concentrations occur in winter, followed by spring and autumn, while the lowest values appear in summer [34]. This is due to seasonal pollutant emission intensity and atmospheric diffusion condition variability. In winter, conventional coal heating in northern areas as well as blind straw burning in most villages are the chief culprits of stupendously increasing PM2.5 which gradually spreads nationally through current convection. In contrast, with no heating demand, summer monsoon accelerates airflow, which is beneficial for dispersing airborne particles. The relatively high humidity of air in summer enhances wet deposition of particulate matters as well.

(3) Spacial variability

From spacial point, the distribution does not correlate perceptibly with horizontal direction [35], but does with vertical altitude. The concentration of PM2.5 decreases with increasing altitude [36], but unlike coarse particles whose concentration shows evident decrease with height, the attenuation of PM2.5 is only noticeably above 30 storey [35]. This is due to the relative small deposition velocity of fine particles, which makes it easy for PM2.5 to diffuse and mix uniformly within certain altitude range. The relationship is also relevant with the weather. In smog weather, the concentration is much higher near surface layer, while in haze days it presents even mixture vertically [37]. It can be inferred that the distribution principle of PM2.5 in vertical direction is influenced by various factors, such as instant airflow, wind direction, thickness and stability of atmosphere layers, and so on.

2.3.3 Distribution characteristics in Shanghai

The distribution of PM2.5 of Shanghai shares similar features with that of the country in a rough. Located just at the coastal line of the Donghai Sea, sea breezes coming from the ocean while bringing clean air compose the majority of winds in the city, which relieves the severity of air pollution. According to the monitoring data of U.S. State Department from 2011 to 2014 (see Figure 4), the annual distribution curve of PM2.5 in Shanghai is roughly U-shape. The best air quality concerning PM2.5 is in August, while the highest concentration appears in and around December. This seasonal variation is in accordance with the nationwide curve as mentioned before.

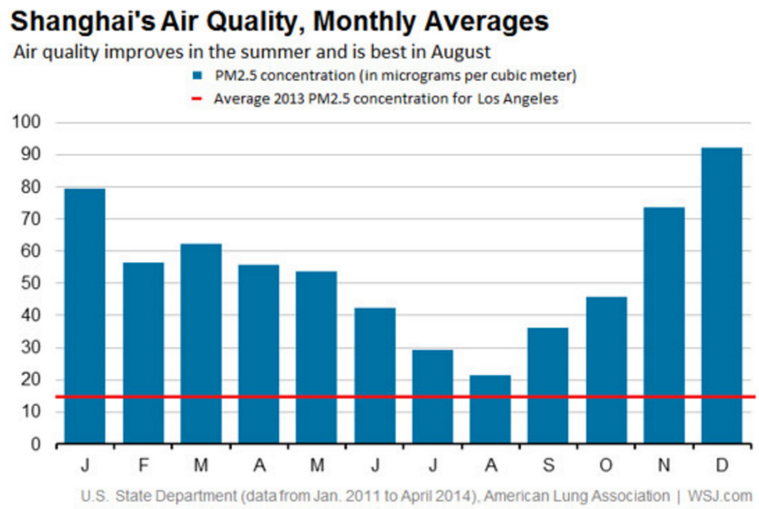


Figure 4. Annual distribution curve of PM2.5 in Shanghai. (Source: The Wall Street Journal)

Furthermore, a daily distribution curve was also illustrated by China Real Time (see Figure 5). It indicates that the highest concentration appears in both morning and night during rush hour, while a low level is remained during the day and mid-night. This is quite different from the daily distribution characteristics in Beijing (better air during the day and worse at night) (see Figure 6). This distinction originates from different climate conditions of the two cities. The temperature difference between day and night is apparent in Beijing. During night, cool air goes down bring airborne particles near the surface, while warm air rises and takes fine particles to higher altitude during the day. On the other hand, the temperature difference between day and night is not distinct in Shanghai, so the influence of airflow could be ignored. Instead, human behavior predominates the air quality. During rush hours there are more exhaust gases emitted by vehicles, which explained the fluctuation of the concentration.

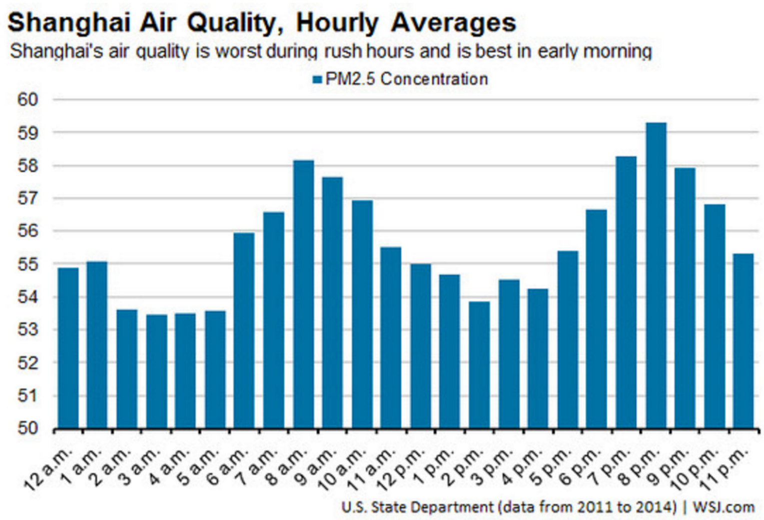


Figure 5. Daily distribution curve of PM2.5 in Shanghai. (Source:The Wall Street Journal)

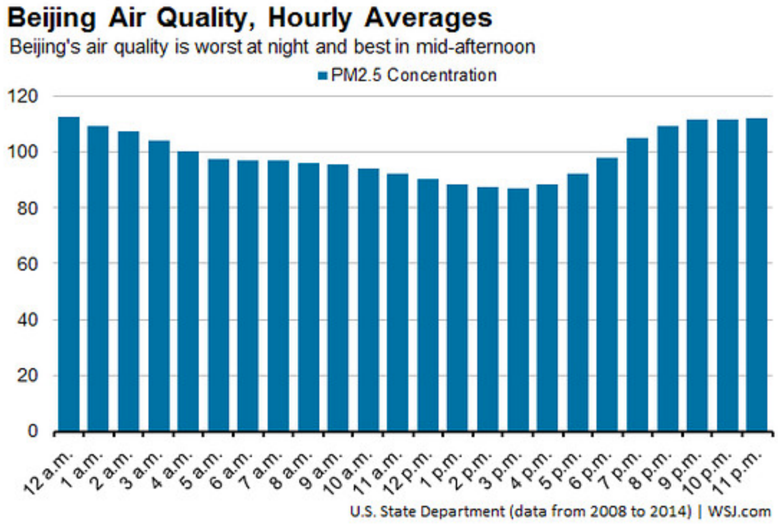


Figure 6. Daily distribution curve of PM2.5 in Beijing. (Source:The Wall Street Journal)

To explore the composition of PM2.5 in Shanghai and Beijing, a study sponsored by the General Motors Co., was initiated in March 1999. The sampling in Shanghai was conducted by Tongji University in two different sites. After extraction and chemical analysis, the results suggested that [38]:

(1) SO_4^{2-} NO_3^- NH_4^+ were the most dominant ions/anions in PM2.5 in Shanghai, which respectively occupied 46%, 18% and 17% of the total mass of ions.
(2) Local SO2 emissions played an important role in the source of sulfate in PM2.5.
(3) PM2.5 in Shanghai is likely to be acidic.

Some other recent research also indicated that NH_4^+ NO_3^- and organics were the main constitutes of PM2.5 in Shanghai, taking up more than a half of the total mass of ions [39-40].

2.4 Indoor concentration

It was reported that compared to outdoors, the harm of indoor PM2.5 is more dominant to human health since nowadays people tend to spend much more time indoors, either working or relaxing [41]. According to a survey conducted by Tsinghua University, the inhalation of indoor PM2.5 is approximately four times as much as outdoors, and the concentration for office buildings decreases from 16th floor [42].

2.4.1 Indoor emission sources

The particle concentration of the indoor environment is dependent on the ambient air pollution level, rate of air exchange through ventilation system, deposition and filtration characteristics, and additional generation within the building [43].

Outdoor particles get access into rooms through infiltration of enclosure like door and windows, cracks and gaps, entered personnel and fresh air supplied by mechanical ventilation systems. Indoor particle sources mainly focus on human behaviors such as smoking, cooking and using electric equipments.

Besides outdoor particle source, the main indoor emitters of fine particulate matter are:

Resource	Particle size (micron)	Caused by
Cigarettes	0.25-5.0	Smoking
Fuels	0-1000	Cooking; Heating; Burning
Radiation	0-0.1	Electric appliance
Biologies	0-750	Plants; Human beings; Bacteria growth

Table 1. Different indoor resources of PM2.5. (Source: Zhao., et al. 2005)

2.4.2 Influencing factors

The level of indoor PM2.5 are affected by several factors, ambient particles infiltration which remain suspended, indoor particle emissions, and other factors, among which outdoor pollution level is the decisive one [44]. The relationship between indoor and outdoor concentration can be assessed by I/O ratio [45].

Zhao and others conducted a real-time monitoring from June 2013 to February 2014 in Beijing to explore the influence factors of I/O ratio for PM2.5 under the condition of closed windows, no interior pollution sources and no mechanical ventilation system [46]. The results showed that (1) the indoor concentration increased from Monday to Friday (2) the I/O ratio was higher in winter than in summer (3) with the increases of relative humidity of outside air, PM2.5 mass concentration grew, while I/O ratio decreased (4) with the increase of outdoor wind speed, PM2.5 mass concentration decreased, while I/O ratio got higher.

Cyrys and others did a measurements from May 2001 to October 2002 in Erfurt to quantify the value of I/O ratio for PM2.5 under the condition of no interior particle sources, no human activities and different natural ventilation modes [47]. The results showed that (1) outdoor particle concentration, particle penetration efficiency from exterior to interior, air exchange rate, particle deposition rate on indoor surfaces and meteorological factors all contributed to the indoor particle concentration [48-49] (2) ventilation mode had a direct influence on the I/O ratio (3) the value of I/O ratio varied from 0.63 (window closed) to 0.83 (windows tilted open) (4) 75% of the indoor concentration variation was due to the outdoor change.

Another measurement was conducted by Li and others in 2014 in a kindergarten and an office building of Beijing to analyze the distribution principles of indoor PM2.5 concentration [50]. Data of the office building was collected on the 23rd floor during both work and after work time. The results indicated that (1) after work, with less people, closed air-conditioners and few human activities, the indoor concentration was mainly determined by outdoor pollution level, while during office time the influence of outdoor factor decreased (2) the air conditioning purification system had effects more or less on controlling indoor PM2.5 (3) outdoor wind velocity had less impact on indoor particle concentration compared to outside (4) interior hysteresis effect was observed in case of sudden change of outdoor particle concentration.

In addition, apart from particles sources and enclosure characteristics, the climate condition is also regarded as a crucial influence factor in terms of determining the correlation between indoor and outdoor concentration levels [51]. This is because the air exchange rate and infiltration factor, two key parameters in assessing I/O ratio, would be changed with the change of different climate conditions [52].

2.5 Architectural controlling principles

Pollution resource control, attenuation through ventilation and air purification are the three basic approaches dealing with indoor PM2.5 [53]. Both passive and active strategies should be applied. Passive solutions include:

(1) Site and orientation selection

Mainly targeted at buildings with special programs, like nursing homes for those with weak immune systems or resorts for vacation. City centers or centralized populated areas should be avoided during site selection phrase. With regards to commercial or office buildings, this solution provides little freedom.

(2) Reasonable function layout

Mainly applicable for indoor particle resources. For example, offices where dense personnels work and stay for a long time should be separated or away from smoking rooms, kitchens or other areas where lots of PM2.5 would be produced through indoor activities.

(3) Air tightness of the envelope

For most residential buildings without central ventilation system, or during after work time when the fresh air handling units do not work for public buildings, the indoor air pressure could be negative, so that PM2.5 can easily enter through the envelope with infiltrated air [54]. This infiltration is related to the air tightness level of the building [55], which should be paid attention in design phase.

Active solutions include:

(1) Ventilation control

Since outdoor source is an important factor of indoor particle levels, the ventilation system plays a significant role in reducing indoor pollutants. Various ventilation rates (frequency for air exchange), modes (natural or mechanical or combined), process in case of mechanical mode (filtration method during air handling) would lead to different efficiency. Meanwhile, for energy saving, the ventilation system should cater for the building functions, in commercial building cases durations of office or after work periods, and make use of the distribution characteristics of indoor PM2.5 if possible.

(2) Indoor purification

Another important strategy is to clean indoor existing air and remove particles from it by applying individual indoor filtration systems. This is because some anthropogenic activities and penetration effect through building enclosure could contribute to the indoor particle concentration, as well as to avoid the efficiency loss of the HVAC filtration system.

An experiment was conducted by Wang in 2013 in an office building of Beijing, in which three indoor PM2.5 purification scenarios were implemented—both attached filters (for fresh air before supplying) and individual filters (for internal air) in scenario A, individual filters solely in scenario B, and attached filters solely in scenario C [7]. With other conditions remaining the same, the measured results demonstrated that after some time, the indoor PM2.5 concentration in scenario A met the standard, while in scenario B it was far from qualified suggesting the little purification effect, and in scenario C the air quality was improved but insufficient. The result suggested the necessity of both fresh air filtration units and additional indoor purification devices.

3 Indoor air purification

In this chapter, some commonly utilized indoor air purification technologies are presented. Usually different technologies are designed to remove specific contaminants, including airborne particles and other gaseous pollutants. The exploration of these common purification technologies are explored in section 3.1. Then a comparison of these technologies is provided in section 3.2.

3.1 Available purification technologies

An air purifier is used for purifying indoor air and removing pollutants that do harm to human health. It could be either an individual unit standing alone or an attached part of an air handler unit. In spite of thousands of purifiers on the market varying in different aspects, the common principles they share are limited to the following basic mechanism applied technologies.

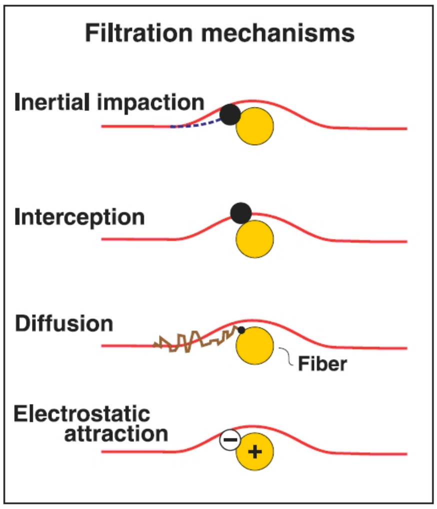


Figure 7. Basic filtration mechanisms for particles. (Source: Totobobo mask)

3.1.1 Fibrous media filters

Air filters could be manufactured for removing contaminants from the indoor environment either physically or chemically. A chemical one is to remove airborne odor and chemicals and thus contains catalysts or absorbents. A physical one consists of fibrous materials such as cotton, foam, paper and so on, which is for filtering solid particulates like physical dust, hair and pollen. The mechanism of fibrous media filters is size-resolved. For a large particle, its momentum would lead to deviation when going through the streamlines of a fiber. Thus it could be captured owing to inertial impaction or interception. This does not apply to small particles, whose inertia is small enough to follow the streamlines while the rapid diffusion toward surfaces with low concentration would also lead to capture by fiber media (see Figure 8).

According to the filtration effect, air filters could be divided into several classes. European standard BS EN779 (released in 2012) recognizes filter classes G1 to F9, while BS EN 1822(released in 2011) normalizes Efficient Particulate Air filter (EPA), High Efficiency Particulate Air filter (HEPA) and Ultra Low Penetration Air filter (ULPA) from class E10 to U17 (see Figure 9).

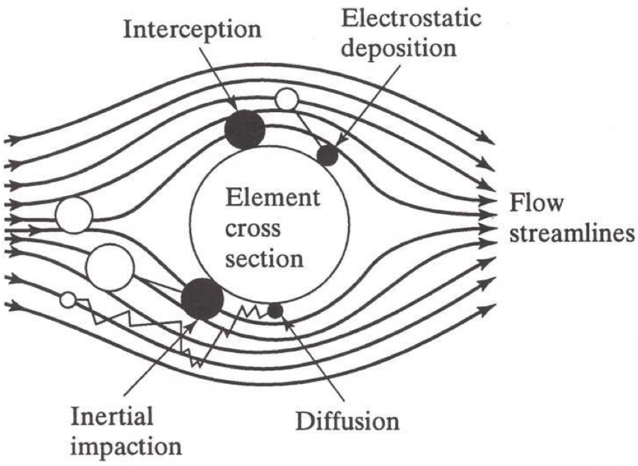


Figure 8. Particle capture mechanisms for a fibrous media filter.
(Source: Mechanical Engineering Department, University of Minnesota)

Fibrous media filters could be roughly divided into pre-filters, fine filters and HEPA. A pre-filter traps large particles in the air like hair and dusts, and thus is often used as the first line of filtration before fine filters, which to a great extent protects and extends the service life of fine filters. As pre-filters aim at capturing coarse particles, fine filters are necessary to remove smaller ones. The most common classification is standard ASHRAE 52.2, which is discussed later in chapter 5.

High efficiency particulate air filter refers to the most meticulous fibrous media filters used for intercepting fine particles. According to the United States Department of Energy (DOE), a qualified HEPA is a filter effective in removing 99.97% of particles with a size of 0.3 micrometer [56]. Most applications are for dust-free plants in industry, at which the demand of filtration is quite strict due to the highly polluted exhaust. In spite of high efficiency, it is not quite often used in dwellings or public buildings, mainly due to the high cost from both manufacturing and maintenance (frequent replacement required), high resistance and resulted serious noises. Just like electricity described by Lenz law, when a high resistance filter like a HEPA is standing in the way of airflow, air will prefer and look for another path with the least resistance. This law of nature results in potential situation that air would go around filter edges or gaps and the filter becomes useless for the air leakage. Therefore, HEPA should be replaced frequently in case of blocked streamlines to ensure normal functioning, which is difficult for filtration connected with a HVAC system.

	Filter application		Particulate air filters for general ventilation							EPA, HEPA and ULPA						
	Test		EN 779:2012 evaluation of filter performance at 0,944 m³/s (or nominal flow)							EN 1822:2011 (Part 1 to 5) Evaluation of filter performance by nominal flow						
Filter stage	Suitable for	Group designation	Filter classes	Test dust / aerosol	Final pressure drop in Pa	Average arrestance (A_m) compared with test dust in %	Average efficiency (E_m) for particles of 0.4 microns in %	Minimum efficiency for particles 0.4 microns in %	Previous: DIN EN 779:2003 (Predecessor: DIN 24185)	Filter classes	Test dust	Integral value of separation in the MPPS in %	Integral value of transmittance in the MPPS in %	Local value of separation in the MPPS in %	Local value of transmittance in the MPPS in %	Previous: DIN EN 1822:1998 (Predecessor DIN 24184)
1st filter stage (prefiltration)	Coarse dust	G	G 1	ASHRAE dust (72 % fine test dust ISO 12103-1:1997 A2 23% carbon black and 5% cotton linters)	250	$50 \le A_m < 65$		–	G 1							
			G 2		250	$65 \le A_m < 80$		–	G 2							
			G 3		250	$80 \le A_m < 90$		–	G 3							
			G 4		250	$90 \le A_m$		–	G 4							
1st filter stage (prefiltration) / 2nd filter stage (fine filtration)	Fine dust	M	M 5	DEHS (Di-Ethyl-Hexyl-Sebacate) 0.2–3.0 μm	450	–	$40 \le E_m < 60$	–	F 5							
			M 6		450	–	$60 \le E_m < 80$	–	F 6							
2nd filter stage (fine filtration)		F	F 7		450	–	$80 \le E_m < 90$	35	F 7							
			F 8		450	–	$90 \le E_m < 95$	55	F 8							
			F 9		450	–	$95 \le E_m$	75	F 9							
3rd filter stage (final filtration)	Suspended dust	E	EPA: Efficient Particulate Air filter							E 10	DEHS (Di-Ethyl-Hexyl-Sebacate) MPPS 0.1–0.3 μm	≥ 85	≤ 15	–	–	H 10
										E 11		≥ 95	≤ 5	–	–	H 11
										E 12		≥ 99.5	≤ 0.5	–	–	H 12
		H	HEPA: High Efficiency Particulate Air filter							H 13		≥ 99.95	≤ 0.05	≥ 99.75	≤ 0.25	H 13
										H 14		≥ 99.995	≤ 0.005	≥ 99.975	≤ 0.025	H 14
		U	ULPA: Ultra Low Penetration Air filter							U 15		≥ 99.9995	≤ 0.0005	≥ 99.9975	≤ 0.0025	U 15
										U 16		≥ 99.99995	≤ 0.00005	≥ 99.99975	≤ 0.00025	U 16
										U 17		≥ 99.999995	≤ 0.000005	≥ 99.9999	≤ 0.0001	U 17

Figure 9. Air filters by filter classes. (Source: Freudenberg Filtration Technologies)

3.1.2 Ultraviolet germicidal irradiation

UV light purification is a sterilization approach that uses sufficient short-wavelength ultraviolet (UV-C) light to kill or inactivate pathogens by destroying nucleic acids and disrupting their DNA, leaving them unable to perform vital cellular functions [57].

The history of its application could date back to the late 19th century, when the bactericidal effect of solar light was discovered. Later William F. Wells revealed the ability of UVGI to prevent the spread of airborne infection by droplet nuclei [58].

For a long time UV light was primarily employed in medical field. In 1903 the Nobel Prize for Medicine was awarded to Niels Finsen, the inventor of UV use against tuberculosis [59]. In recent years the application has been extended generally to other functions, such as water treatment and air purification.

Air purifiers using UVGI technologies to work with UV lamps that sterilize air during the course of going through. It could be either an individual standing alone unit with a fan to force airflow passing the shielded UV lamp, or a combined part of forced air systems in which circulated air helps to filter the dead sterilized micro-organisms from the lamp [59] (see Figure 10).

Owing to the effective disinfection of destroying microorganism, it is mostly applied in hospital or food factory. Meanwhile, UVGI also brings some potential risk. Excessive exposure to germicidal wavelengths of UV light may lead to some skin diseases, as well as harm to eyes. In case of application of air purifiers, the incidence of such kind of potential is limited. However, another issue is brought to the stage—ozone generation. UV-V, produced by ultraviolet lamps, produce ozone when it reacts with oxygen and break it into atomic oxygen which may result in ozone [60]. The negative effect of ozone would be introduced in 3.2.4.

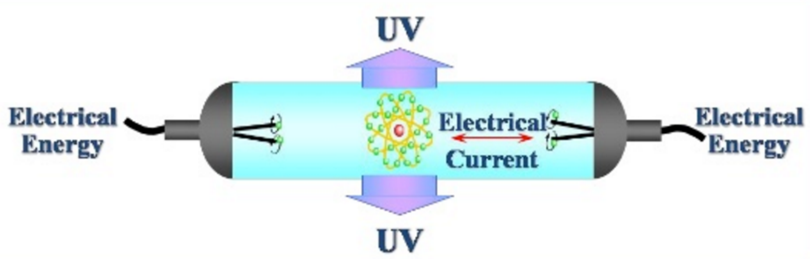


Figure 10. Working Mechanism of UV lamps. (Source: Alfaa UV.)

3.1.3 Titanium dioxide photocatalytic

TiO2 photocatalytic is an enhancing disinfection method which mixes TiO2 nano particles and calcium carbonate neutralizing adsorbed acidic gasses into porous paint material [61]. Airborne contaminants at the surface are decomposed with the force of photocatalysis.

As a semiconductor, usually a little bit Titanium dioxide sufficient to cover the surface of the substrate is required. UV light irradiating the surface would activate the photocatalytic effect by releasing electrons, which would break up water molecules in the air into hydroxyl ions. When harmful organic chemicals pass the surface, these hydroxyl radicals would break apart the chemical bonds and transform them into carbon dioxide and water [62] (see Figure 11).

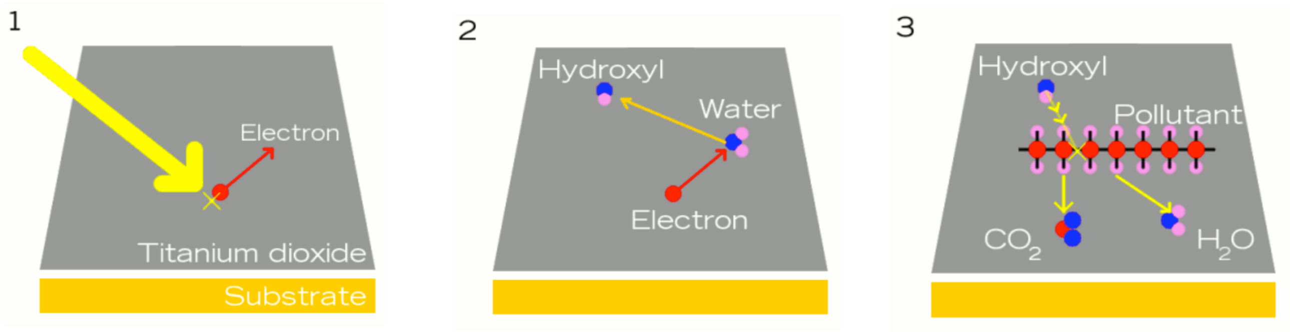


Figure 11. Working mechanism of Titanium dioxide photocatalytic.
(Source: http://www.explainthatstuff.com/how-photocatalytic-air-purifiers-work.html)

Titanium dioxide photocatalytic works as a catalysis rather than an independent purification technology, only effective when supporting other related technologies (in most cases UVGI). It could enhance the UV light irradiation effect up to 4000% to kill bacteria, viruses, mold and germs [63].

3.1.4 Ozone generators

A large amount of ozone is generated in this technology as a strong oxidant gas to oxidize and remove chemical contaminants [64]. Besides the basic oxygen molecule, an unstable oxygen atom is used to attache on other molecules and alter the chemical composition of these substances.

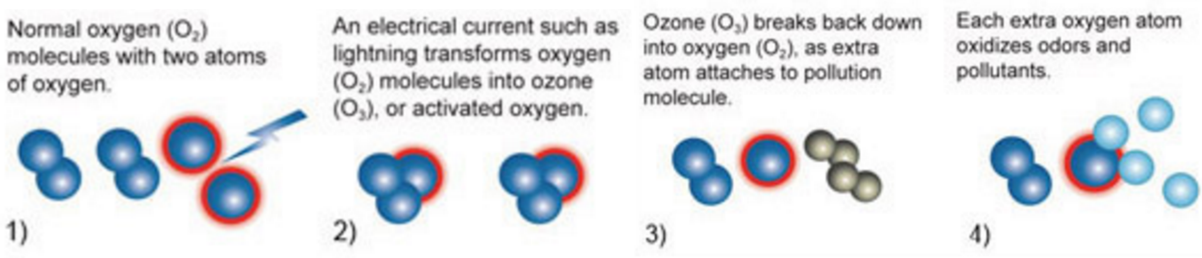


Figure 12. Working mechanism of Ozone generators. (Source: Odor Free Machines.)

It functions quite well in removing odors, but the application is limited to a great extent considering the safety effects. The reaction between ozone and other chemicals could release fine particles and some substances hazardous to human health. Exposure to high concentration level of ozone even for a short period could induce various syndromes such as coughing, wheezing, chest pain, irritation of throat, eye, nose, even lung tissue and respiratory infection [65]. Other pre-existing chronic diseases could also be worsen through breathing ozone. These negative health effects of ozone has already studied and reported by US EPA, suggesting the prudence when applying it as a purification technology, especially in indoor environments with humans [66].

3.1.5 Activated carbon

With the longest application history, the first use of activated carbon for air purification dates back to 1854 for removing gases and vapors in the ventilation system of London sewers [67]. It is a porous form of carbon with large surface area which is a little bit positive-electronic charged. Thus the added charge is beneficial for attracting and absorbing negatively charged volatile chemicals.

Activated carbon, or sometimes referred as charcoal, is widely used in air and water filters. When applied to air purifiers, usually other minerals like zeolite is also combined as a chemical sieve [68]. The amount of carbon and the amount of contact time with contaminants are the two crucial factors determining the efficiency of the activated carbon filters [69]. The performance of activated carbon technology in removing various sorts of indoor contaminants is roughly assessed as follows (see Figure 13).

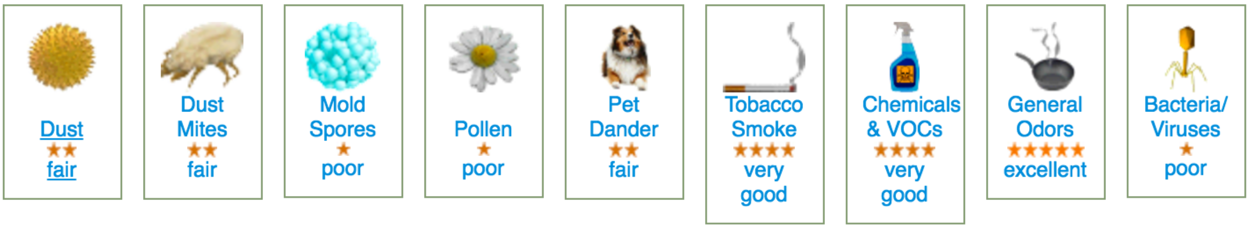


Figure 13. Effectiveness assessment of activated carbon for different indoor pollutants.
(Source: Home Plus Air Filters.)

Activated carbon plays a role more in changing contaminants from gas to a solid phase than in removing them completely, since the absorption process will reach equilibrium [70]. Despite of various alternative technologies in gaseous contaminant removal, given the fare cost and excellent removal performance compared to other adsorption materials, nowadays it is still popular in combination with other filtration technologies in air purifiers.

3.1.6 Air ionizer

Also called negative ion generator, an air ionizer uses high voltage to ionize air molecules. Electrostatic adsorption is the basic physical mechanism behind this technology, and has already been applied in wider spread. Electric neutral media like a plate is polarized by ionizer to create either positive or negative electrons. Later these electrons are discharged into the air, attach to air molecules and form ions, which would attract and attach to airborne particles when they pass through the electric field, making it easier to trap these particles due to electrostatic adsorbability [71].

Although capable of adsorbing both airborne and microbiological particles, this method is not as effective enough on its own as working in collaboration with other technologies. In addition, the potential of releasing ozone as a by-product during the charging process is another health concern through the emitted amount is far less than ozone generators.

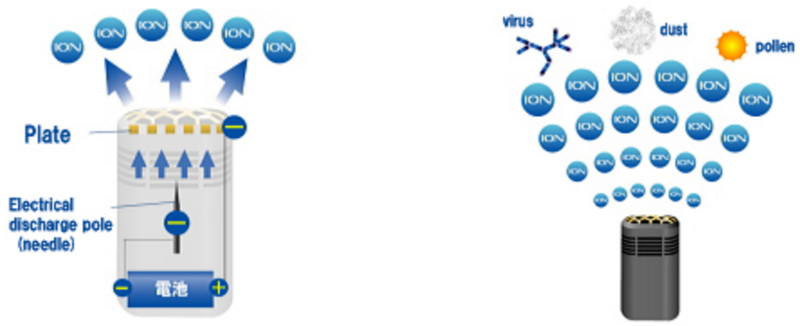


Figure 14. Working Mechanism of air ionizers. (Source: Daisaku Shoji Ltd.)

3.1.7 Thermodynamic Sterilizing System (TSS)

The key element of this technology is inherent heat. By heating a ceramic core with micro capillaries heated up to 200 degree, microbiological particles are killed. It is claimed that 99.9% of germs, bacteria, mold and viruses are eliminated using this technology [72]. Due to natural air convection, air pass through the ceramic core will be sterilized and then cooled using heat transfer plates (see Figure 15).

By exposing living microbiological particles to extreme high temperature, TSS is effective in incinerating 99.9% of pathogens in the air. As well, the generation of by-products like ozone is not a concern as it is claimed. However, it could not be combined with HEPA due to the high temperature [73].

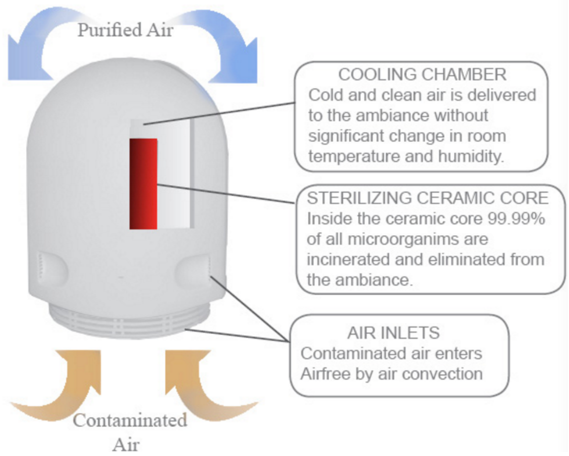


Figure 15. Working mechanism of TSS. (Source: Allergy Buyers Club.)

3.1.8 Water

Purifiers using water as the main purifying medium are emerging recently. Water-based filters aim at removing airborne particles like dust and dirt from air, while they do not work for chemicals or pollutants. Additional moisture brought by water into air also brings potential mold issue, which limits the popularization of this technology, together with the huge energy consumption.

The water based purifier could be extended to wet scrubbing, a technology designed for purifying heavily polluted industrial air. Plain water or other chemical solutions are applied as the medium washing the contaminant containing air as it passes through. The main target pollutants for this technology is water-soluble toxic gases, especially acid components like HCl, NO2 and NH3. If there are large amounts of particulate matter in the air, slurry accumulation in the liquid after purification would be the result, and has to be filtered to keep it work again [74].

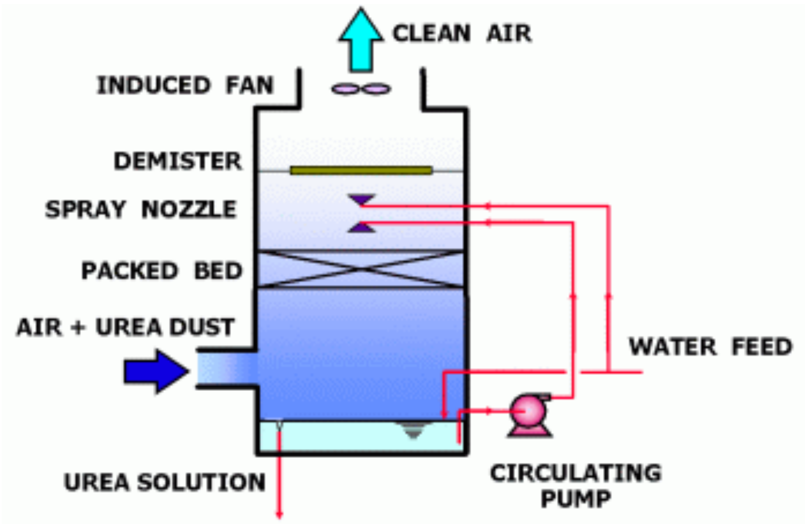


Figure 16. Working mechanism of wet scrubbing. (Source: TOYO Engineering)

3.2 Comparisons & Conclusions

According to different characteristics of each technology, a comparison is shown in Table 2 listing respective strength, weakness, effectiveness and cost-efficiency. It can be concluded that pre-filters, HEPA, ionizers and water are applicable in removing airborne particles from polluted air.

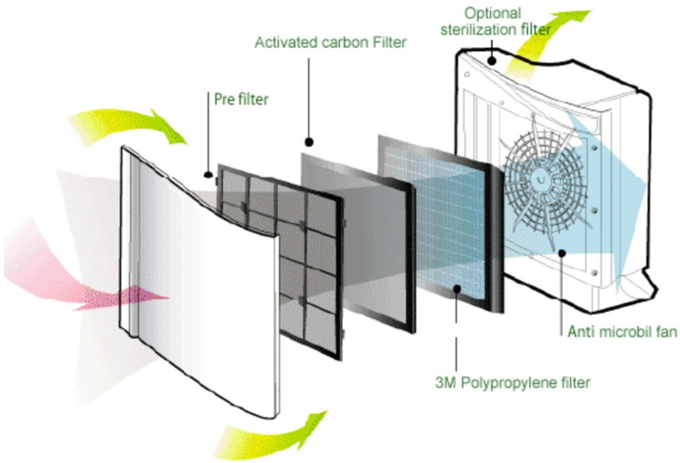


Figure 17. A typical air purifier combing several technologies. (Source: Retsel Corporation.)

In a conventional air handling unit for residential buildings, a pre-filter is applied as the last process before supplying air into rooms. However, it only works for particles with a larger size than 2.0 micron, and the filtration efficiency is around 20%—50%. In some centralized fresh air handling units for public buildings, sometimes another fine filter is applied which can remove 40%—60% airborne particles with a size of 0.5 micron. Even so, removing PM2.5 from fresh air still remains a big issue considering the low efficiency of the device, as well as the potential secondary pollution [7].

According to a number of research and market investigations, among the air purification technologies, the most effective one for PM2.5 removal is HEPA (for particles with a size of 0.3 micron) and ionizer (for particles with a size of 0.01micron) [75-76].

Technology	Target contaminant	Advantages	Disadvantages	Cost
Pre-filter	Airborne particle (coarse)	Easily washable	Only applicable for large particles	Low
HEPA	Airborne particle (fine)	High efficiency	Frequent replacement; Potential leakage	High
UV light	Microorganism	High cost-efficiency	Frequent replacement	Low

Technology	Target contaminant	Advantages	Disadvantages	Cost
TiO2 photo-catalytic	Microorganism	Effective UV light enhancement	Catalyst other than individual technology	Low
Ozone	Chemical/ Gas	Excellent in absorbing ordor	Health and safety risks	Medium
Activated carbon	Chemical/ Gas	High cost-efficiency	Incomplete adsorption; Periodic replacement required	Low
Ionizer	Airborne particle; Microorganism	Affordable; Applicable for both airborne and microbiological particles	Necessary to be combined with other technologies	Low
Thermodynamic sterilization	Microorganism	High efficiency	Huge electricity consumption	Medium
Water	Airborne particle	Replacement not necessary	Low efficiency; Potential secondary pollution	Low

Table 2. Comparison of different air purification technologies.

4 Botanic biofiltration

In this chapter, an innovative air purification technology based on biological processes is explored. In section 4.1, the theory ground suggesting the air purification effects of plants is introduced. This is followed by a brief summary of the advantages and disadvantages of plant-filtration in section 4.2, inducing the botanic biofiltration which would be presented in section 4.3. After a little bit mechanism introduction, several applications of plant-based biofiltration technologies and their potential of being applied in high-rise office buildings are discussed in section 4.4.

4.1 Effects of plants on air pollution

4.1.1 Purification mechanism

Vegetations purify air directly by absorbing or capturing pollutants through stoma of the leaf surfaces. Plants absorb particles with leaf surfaces through impaction with the influence of wind air flow or sedimentation with the influence of gravity. Plants with smaller leaves and rough surface do a better job in particulate absorption than larger or smooth leaves. The efficiency also varies according to the particulate sizes. The deposition of larger particles is easier and quicker than smaller ones. However, unlike gases which can produce chemical reactions and be converted into other contaminants, the absorption of particles by plants is only a temporary retention. Held back by leaf surfaces, the retained particles could be resuspended into atmosphere after some time, if not washed off or drop down by either natural or anthropogenic forces. The accumulation of particles on leaves could clog the stomata of leaf surfaces and thus reduce photosynthesis effect as well [77].

4.1.2 Capacity of PM2.5 adsorption

The capability of absorbing PM2.5 varies a lot among different plant species, depending on the size, geometry, roughness, porosity and other characteristics of leaves [11].

Gao et al measured the captured amount of PM2.5 on leaf surfaces of Buxus megistophylla and other two species in two outdoor scenarios in busy districts of Beijing. The results indicated that (1) the adsorption capacity of leaf surfaces varied among species due to diverse microstructure characteristics of leaves (2) smooth and wax leaf surface had a negative impact on the captured amount (3) buxus megistophylla performed better in particle adsorption than the other two species (4) beyond certain time limit, the leaf surfaces would not be able to deposit particles any more (5) the pollution level of the ambient did not have a remarkable impact on the adsorption capacity of species [78].

Given the fact that most serious haze days happen in winter, deciduous plants are ineffective for the lack of leaf surfaces. Ji and other conducted a study in 2013 to analyze the potential of common used plants in north China for PM2.5 purification, and found that (1) for easy clean and maintenance, species with low height were more favorable (2) Chinese roses, corns, privets and some evergreen species were suitable to be grown for large areas (3) the only effective adsorption species for particles in winter were moundlily, euonymus japonicas and dragon cypress (4) moundlily performed best followed by dragon cypress then euonymus japonicas from the point of efficiency per leaf unit, while euonymus japonicas was in the ascendant of leaf quantity and surface [14].

The time dependence of retention was investigated in another experiment by Bao and others as well. Eight evergreen species commonly cultivated as landscape in China were tested one by one. An individual plant was placed in a one-cubic-meter chamber under the condition of indoor environment with no wind, constant temperature and humidity. The results revealed that (1) the adsorption speed presented gradual decrease with time (2) there was a duration limit of particle retention for each plant species (around 12 to 14h for PM2.5), beyond which the adsorption effect would approach zero (3) needle-leaved plants performed better than broad-leaved ones, while conifer was better than cypress (4) the purifying rate varied among species [79].

Similarly, Wang et al did a research exploring the particle adsorption capacity of ten evergreen species in 2014 [80]. The sampling was in a rural outdoor park in Beijing, and the amounts of particle deposition on leaf surfaces were weighed in a lab. The result data of the same tested species are shown in Table 3.

The values in the second column were achieved by collecting the outermost lateral leaves and measured their captured particle amounts after experiments. This was to ensure a comprehensive contact between air and leaf surfaces in order to explore the adsorption capacities of species, since outer leaves would be fully exposed while inner ones might be sheltered by others. The values in the third and forth column were calculated by measuring the initial and finalized mass concentration of PM2.5 in the test chamber. The difference value is the amount captured by the plant, and the removal ratio could also be calculated.

It should be highlighted that while the unit captured amount of leaf surfaces is substantial, the captured amount of each species is not considerable. It could be inferred from the second and third columns that the capture capacity of an individual plant is far less than multiplying the unit capture capacity with total leaf surfaces. This is probably due to two reasons: (1) the closely arrayed leaves are sheltered by each other, as explained previously (2) with no wind flows the static air prevents the transport of airborne particles. As a result, most leaves were not in full touch with air, and only the exterior leaf surfaces made a contribution to particle adsorption.

It could be seen from the last two columns that even for the same species, test data in different experiments varied. The adsorption capacity of buxus megistophylla measured by Gao is much higher than the data from Bao. On the other hand, for the other four species the values measured in the outdoor area are similar, even a little bit lower than than in the indoor chamber. The diversity might be caused by different test fields. The experiment conducted by Gao et al was in the city center, compared to the indoor test and rural measurement. Therefore, it could be inferred that the adsorption capacity of leaf surfaces of greenery species differs in diverse environments. It is highly likely that frequent airflows facilitate particle deposition, and leaves perform better in adsorbing PM2.5 in environments with intense concentration.

	Data from Bao et al (2015)			**Data from Gao et al (2016)**	**Data from Wang et al (2015)**
Species	Unit captured amount of leaf surfaces $(\mu g / cm^2)$	Captured amount $(\mu g / plant)$	Removal ratio (%)	Unit captured amount of leaf surfaces $(\mu g / cm^2)$	Unit captured amount of leaf surfaces $(\mu g / cm^2)$
Cedrus deodara	0.689	16.881	14.68	N	0.67
Pinus bungeana	0.602	14.943	12.99	N	0.23
Platycladus orientalis	0.312	10.861	9.45	N	0.18
Ground hemlock	0.365	8.882	7.72	N	0.19
Buxus Megistophylla	0.214	3.881	3.38	4.7-6.0	N

Table 3. PM2.5 adsorption efficiency of different species. (Source: Bao, Gao, Wang, et al.)

Given that the focus of this thesis in on indoor office environments, the test data from Bao are adopted. The order of magnitudes is in accordance with other related researches, suggesting a value less than 1 $\mu g / cm^2$ for adsorption capacity of leaf surfaces [81].

4.1.3 Capacity of VOCs removal

The airborne contaminant removal technologies mentioned in Chapter 3 are based on either physical (e.g. electrostatic ionizer, etc) or chemical (e.g. ozone generators) processes. They are efficient but only appropriate for removing high level pollutants in the air, particularly in industry waste gases treatment, for the high energy demands and operating costs. For indoor office environments, the concentrations of VOCs and other inorganic gaseous contaminants are relative low (less than 1 ppm), which is not applicable for most purifier operation. Instead, biological processes like plant absorption is considered as an alternative [82].

Compared to the removal effect of plant species itself, plants eliminate odorous compounds mainly through root systems [83]. A lot of research has reported the ability of potted plants in eliminating VOCs, and the microorganisms of potting mixtures rather than plant leaves are the primary removal agents [84]. The degradation first starts with transferring gaseous contaminants into liquid phase, absorbing it into a biofilm, where biodegradation happens then by soil microorganisms to turn it into nutrient sources [85].

A field-study in 60 offices revealed that potted-plants bring up to 75% reduction in total VOC (TVOC) level within 5-9 weeks when the initial indoor TVOC concentration exceeds 100 ppb [84]. A database analysis of indoor TVOC concentration in 176 office buildings suggested 250 microgram per cubic meter as the average level of TVOC [86], which is higher than 100 ppb and therefore implies the potential removal effectiveness of potted-plants. The ability of common indoor ornamental species in removing different VOCs were tested in chambers first by NASA in 1989 [87], followed by various series of research. In one recent study conducted by University of Georgia, twenty-eight species were analyzed and evaluated with respect to efficiencies in removing five VOCs after 6h. The results of the five highest removal efficiency species are shown in Table 4 [88].

Species	**Benzene**	**Toluene**	**Octane**	**TCE**	$\alpha -$ **Pinene**	**Total**
Hemigraphis alternata	5.54 ± 0.29	9.63 ± 0.94	5.58 ± 0.68	11.08 ± 0.99	12.21 ± 1.61	44.04 ± 2.98

Species	Benzene	Toluene	Octane	TCE	$\alpha-$ Pinene	Total
Hedera helix	3.63 ± 0.33	8.25 ± 0.64	5.10 ± 0.49	8.07 ± 0.77	13.28 ± 0.95	38.33 ± 3.17
Tradescantia pallida	3.86 ± 0.58	9.10 ± 1.17	2.76 ± 1.08	7.95 ± 1.20	10.45 ± 1.78	34.12 ± 5.52
Asparagus densiflorus	2.65 ± 0.24	7.44 ± 0.28	3.76 ± 0.64	6.69 ± 0.49	11.40 ± 0.78	31.94 ± 2.40
Hoya carnosa	2.21 ± 0.21	5.81 ± 0.67	3.80 ± 0.62	5.79 ± 0.75	8.48 ± 1.17	26.08 ± 3.40

Table 4. VOCs removal efficiency of different species. (Source: Yang., et al. 2009) $(Unit: \mu g.m^{-3}.m^{-2}.h^{-1})$

4.2 Benefits and defects of plant filtration

Besides improving indoor air quality, greenery also brings other benefits. For example, indoor plants demonstrate remarkable contribution to improving the productivity and wellbeing of staff, which is desirable in office environments [89-91]. Faster reaction time in greenery laboratory was shown in a comparison test [92]. An environment with plants is also beneficial to help people relax and thereby reduce trauma mentally and physically [93].

Although the filtration effect of green plants for PM2.5 has already been verified, there are several obvious limitations that hinder its application as a mainstream indoor purification technology.

(1) Low efficiency

As can be seen from Table 3, the purification rate of some highly efficient species as an individual plant is far away from the professional air purifiers. To ensure sufficient efficiency, a large indoor space for plants, especially for trees, is required, which is often not the case for high-rise office buildings.

(2) Limited capture

Vegetations do a great job in removing outdoor airborne particles, as a mass of plants is in contact with particles through airflows. In contrast, plants in a static indoor environment do not function well, unless airborne particles are transported and recirculating nearby, in which case the stoma on leaf surfaces would adsorb the particles.

(3) Dispersive maintenance

Daily watering, regular trimming and frequent cleaning are required for plants. Often more than one individual plant or species are applied for more effective indoor air purification, which leads to repetitive and dispersive maintenance work.

To make full use of the filtration potential of plants and improve the defects, some improved technologies combing greeneries and other measures could be a better option— botanic biofiltration.

4.3 What is biofiltration?

Biofiltration is a purification technology which uses organic materials to absorb, separate, remove or degrade contained pollutants from air [94]. A biofilter consists of a fan system to force airflow, and a box containing media bed such as soil, sands or gravels layer to provide nutrients to the microorganisms and support biofilm formation, which act as wet scrubbers to absorb water soluble compounds [95]. Polluted air is transported to the media bed through pipes and then biologically degraded.

Various types of biofilters are developed for contaminated air or waste water treatment, most of which are intentionally designed for industries with higher than 100 ppm contaminant concentration level, such as bioscrubbers [82]. Considering the space and cost of industrial biofilters, generally in typical dwellings and office buildings it is not sensible to apply these types since the pollutant level seldom exceeds 1 ppm. Instead, in recent years more and more research is leading the development of innovative plant-based biofilters specifically for removing low concentration air contaminants, in the form of either standing alone in indoor environments or integrated with HVAC systems. In this section typical types of botanic biofilters are discussed.

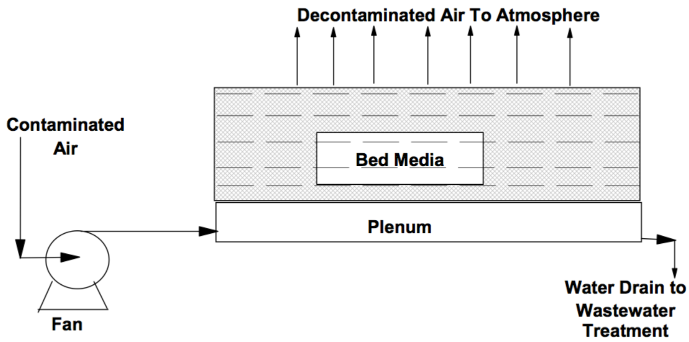


Figure 18. The scheme of a basic biofilter. (Source: U. S. Environmental Protection Agency.)

4.4 Application of botanic biofiltration

4.4.1 Biowall technology

A biowall system is made up of various plant species, whose root microorganisms are embedded into a vertical porous matrix, and usually some supporting devices like a water pump for irrigation, a fan system to enhance convective air flow [95] (see figure 19).

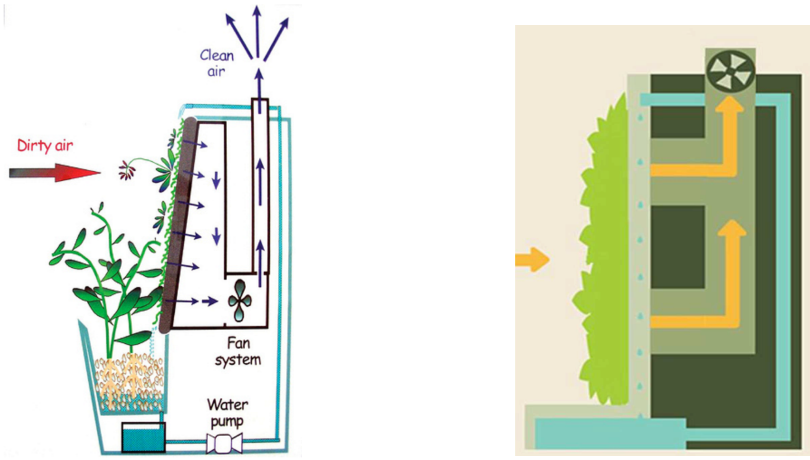


Figure 19. Illustrations of a biowall. (Source: www.naturaire.com. & ASHRAE)

For a large area of vegetations, the air filtering capacity of uncut meadows with a variety of plant species is higher than those mowed lawns with monocultures [96]. This also applies to vertical biowalls, since a mix of species with various densities, microstructures and sizes could adsorb different airborne particles.

Spreading in the vertical directions, a biowall occupies a small area in indoor office buildings. Like an exterior green facade, an indoor biowall system includes cultivation substrates, waterproof supporting structures, an irrigation system and plants. A biowall is usually composed of diverse plant species with a dense cultivation. Hence the purification efficiency of greenery is greatly improved.

The efficiency of a biowall in filtering PM2.5 varies according to different selection of plants, areas, connection with other systems and so on. To quantitatively verify the purification effects, a test was conducted by China State Construction Engineering Corporation (CSCEC). A one-meter-square movable biowall with scindapsus aureus, bracketplant, chamaedorea elegans and monstera deliciosa species was placed in a 30-cubic-meter airtight chamber filled with high pollution concentration. The microcirculation of inner air was ensured by parallel fans for full contact between the biowall and pollutants. The results confirmed the high purifying performance of the biowall, which removed 80% of PM2.5 in the carbon [97] (see Table 5).

Contaminants	PM2.5	PM10	Methanal	Benzene	Methylbenzene	TVOC
Duration (h)	4	4	6	6	6	6
Efficiency (%)	80	92	90	82	85	83

Table 5. Purification efficiency of a biowall. (Source: Wang., et al. 2014)

Figure 20. Individual biowall purifiers in an indoor environment. (Source: Biotecture.)

Potential applications of biowalls in indoor office environments could be:

(1) Utilized for the interior biofilter for supplied fresh air before the HVAC process. Biowalls could serve as a small-scale separate green garden, drawing air to go through as the first step of treatment, with ducts connecting to the subsequent air handling processes.

(2) Utilized for the indoor air filtration standing alone for interior emissions. For fine particles already existing in the indoor environment infiltrated through enclosure, carried by humans or produced by indoor emission resources, biowalls serve as the individual air purifiers (see Figure 20).

4.4.2 Green roof & moss mats

Mosses are very ideal plants for bio-roof materials. Compared to higher species, they occupy less vertical space while have a large leaf surface area, and is beneficial for not sheltering each other. With no roots that feed from the soil, they absorb water and nutrients from the surface, which does not restrict the growing substrate a lot compared to conventional vascular plants. Thus they are quite sensitive to the environment. It is believed that mosses absorb more heavy metals in the air than other plants, since it is closer to the ground where is exposed to higher dust concentration [98]. The air purification ability of mosses is also influenced by altitudes. The higher altitude, the stronger adsorption capability [99].

To improve adsorption efficiency, pre-cultivated moss mats, consisting of non woven fabric, moss sprouts and a mat layer were developed as a biofiltration technology in Europe (see figure 21). The leaf surface of mosses is negatively charged and filled with positively charged H+ ions. Therefore both coarse and fine particles, normally with a positive charge, could be captured more effectively by different electrostatic charges on the leaf surfaces [59]. Different from just adsorbing fine particles through adsorption, inorganic water-soluble substances of fine particles are metabolized by ion exchange of the mosses. The resuspension of particles after temporary retention is also prevented. Meanwhile, once adsorbed, ammonium nitrate, which take up 20% to 80% of the fine particles, could be fertilizers to mosses once adsorbed. The surface of mosses is covered with a biofilm of bacteria, which could decompose the organic substances consisting 25% of the fine particles. Other inorganic insolubles could be held in the mosses and decomposed by hydrolysis, considering the long-term effect of acid rainwater [100].

The application of mosses as bio-filters are being popularized in Europe especially Germany. The famous Motor City, Stuttgart, is an example. Owing to the large amounts of vehicles, the low terrain and other influencing factors, Stuttgart is one of the most heavily polluted cities in Germany, with a higher particulate matter concentration than European standards. Mosses are being applied as bio-roof and bio-wall materials for air purification, which could remove approximately 75% of the airborne particles, according to the research institutions of University of Stuttgart [101]. Tested at the Nees Institute of Biodiversity at the University of Bonn, moss mat is mainly used along traffic roads with heavy pollution, but could also be utilized for more applications owing to its flexible installation both in directions and sizes. In addition, no maintenance is required for the slow growth of mosses [99].

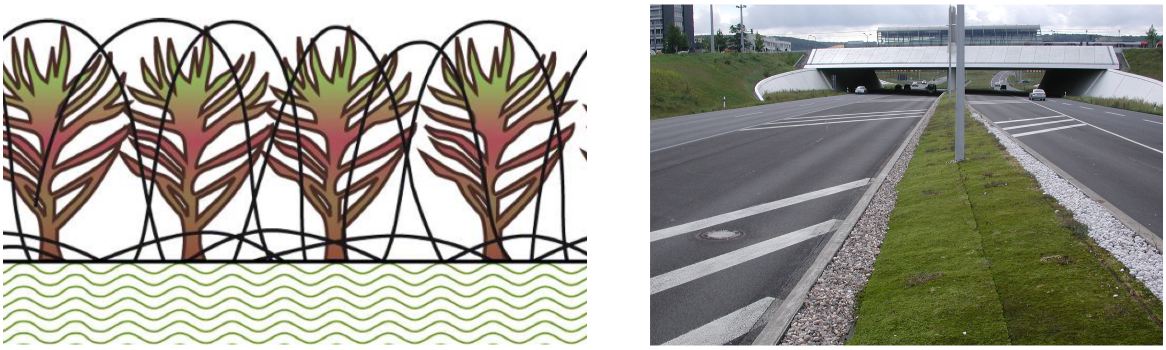


Figure 21. The constitution of moss mats. (Source: Low & Bonar PLC.)

The only disadvantage of moss mats as particle adsorptions is the high demand of perpetual humidification, coming from rainwater or water vapor in the air. Only when mosses are moist, with air humidities of >80% rH will they metabolize [102]. This is not difficult to realize in Shanghai, where the average air humidity is 76.25% [103].

Moss mats could contribute to the purification of indoor air of an office building in the following applications:

(1) Utilized for the exterior green roof as the first line of defense for supplied fresh air with air inlets on the top of the building. Since moss mats do not require maintenance and could adsorb more fine particles with the increase of altitude, serving as a green roof would effectively purify the ambient air on the top of high-rises. Therefore, passing through these mats the airborne particles are reduced greatly from the air before being supplied into the building from rooftop inlets. Another particular advantage in this case is that not only the indoor air is purified, but also the fine particles in the city decrease if applied widely.

(2) Utilized for the interior biofilter for supplied fresh air before the HVAC process. Similar to the first application of biowalls.

4.4.3 Individual botanic air filters

As a small-scale biofilter occupying little space, an individual botanic air filter combines plants with other purification technologies such as activated carbon, and is thus suitable for cleaning indoor air separately. The working principle is the same as a living wall, recirculating ambient air with a fan system and removing the contaminants through microorganisms. For fine particles, inorganic water-soluble substance would be degraded as nutrients while other leaf surface facilitates the deposition of other compositions. For VOCs, the removal effect has been verified by both chamber and field test [104]. For a given botanic filter type, three plants were claimed to be sufficient in removing 75% of an office with a floor area of 13 square meter [105]. Working as potential individual indoor purifiers, the efficiency for specific botanic filters combining different purification technologies should be respectively tested and evaluated.

Figure 22. Scheme of a portable botanic air filter. (Source: Plant Air Purifier.)

5 Filtration Efficiency Calculation

In this chapter, the filtration performance of HVAC filters is evaluated. In section 5.1, an illustration of the mechanical ventilation scheme of high-rise office buildings is contained. Then a numerical calculation is given in section 5.2 to propose the filtration efficiency requirements of the HVAC system, leading to an equivalent performance guideline of central filters in PM2.5 removal.

5.1 Ventilation Scheme

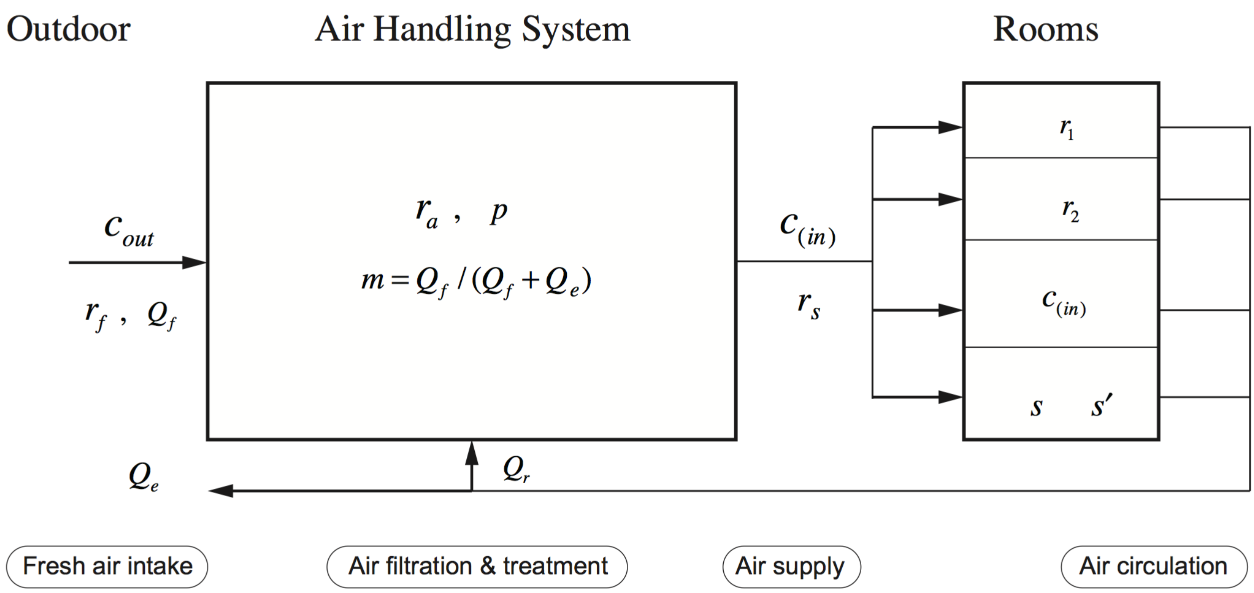


Figure 23. Scheme of the ventilation system.

Two central air handling units are applied in the building as a HVAC process, each responsible for supplying conditioned air to 15 storeys after purifying the mixed ambient and recirculated air in a central plant room. To minimize the impacts of street traffic, the air inlets are respectively on mid-height and rooftop level of the building.

For each air handling system, the ventilation process is shown in Figure 23. First, ambient air containing a fine particle concentration of c_{out} goes into the air handling room through inlets, with an intake rate of $Q_f(m^3/s)$ $(r_f(s^{-1}))$. The air is then purified and conditioned in the treatment room with an handling rate of $r_a(s^{-1})$. This includes air from both ambient or indoor exhaust, with a mixing ratio of m. After central filtration, only a certain part of airborne particles could penetration the filter and remain contained in the air, depending on the efficiency of the filter (indicated by a particle penetration factor p). In this phase the contaminant concentration drops to c_{in}. Then the purified air is supplied through ducts to various rooms. The fine particle level in each room depends on respective indoor sources and sinks, which more or less influences the concentration. The deposition and decay rates of fine particles are also considered as a natural sink during this process. It is assumed that any chemical reaction of fine particles is negligible. After that, the indoor air is either exhausted or circulated through return ducts.

5.2 Filtration demands

5.2.1 HVAC filtration

The real-time outdoor PM2.5 concentration in Shanghai was recorded constantly everyday in the U.S. Department of State Air Quality Monitoring Program. According to the historic data, the 24-hour average concentration value in within one year (from April 2015 to March 2016) is summarized in Table S1 in Appendix A.

The measurement was conducted in a densely populated area, while the location of data acquisition instruments was not mentioned. For high-rise buildings with mechanical ventilation systems, air inlets are usually placed at the middle height of the building or rooftop level to avoid street-level pollutants from traffic.

As discussed in Chapter 2, the vertical distribution of fine particles does not show noticeable decrease with increasing altitude until 30 floors [35]. This was also verified in a research exploring the relationship between particle level and altitude [106]. An experiment was conducted in a typical downtown area (a street canyon) of Shanghai both in hot and cold climate in 2005. For ultra-fine particles, the particle number (PN) is an important indicator, since they compose around 90% of particle numbers (PN) in the air, while only taking up a little bit of particle mass concentration [107]. So both particle number and mass concentration of ultra-fine particles (with a size smaller than 1 micron) were measured at different heights. A comparison was made in the experiment to explore the influence of altitude with four data groups: 1.5m (presenting street level), 8m, 20m, 38m. As shown in Figure 24, the mass concentration of fine particles keeps the same level with height variations. In contrast, the particle number size distribution shows close correlation with the height (see Figure 25). It could be seen that PN drops conspicuously with increasing height, especially between street level and other groups. This could be inferred as the impact of heavy traffic, which emits a great deal of UFP. Totally different from mass concentration, little seasonality is shown in the particle number distribution curve, in accordance with related reference [108]. The result also suggested a poor correlation between mass and number concentrations, as proposed and verified by previous literature [109-110].

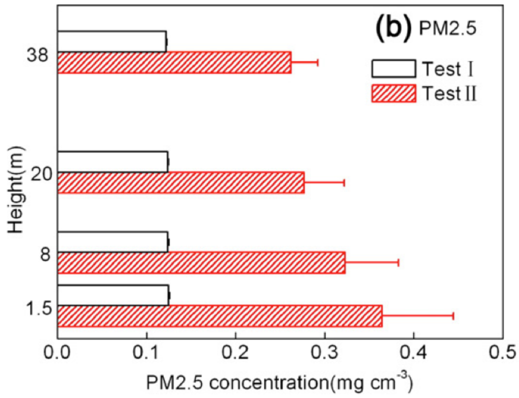


Figure 24. Average mass concentration of PM2.5 in different height groups. (Source: Li et al.)

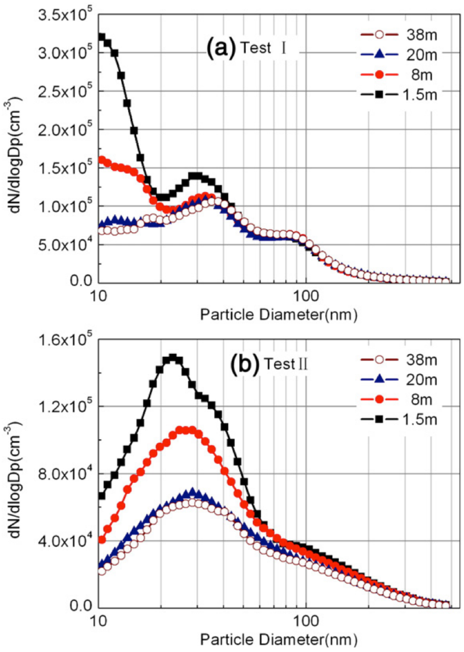


Figure 25. Average particle number distribution in different height groups. (Source: Li et al.)

Therefore, the monitored values are directly referred without applying modifier factors. It could be concluded that within a year, the highest value appeared in December, while the lowest was in September. The results showed that the trend of densely high concentration is in winter and the best quality is in summer, in accordance with the annual trend curve presented in Figure 4.

Considering possible missing, deviation or error of the sampling data within the same day, an average value of 24-h concentration within one month is chosen instead of the highest recorded 24-h value.

The target indoor concentration is chosen according to the air quality guidelines of the World Health Organization, instead of the Chinese national standards published in 2016. The limit value of 24-hour mean concentration is 25 $\mu g/m^3$ (indicating moderate air quality as in the index of EPA) as the threshold set by 2015 [111] (see Table S2, S3 in Appendix A).

On the basis of assuming that air goes into the building only through the central HVAC system, which neglects the infiltration and penetration effects through the envelope, indoor particle mass concentration is determined by the ambient pollution level, transport from outside to interior environment through infiltration and penetration, indoor emissions and deposition. The mass balance of indoor PM2.5 concentration in a ventilation zone is as follows:

$$dc/dt = pr_s mc_{out} + pr_s(1-m)c + s - (r_e + r_1 + r_2)c - s' \qquad (5-1)$$

where : c the indoor PM2.5 concentration $(\mu g/m^3)$

p : the penetration factor of the HVAC filtration system (%)

r_s : the air supply rate of the inlet (s^{-1})

m : the ratio of fresh to recirculated air flow passing the air handling system (%)

c_{out} : the outdoor PM2.5 concentration $(\mu g/m^3)$

s : the indoor source strength $(\mu g/m^3.s)$

r_1 : the deposition rate of PM2.5 (s^{-1})

r_2 : the decay rate of PM2.5 (s^{-1})

r_e : the air exhaust rate of the outlet (s^{-1})

s' : the indoor removal rate $(\mu g/m^3.s)$

$pr_s mc_{out}$ is the rate of supplied particles from the outdoor environment. $pr_s(1-m)c$ is the rate of supplied particles from the recycled indoor air. s refers to supplied particles contributed by indoor activities (e.g. smoking, cooking, etc.). $(r_e + r_1 + r_2)c$ represents the total rate of removed particles owing to fan exhaust, particulate matter decay and deposition. s' refers to removed particles through individual indoor filters or other sinks.

The mass balance of air in the central air handling room is similar. Without additional indoor sources or sinks except the HVAC filtration system, both s and s' are zero.

The air flow going through the HVAC system consists of fresh outdoor air and recirculated indoor air, indicating by the mixing ratio m varying among 10% to 100% [112]. Given the heavy pollution level of the outdoor environment, an apparent principle is that the filtering load increases with the increase of m. To verify the limit of filtration capacity, the maximum value for m, 100%, is selected, in which case a full fresh air ventilation system (common mode in a mechanical ventilation system for less health risk) is assumed to be the scenario.

Therefore, the air supply rate rs is equal to the fresh air change rate rf of the ventilation system. According to the local design code for typical office buildings, the minimum net ceiling height should be higher than 2.6m (assumed to be 2.8m in the analyzed building). The occupancy during working hour could be calculated according to the local design guideline stating that the minimum average floor area is 8 square meter per person in a new office building. Therefore it could be inferred that the maximum occupancy in one office zone is 50 persons. The standard for the fresh air quantity should exceed 30 cubic meter per hour per person [112]. Thus the guideline of the fresh air change rate could be inferred using equation

$$r_f = \frac{Q}{V} = \frac{30m^3.h^{-1}.person^{-1} \times 50 person}{2.8m \times 300m^2} = 1.79h^{-1} = 4.96 \times 10^{-4} s^{-1} \qquad (5-2)$$

For a typical breathing zone in office layers, the area is around 300 square meter. So the ventilation airflow should be:

$$Q_v = 4.96 \times 10^{-4} s^{-1} \times 300m^2 \times 2.8m = 0.417m^3 / s \qquad (5-3)$$

To meet the requirements in ASHRAE Standard 62-2001, the ventilation should also satisfy [113]:

$$V_{bz} = R_p P_z + R_a A_z \qquad (5-4)$$

where V_{bz} : design outdoor airflow in a breathing zone $(L.s^{-1})$

R_p : outdoor airflow rate required per person $(L.s^{-1}.person^{-1})$

P_z : expected largest occupant population $(person)$

R_a : outdoor airflow rate required per unit area $(L.s^{-1}.m^{-2})$

A_z : zone area (m^2)

The values for R_p and R_a are determined in Table 6:

	People Outdoor Air Rate Rp		Area Outdoor Air Rate Ra	
	$cfm / person$	$L / s.person$	cfm / f_t^2	$L / s.m^2$
Office space	5	2.5	0.06	0.3

Table 6. Minimum airflow rate for office zones. (Source: ASHRAE Standard 62-2001)

The maximum occupant density could be determined by the minimum average floor area (4 square meter per person), which leads to 75 person in one zone.

$$V_{bz} = 2.5L / s.person \times 50 person + 0.3L / s.m^2 \times 300m^2 = 0.215m^3 / s \qquad (5-5)$$

The zone air distribution effectiveness is assumed to be 1, as the average of different air distribution configurations [113]. So the outdoor air intake flow for a single ventilation zone is equal to $0.215m^3 / s$.

Therefore, the fresh airflow for a ventilation zone V_{ot} is taken as $0.417m^3 / s$.

The exhaust air rate r_e depends on the expected net pressure balance within the zone. When the r_s air intake rate is less than exhaust rate, the zone will be depressurized which would be favorable for particle infiltration through the envelope. In contrast, a pressurized zone will be formed with excess net supplied air, which could be overcome by stack effect. To control unintentional air leakage and prevent unconditioned outside air, a little bit more air is supplied than exhausted to slightly pressurize the ventilation zones. The ratio of return to supply air rate is assumed to be 0.9 in the HVAC system.

The deposition rate is a value below 1/h [114-116]. Compared to air exchange, both deposition and decay effects of particles are relatively minor. So a value of 0.2 per hour is used here following an previous research [117]. The decay rate could be approximately assumed to be 0 [118].

The solution for the steady state is derived from Equation 5-1 and 5-2.

$$c_{in} = \frac{pr_s}{r_e + r_1} c_{out} \qquad (5-6)$$

With the input of the parameters, the limit value of the penetration factor is given.

$$p = \frac{c_{in}(r_e + r_1)}{c_{out}.r_s} = \frac{25\mu g/m^3 \times (1.79h^{-1} \times 0.9 + 0.2h^{-1})}{82.19\mu g/m^3 \times 1.79h^{-1}} = 0.308 \qquad (5-7)$$

This result suggests that to effectively control the indoor concentration level of fine particulate matter from the supplied source, the average filtration efficiency of the central HVAC system for PM2.5 fresh air should be higher than 70%.

For a specific filter, the particle removal efficiency is usually size-resolved since the filtration efficiency varies a lot among particles with different sizes, and the capacity of filtering particulate matter 2.5 is seldom verified.

Therefore, before applying a filter in a HVAC system, its average value of size-resolved efficiencies smaller than 2.5 micron should be tested. Based on the particle number balance, the equivalent efficiency of a filter could be expressed as follows:

$$\eta_{PM2.5} = 1 - \frac{\sum_{i=1}^{2500} N_i.\rho_i.\frac{\pi d_i^3}{6}.(1-\eta_i)}{\sum_{i=1}^{2500} N_i.\rho_i.\frac{\pi d_i^3}{6}} \qquad (5-8)$$

$\eta_{PM2.5}$: the removal efficiency of a filter for fine particulate matter (%)

d_i : the diameter for particles with a specific diameter (cm)

N_i : the number of concentration of particles with diameter d_i (cm^{-3})

ρ_i : the density of particles with diameter d_i (g/cm^3)

η_i : the removal efficiency of a filter for particles with diameter d_i (%)

Equation 5-8 is based on the ground of assumption that 100% outdoor air is filtered, neglecting the loss of particles during the transportation course before going through the filtration system, which could be caused due to particle penetration and deposition on surfaces [119].

In the most commonly adopted standards published by ASHRAE (American Society of Heating, Refrigeration, and Air Conditioning Engineers) for filter evaluation in HVAC systems, particles were first classified into three bins according to the diameter (0.3-1, 1-3, 3-10 micron), which composed three important indicators, E1, E2 and E3, as the removal efficiency specific to this range. A minimum efficiency reporting value (MERV) was then calculated according to the test results to grade the filtration performance of different filters [120]. Some typical MERV curves are showed in Figure 26.

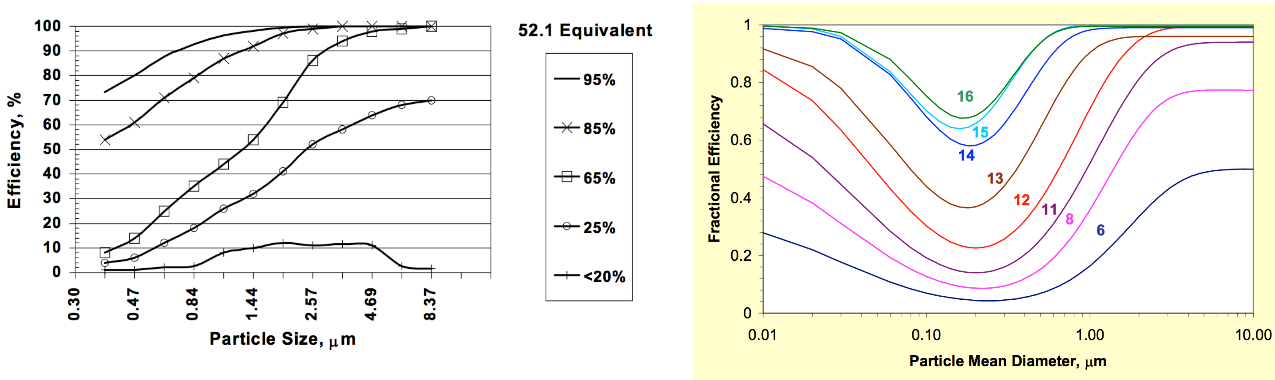


Figure 26. Typical MERV curves. (Source: The Pennsylvania State University.)

An evident trough is revealed in almost all fractional efficiency curves between the size range 0.1 to 1 micron (ultra-fine particles). This is because particles smaller than 0.1 micron are diffusion dominated, and those larger than 1.0 micron are dominated by internal impaction and interception, while within the intermediate range both diffusion and interception effect decrease.

5.2.2 Effectiveness of HEPA

For ventilation zones in the office building, the contribution of indoor sources due to human activities are negligible, especially during working hours. As introduced in Chapter 2, combustion and radiation are the two main indoor sources of particulate matter. The former includes cooking, fuel burning and smoking, which are inapplicable in office buildings (separated smoking rooms are not taken into account), and the latter involves the use of electrical appliances, among which coffee machines, electric kettles, printers and copying machines are common in office areas. Particle resuspension due to human movement like walking is expected to make a significant contribution to coarse particles (within the size range of 5 to 25 micron), without affecting fine ones evidently [121].

Scientific research concerning these indoor emission sources has not been well developed. It was referred that laser printers mostly emit liquid and volatile aerosols [29], which to a great extent could be eliminated by applying proper printer types or filter appliances [122]. The average emission rate of a contemporary printer is estimated as 0.75 microgram per min [123]. It is assumed that in an office zone with the area of 300 square meters, the total amount of printers, copiers, faxes and other office devices is eight, based on the average level in general cases in Shanghai. So the total emission rate is estimated to be six microgram per minute.

However, in another research conducted in an office building in Athens, the total indoor PM2.5 emission rate was considered as 1200 microgram per minute [124]. The volume of the tested zone is 187.3 cubic meter, leading to an indoor source strength of 6.41 microgram per minute per cubic meter. The dramatic deviation may be due to the specific layout and function of the investigated floor, since a small kitchen for employees was included. This led to the possibility of involving light cooking, combustion or smoking activities, which was not explicitly mentioned in the experiment while would make a dominant contribution in the rise of indoor fine particle concentration.

Considering the uncertainty of anthropogenic activities, it is assumed that the during work time the only indoor source emitting PM2.5 is the office devices, while during lunch break the peak generation rate increases to 5382 microgram per minute, in accordance with the emission strength of indoor sources reported in the research discussed in the last paragraph, though the applicability of the data is to be verified.

In the scenario of sole filtration through central HVAC process before air supply, the indoor particle concentration in steady state should follow:

$$c_{in} = \frac{pr_s c_{out} + s}{r_e + r_1} \qquad (5-9)$$

If a HVAC filter with limit efficiency 70% is applied, Equation 5-7 is also workable. In this case, during peak emission the indoor PM2.5 concentration would be higher than guideline $(25\mu g/m^3)$ within:

$$t = \frac{25\mu g/m^3}{5382\mu g.\min^{-1}/840m^3} = 3.9\min \qquad (5-10)$$

The maximum centralized filter efficiency (e.g. HEPA) is around 99.97% so that almost no particles would be able to penetrate through the HVAC system (p=0). In this case, the indoor particle concentration for the steady status should follow:

$$c = \frac{s}{r_e + r_1} = \frac{5382\mu g.\min^{-1} / 840 m^3}{1.79 h^{-1} \times 0.9 + 0.2 h^{-1}} = 212.27 \mu g / m^3 \qquad (5-11)$$

The result suggests that even if HEPA or equivalent high-efficiency filter is applied as the central filtration process for fresh intake air, in case of intensive indoor sources, the emissions would greatly contribute to the mass concentration of PM2.5 in office buildings leading to higher pollution level than guideline, which would pose health risk with long exposure. It should be highlighted that the results from Equation 5-10 and 5-11 are not practical, since infiltration effect is neglected. However, it qualitatively poses the myth that HEPA filters must be applied to control fine particles.

Instead, filters with a higher efficiency than 70% in removing PM2.5 is sufficient as a central HVAC process. Referring to the Minimum Efficiency Reporting Value rating listed in ASHRAE Standard 52.5, MERV 12 (F6 grade assigned in EN779:2002) or a higher grade filter is applicable [120]. Considering the extreme situations with higher concentration than the average level (see Table 7, taking the most serious month December in 2015 as a reference), MERV 13 (F7) with filtration efficiency 75% for 0.3 to 1.0 micron particles, 90% for particles larger than 1.0 micron is appropriate.

Date	12.6	12.14	12.15	12.21	12.23	12.25	12.26	12.30	12.31
c_{out} $(\mu g / m^3)$	102.04	146.59	220.96	138.25	187.50	174.13	96.63	93.25	137.54
Penetration factor	24.78%	17.37%	11.45%	18.29%	13.49%	14.52%	26.17%	27.12%	18.39%

Table 7. Extreme pollution levels in December in 2015.

5.2.3 Effectiveness of indoor plants

For qualified air, additional individual indoor filtration is necessary. In this scenario, new balance is achieved:

$$p r_s c_{out} + s = (r_e + r_1) c + s' \qquad (5-12)$$

The efficiency requirement of indoor filters depends on the selection of HVAC filtration, air exchange rate and airflow pressure of the zone. Combining Equation 5-9, the indoor sink should at least cover the rate of source, while in actual cases the removal rate should be higher than indoor emission rate due to air infiltration, which would be discussed in details in Chapter 6.

If natural plants are applied as indoor purifiers, for example an atrium with greenery, the required amounts of some reference species could be estimated on the basic of previous research concerning the efficiency of plants in removing PM2.5 [79]. Since the adsorption ability of plants is time-dependent presenting a decreasing rate, the time unit of the calculation is per day, to be more specific, 9 hours during a typical work day, which is in accordance with the average adsorption limit of plants.

The basic assumptions behind are as follows:

(1) Air infiltration through the envelope is neglected.
(2) The indoor source strength is only intensive during lunch break for an hour, while in the rest eight hours the emission rate complies to the amount six microgram per minute.
(3) Indoor generated particles could be all transported to or recirculated around the greenery area.
(4) The supply air is already effectively purified after HVAC filtration process which could meet the requirements of IAQ.

Species	**Captured amounts** $(\mu g / plant)$	**Required amounts (plants)**
Cedrus deodara	16.881	19300
Pinus bungeana	14.943	21803
Platycladus orientalis	10.861	29997
Ground hemlock	8.882	36681
Picea meyeri	5.224	62366
Picea wilsonii	5.245	62116
Common Boxwood	4.062	80207
Euonymus japonicus	3.881	83947

Table 8. Required species amounts for indoor PM2.5 removal.

The calculated values showed that it is far from sufficient to use individual plants as indoor particle purifiers, unless quite large areas are used to cultivate vegetations. This is impossible for high-rise office buildings in urban region. Nevertheless, it was also pointed out in section 4.1 that the particle adsorption capacity of greenery species is potential since it differs in specific situations. If the static indoor air circulates adequately, the deposition of PM2.5 would increase considerably. This also explains the mechanism of including fan systems in biofilters. Therefore, more effective technologies are necessary to filter indoor emissions, such as standing biowalls or portable combined ionizers, while the respective efficiency is to be studied and tested.

6 CONTAM Simulation & Sensitivity Analysis

In this chapter, the office building is simulated in CONTAM software with several different scenarios. First, the conclusions in Chapter 5 are verified based on simulation data. Then four parameters presenting the main concerning factors during building design (envelop airtightness grade, air exchange rate, indoor pressure mode and temperature difference between interior and exterior) are adjusted in each comparison group to qualitatively explore the impacts. In addition, the results are also quantitatively compared through a sensitivity analysis and shown in tornado diagrams to find out which factor is dominant. Last but not least, an analysis of indoor filtration demands is conducted.

6.1 Theoretical background

Instead of dealing with a single zone model in a microscope view as what computational fluid dynamics (CFD) does, multi-zone network modeling in CONTAM requires less accurate boundary condition input information and provides a macroscopic model focusing on the intercorrelation between different parts of the whole building. It was developed to analyze airflows, pressures, contaminant concentrations and personal exposures through multi-zone modeling. Steady state, transient and cyclical contaminant could be performed through the software. Thus it (version 3.2.0.2) is applied as the tool to simulate the dispersal of fine particulate matter within a high-rise building.

The basic assumptions of CONTAM modeling are [125]:

(1) Well-mixed zones

The first step of multi-zone modeling is to idealize a building into several interconnected zones. Each zone in the model is treated as a single node, in which the pressure, temperature and contaminant concentration is uniformly distributed. Dramatic difference of fluid within a zone could be ignored.

(2) Mass conservation

For a steady-state simulation, the total mass of air is considered to be constant, which could not be created nor deducted within one zone. While for a transient simulation, it could be achieved due to potential density or pressure difference in the zone.

(3) Air density

In case of contaminant sources, the concentration of trace ones does not have an impact on the density of air. However, the air density could be influenced by some contaminants once defined. The commonly used value for particle density is $1g/cm^3 = 1000kg/m^3$ while the default density for dry air is $1.20 kg/m^3$ (at standard conditions with pressure 101.325kPa and temperature 20 degree centigrade) [126]. Since the effect of particles on air density is assumed to be dominant, it is treated as non-trace contaminant in the project.

The basic theory of multi-zone modeling is the balance of flow between zones driven by pressure difference [127]. Once a steady state is achieved, the sum of airflows in a zone (control volume) is zero. The mass balance equation within a zone is as follows:

$$\sum_j F_{j,i} + F_i = 0 \qquad (6-1)$$

where $F_{j,i}$: airflow from zone j to control volume i

F_i : airflow from control volume i to others

For a transient simulation, the equation could be presented as:

$$\sum_j F_{j,i} + F_i = \frac{dm_i}{dt} \qquad (6-2)$$

where m_i : mass of air in control volume i

For contaminant simulation, the mass balance is based on the ground of transient contaminant transport:

$$\sum_j F_{j,i}(1-\eta_j^\alpha)C_j^\alpha + G_i^\alpha + m_i \sum_\beta K^{\alpha,\beta} C_i^\beta - \sum_j F_{i,j} C_i^\alpha - R_i^\alpha C_i^\alpha = \frac{dm_i^\alpha}{dt} \qquad (6-3)$$

where C_j^α : concentration of contaminant α in zone j

C_i^α : concentration of contaminant α in control volume i

R_i^α : removal rate of contaminant α in control volume i

m_i^α : mass of contaminant α in control volume i

η_j^α : filtering efficiency in the flow path

G_i^α : effect of indoor contaminant sources

$K^{\alpha,\beta}$: kinetic reaction coefficient between contaminant α and species β

C_i^β : concentration of species β in control volume i

R_i^α : removal coefficient for contaminant α

6.2 Model & Scenarios

6.2.1 Baseline scenario

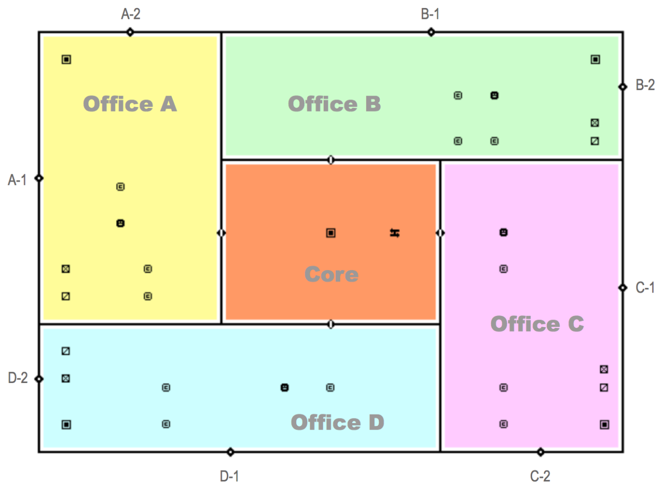


Figure 27. Basic model scheme of CONTAM.

Zones

The modeled building is a 32-storey office tower. The typical office floors share the same layout. Specific subareas within one ventilation zone separated by partitions are neglected. Therefore, four perimeter zones for office areas (marked as Office A-D in Figure 27) and a core zone for supporting and service compose the floor plan. Since the research focus is laid on IAQ in working environment, the other space (e.g. restroom, staircase) in the core zone is simplified. The area for each office zone is 300-square-meter, while the core zone is around 320-square-meter. The floor to floor height is 4.05 meter, and the net ceiling height is 2.8 meter owing to the plenum space. The initial temperature of the zones is 24 degree, with a rough temperature difference of 20 degree from the outside. The indoor pressures are set as variable.

Airflow paths

A combination of mechanical ventilation and infiltration is included in the airflow analysis. It is regulated in design codes that certain operable windows should be included in high-rise commercial buildings for ventilation and fire safety. Therefore, the sealing of those parts, as well as other interstitial spaces like junctions, gaps and cracks of the enclosure, plays an important role in air leakage control from outside to the indoor environment. The rate of infiltration airflow depends on the driving pressure (wind and buoyancy) and effective leakage area (envelope and other joints). Other airflow paths taken into account between zones only include a two-way path with big openings, representing the doorways between different space.

In this case, infiltration is included mainly on the building envelope to access the influence of airtightness. The average unit leakage area of exterior envelope in office buildings varies between 0.7 to 2.4 square centimeter per square meter (with 10 Pa pressure difference and 0.6 discharge coefficient) [128], in accordance with the suggested leakage area value in ASHRAE (with 4 Pa pressure difference and 1 discharge coefficient) (see Table 9) [129]. Given the fact that the analyzed target is a newly built office building, a high level of airtightness (1.4 square centimeter per square meter) for exterior wall is assumed (at a reference pressure of 4 Pa, a discharge coefficient of 1.0, and a pressure exponent of 0.65). Different unit leakage area values according to Table 9 are adopted as the indicator of infiltration factor to explore its influence on the indoor fine particle mass concentration. The infiltration flow paths of the enclosure are numbered in Figure 27 (A-1 to D-2).

Unit Leakage Area (cm^2 / m^2)	Classification	Description
0.7	Tight	With air-sealing specialist
1.4	Good	Careful sealed
2.8	Average	Typical dwellings
5.6	Leaky	Pre-1970 houses
10.4	Very leaky	Historical houses

Table 9. Unit Leakage Area of Different Buildings. (Source: ASHRAE.)

Air Supply & Return

A “simple air handling system” model is applied to serve the ventilation of multiple zones. To pressurize the building, the returned airflow rate is set as 90% of the supply rate. For each ventilation zone, the minimum air exchange rate is 1.79 per hour, leading to the minimum supply rate 0.43 m^3/s (0.54 kg/s) the corresponding return rate 0.38 m^3/s (0.48 kg/s). This value is also adjusted in different scenarios to investigate its influence on the indoor PM2.5 concentration level.

Contaminant & Filters

PM2.5 is the only contaminant species in this case. A central filter with 70% removal efficiency is set in the central air handling system based on the conclusion drawn in Chapter 5. The outdoor source is reflected in the initial contaminant concentration. To explore the maximum filtration demands of indoor environments, as well as to amplify the influence of each parameter in indoor pollution level, the extreme ambient PM2.5 mass concentration 220.96 $\mu g/m^3$ is adopted.

Source/Sink

Constant mass flow models are applied to represent the additional particle generators and removals in the indoor environment. As mentioned in Chapter 5, the estimated PM2.5 rate emitted by electronic devices in a typical office zone is estimated as six microgram per minute. This value is set as the default source strength, while the intensive one would be also simulated in one scenario. The deposition process of particles is taken into account as an indoor sink with the constant removal rate of 0.2 per hour.

Weather

As the most seriously polluted season, winter period is adopted for simulation. The average temperature is 3.7 $^{\circ}C$ (during work hours) [130]. The relative humidity of air is 81% [103].

Wind

Influenced by wind directions, wind speeds, terrain conditions and building configurations, wind pressure is a combined function. It plays a significant role in high-rise building design due to the relative rapid wind velocity with great heights. The pressure difference caused by wind pressure is a dominant factor in air infiltration through building envelope.

For steady climate conditions, the wind pressure on the exterior facade of the office building could be estimated according to the local load code for the design of building structures [131]. For building enclosure, the wind pressure should be calculated following Equation 6-4.

$$\omega_k = \beta_{gz}\mu_{sl}\mu_z\omega_0 \qquad (6-4)$$

where: ω_k : characteristic value of wind load (kN/m^2)

β_{gz} : gustiness factor at height z

μ_{sl} : shape factor of wind load

μ_z : height variation factor of wind pressure

ω_0 : reference wind pressure (kN/m^2)

Considering the effect of local terrain situations, four grades are classified representing the terrain roughness (D for highly dense urban areas with tall buildings, in this case). To maximize the wind effect, the top office layer is simulated (with a height of 120m).

	100m	**150m**	**120m**	
β_{gz}	1.98	1.87	1.94	
μ_z	1.04	1.33	1.16	
Sides	windward	crosswind 1	crosswind 2	leeside
μ_{sl}	+1.0	-1.4	-1.0	-0.6

Table 10. Values for wind pressure related parameters.
(Source: Load code for the design of building structures, China.)

The reference wind pressure could be estimated according to the average wind speed in winter in Shanghai, 5.66 m/s, referring to the statistic of Pudong meteorological station (located near the Pudong Airport) [132]. This value may be a little bit higher than the practical situation in city center. Nevertheless, it is adopted for wind pressure calculation to both remain a certain allowance and take rural office buildings into account. So the reference wind pressure near ground is around 0.02 kN/m^2.

Given the varying direction of winds, it is assumed that during the simulated period, the wind comes from north. Therefore, the estimated wind pressures on the four sides of the building enclosure are:

$$\omega_1 = 1.94 \times 1.0 \times 1.16 \times 0.02 kN/m^2 = 45Pa \quad (6-5)$$

$$\omega_2 = 1.94 \times (-1.4) \times 1.16 \times 0.02 kN/m^2 = -63Pa \quad (6-6)$$

$$\omega_3 = 1.94 \times (-1.0) \times 1.16 \times 0.02 kN/m^2 = -45Pa \quad (6-7)$$

$$\omega_4 = 1.94 \times (-0.6) \times 1.16 \times 0.02 kN/m^2 = -27Pa \quad (6-8)$$

6.2.2 Control variables

The building ventilation condition is reflected in the air exchange rate. For unintended air infiltration through building enclosures, pressure and thermal differences between ambient and indoors are the driven forces. Hence, the airtightness (unit leakage area as the indicator of infiltration factor), indoor pressure mode (ratio of air supply to return rate to form different pressurization space), interior and ambient temperatures (embodying various temperature differences) are selected as the rest variables. These parameters are adjusted in different scenarios. Several basic scenarios are also simulated to verify the conclusions of hand calculation in Chapter 5. The scenarios are compared in several groups. The parameters for different scenarios are listed in Table 11.

No.	Unit Leakage Area (cm^2/m^2)	Air Supply Rate (kg/s)	Air Return Rate (kg/s)	Interior Temperature $(°C)$	Ambient Temperature $(°C)$	Wind pressure	Indoor source $(\mu g/s)$	HVAC filter efficiency	Comparison groups
1	1.4	0.54	0.48	24	3.7	N	N	70%	A
2	1.4	0.54	0.48	24	3.7	Y	N	70%	A, B, C
3	1.4	0.54	0.48	24	3.7	Y	N	100%	B
4	1.4	0.54	0.48	24	3.7	Y	0.1	70%	C, D, E1, F, G, H
5	0.7	0.54	0.48	24	3.7	Y	0.1	70%	D, H
6	2.8	0.54	0.48	24	3.7	Y	0.1	70%	D, H
7	5.6	0.54	0.48	24	3.7	Y	0.1	70%	D
8	1.4	0.54	0.54	24	3.7	Y	0.1	70%	E1, F
9	1.4	0.54	0.60	24	3.7	Y	0.1	70%	E1, F, H
10	1.4	1.08	0.97	24	3.7	Y	0.1	70%	E2, F, H
11	1.4	1.08	1.08	24	3.7	Y	0.1	70%	E2, F
12	1.4	1.08	1.20	24	3.7	Y	0.1	70%	E2, F
13	1.4	0.54	0.48	14	3.7	Y	0.1	70%	G, H
14	1.4	0.54	0.48	28	38	Y	0.1	70%	G
15	1.4	0.54	0.48	18	38	Y	0.1	70%	G
16	1.4	0.54	0.48	24	3.7	Y	89.7	70%	C
17	1.4	0.27	0.24	24	3.7	Y	0.1	70%	H
18	1.4	0.54	0.38	24	3.7	Y	0.1	70%	H
19	1.4	0.54	0.48	34	3.7	Y	0.1	70%	H

Table 11. Parameters of all simulated scenarios.

When adjusting the range of various parameters, Scenario 4 is set as the reference which best embodies the actual situation. In Scenario 1, wind pressures on all the airflow paths connecting to the ambient environment are neglected. This is to be compared (Group A) with Scenario 2, in which wind pressures with different values on each side of the envelope are applied. Scenario 2 is also compared with Scenario 3 (Group B), 4 and 16 (with intensive indoor emission source rate of 5382 microgram per minute) (Group C) separately with different central HVAC filter efficiencies and indoor sources (no indoor source is induced in Scenario 1, 2 and 3). In comparison group D, four scenarios (4—7) are included with increasing unit leakage areas representing different airtight classifications. Scenario 8 to 12, together with 7, compose group E and F. Different ratios of air supply to return rate are adjusted in group E1 and E2 to simulate depressurized, equilibrated and pressurized situations, while in group F all these six scenarios are compared together. Group G consists of scenario 4, 13, 14 and 15 with various temperature differences between indoor and ambient environment. It should be mentioned that Scenario 14 and 15 represent summer conditions, when the outdoor concentration level of PM2.5 is much more released than winter periods. However, the ambient contaminant concentration remains constant to explore the influence of temperature difference solely.

To investigate the impact strength of each parameter, four more scenarios are also created. In Scenario 17, both the air supply and return rate of the mechanical system are 50% of the reference value, leading to 0.27 kg/s for supply and 0.24 kg/s for return. While in Scenario 18, the ratio of air supply to return rate changes from 0.9 to 0.7. The last scenario, 19, reflects a larger temperature difference between interior and outdoor. All these scenarios are to be compared in group H to explore the influence of ventilation and infiltration theoretically, while not applicable in practice, since the inputs do not meet the requirements of minimum AER or thermal comfort temperature range. The category of the comparison groups are listed in Table 12.

Group	**Included scenario**	**Control variable**	**Objective**
A	1, 2	Wind pressure	To verify the necessity of considering wind pressure.
B	2, 3	HVAC filter efficiency	To verify the necessity of applying HEPA.

C		3, 4, 16	Indoor source strength	To verify the necessity of applying indoor filtration tools.
D		4, 5, 6, 7	Envelope leakage strength	To explore the influence of infiltration.
E	**E1**	4, 8, 9	Air supply to return ratio	To explore the influence of depressurization or pressurization.
	E2	10, 11, 12		
F		4, 8, 9, 10, 11, 12	Air exchange rate	To explore the influence of mechanical ventilation rate.
G		4, 13, 14, 15	Temperature difference	To explore the significance of interior control temperature.
H		4, 5,6, 9, 10, 13, 18, 19, 20	Envelope leakage strength; Air exchange rate; Air supply to return ratio; Temperature difference	To explore the sensitivity of each parameter to the indoor pollution level.

Table 12. Category of the comparison groups.

6.3 Simulation results

The simulation data including the pressure and contaminant concentration in each zone, as well as the infiltrated or exfiltrated airflow rate and pressure balance, is shown in Table S5 in Appendix A.

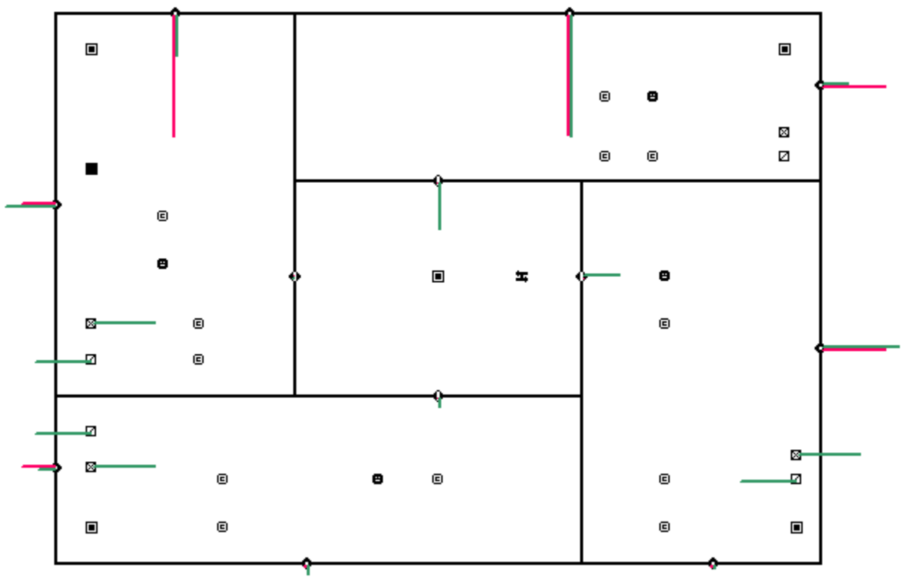


Figure 28. Airflow paths of the model.

The graphical output with airflow paths of the floor is shown in Figure 28 (except for Scenario 1, where only exfiltration with the same magnitude on each side happens due to temperature difference).

It could be seen from the graph that on the north side with positive shape factor, the positive wind load forces air to penetrate through building leakage gaps into the interior, while on other sides with negative shape factors, exfiltration rather than infiltration happens transferring indoor airflow to the outside.

Based on the simulation data, several charts representing each comparison group could be illustrated.

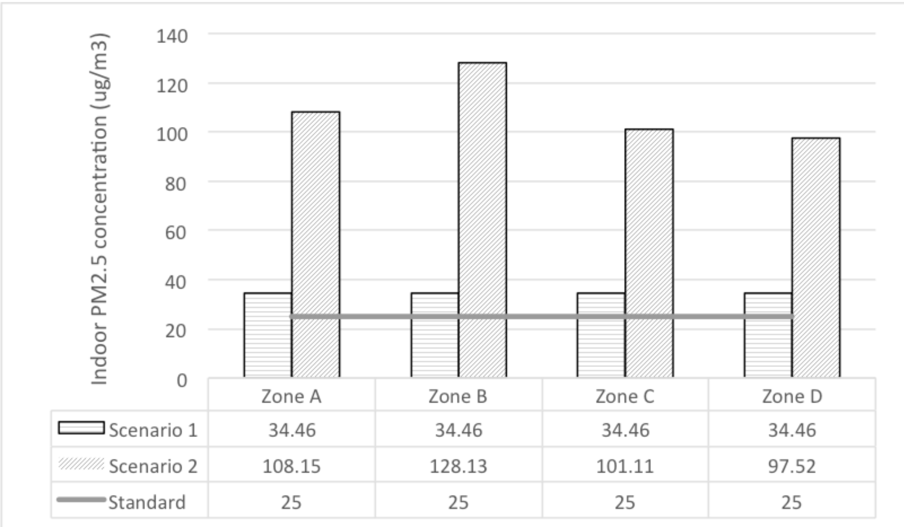


Figure 29. Result of group A.

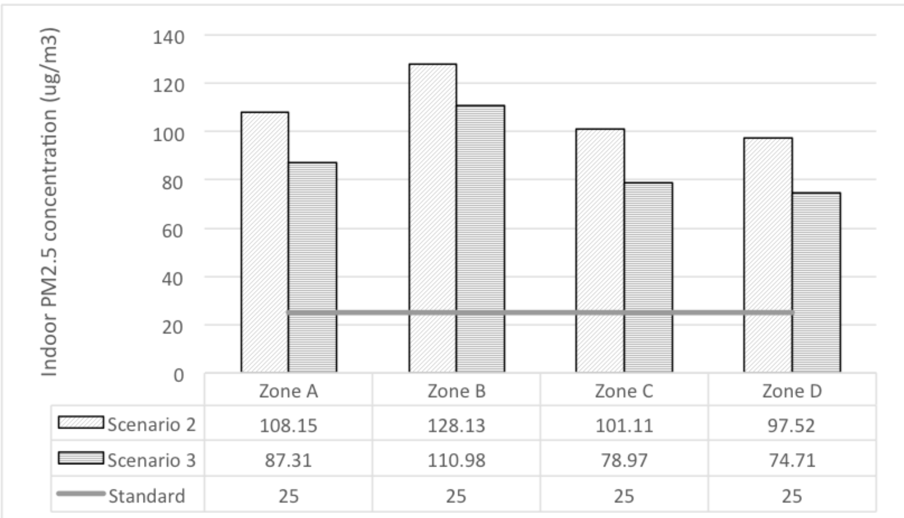
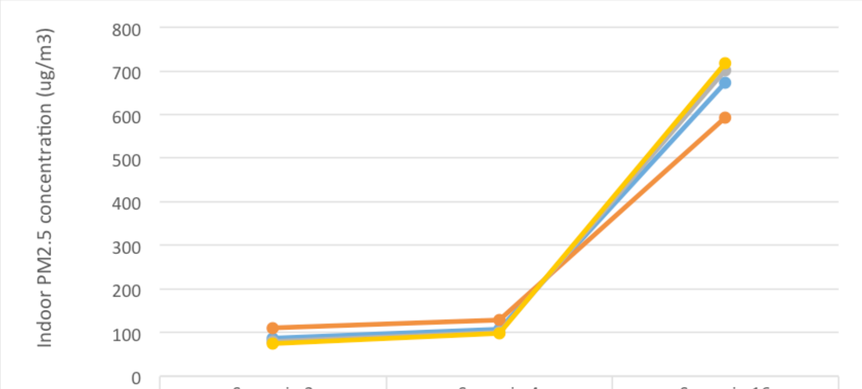
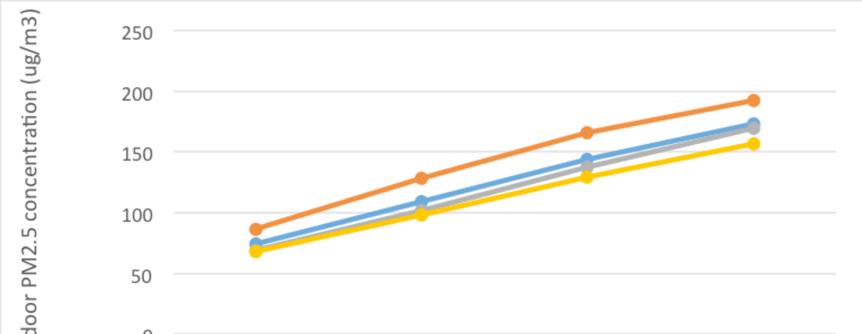


Figure 30. Result of group B.



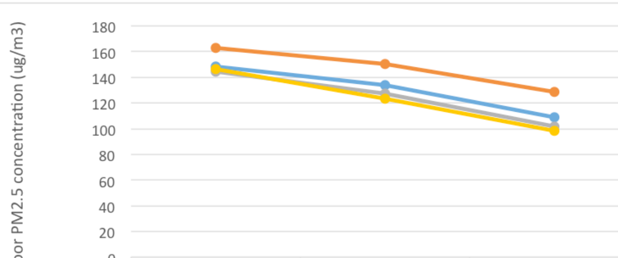
	Scenario 3	Scenario 4	Scenario 16
Zone A	87.31	108.78	674.09
Zone B	110.98	128.65	593.86
Zone C	78.97	101.78	702.38
Zone D	74.71	98.21	716.81

Figure 31. Result of group C.

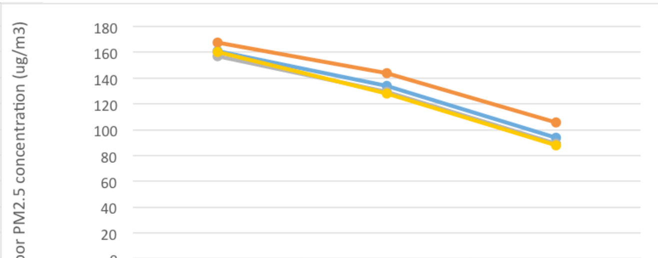


	Scenario 5	Scenario 4	Scenario 6	Scenario 7
Zone A	74.18	108.78	143.89	173.24
Zone B	86.71	128.65	166.22	192.46
Zone C	69.12	101.78	137.65	169.52
Zone D	68.09	98.21	129.64	156.95

Figure 32. Result of group D.

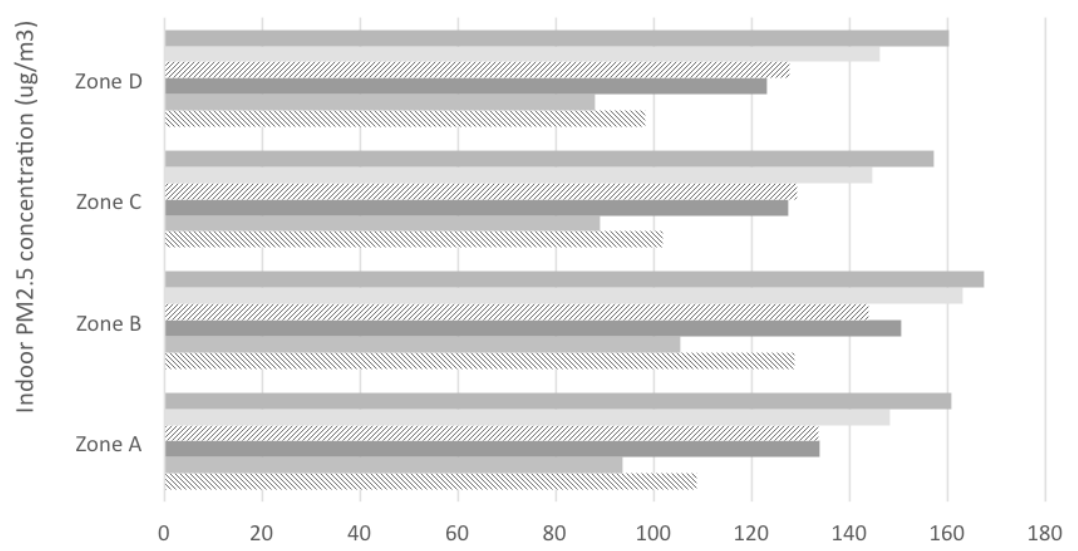


	Scenario 9	Scenario 8	Scenario 4
Zone A	148.22	133.93	108.78
Zone B	163.07	150.6	128.65
Zone C	144.65	127.48	101.78
Zone D	146.2	123.2	98.21



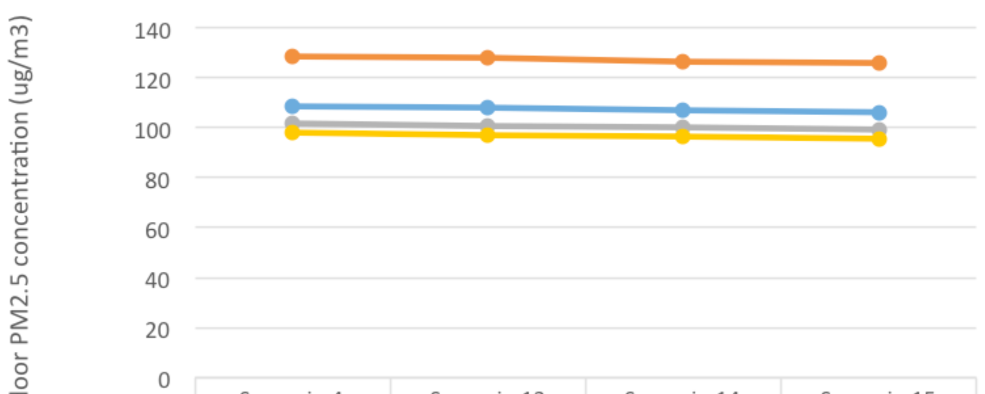
	Scenario 12	Scenario 11	Scenario 10
Zone A	160.75	133.64	93.7
Zone B	167.41	143.9	105.44
Zone C	157.13	129.2	88.98
Zone D	160.34	127.76	87.94

Figure 33. Result of group E (left E1, right E2).



	Zone A	Zone B	Zone C	Zone D
Scenario 12	160.75	167.41	157.13	160.34
Scenario 9	148.22	163.07	144.65	146.2
Scenario 11	133.64	143.9	129.2	127.76
Scenario 8	133.93	150.6	127.48	123.2
Scenario 10	93.7	105.44	88.98	87.94
Scenario 4	108.78	128.65	101.78	98.21

Figure 34. Result of group F.



	Scenario 4	Scenario 13	Scenario 14	Scenario 15
Zone A	108.78	107.96	107.01	106.18
Zone B	128.65	128.01	126.48	125.83
Zone C	101.78	100.9	100.11	99.24
Zone D	98.21	97.22	96.56	95.58

Figure 35. Result of group G.

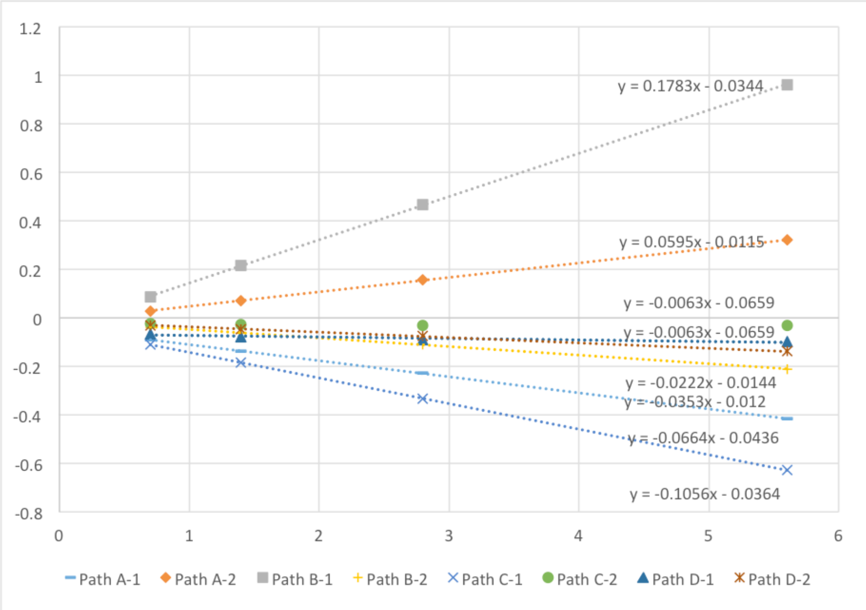


Figure 36. Result of group D (airflow).

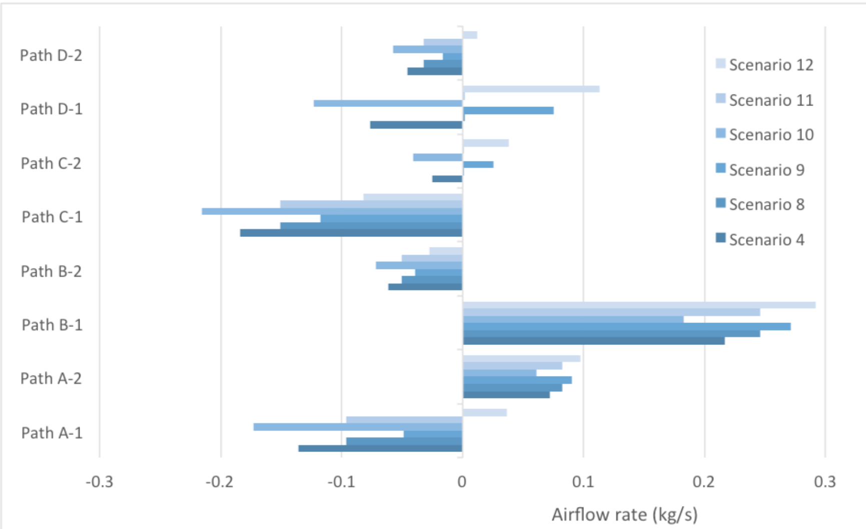


Figure 37. Result of group F (airflow).

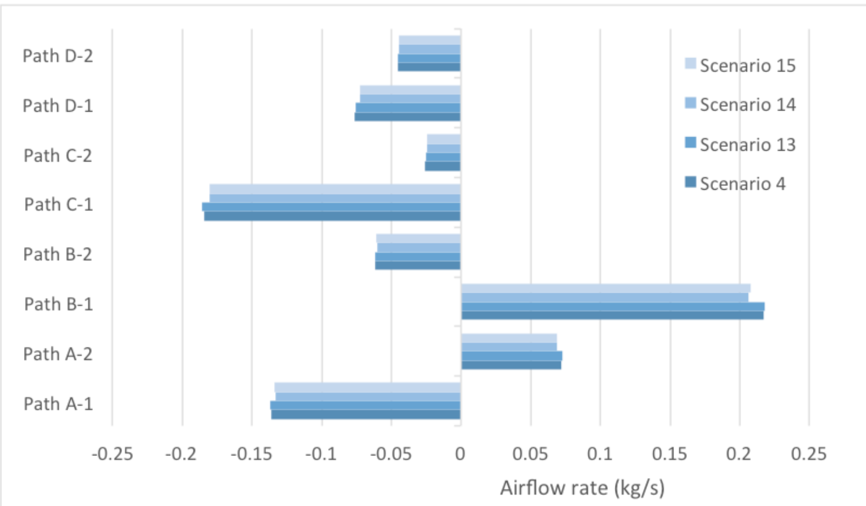


Figure 38. Result of group G (airflow).

6.4 Analysis & discussion

6.4.1 Qualitative analysis

Group A

In Scenario 1, no wind pressure is loaded on either side of the envelope, inducing no air infiltration. Instead, due to the temperature and pressure difference, indoor air with higher temperature and pressure flows outward through the leakage paths of the enclosure. Interior contaminants are also brought out during the exfiltration process, leading to the lower indoor fine particle concentration. With the same zone temperature, mechanical ventilation rate and unit air leakage value of each side, the four ventilation zones also show the even indoor fine particle level. Even with an extremely high ambient pollution level, the indoor PM2.5 concentration is a little bit higher than the limit value 25 $\mu g/m^3$.

In Scenario 2, the indoor concentration levels of PM2.5 in all zones are dramatically higher than Scenario 1. The wind pressure forces infiltration process, in a way offsetting the outward movement of indoor air. With different wind load strengths on the four sides, the impact of infiltration varies. As shown in Figure 28, the resulted airflow paths suggest infiltration on Path A-2 and B-1, while varying degrees of exfiltration on the others. This leads to the diverse indoor PM2.5 levels, among which none satisfies the standard.

This comparison data indicates the significance of wind pressure effect, which is the driving force of air infiltration, especially for high-rise buildings with increasing height and wind speed. It also suggests that even without any indoor source, the indoor contaminant level of airborne fine particles could exceed the limit for human health easily through penetrating the building shell.

Group B

With constant wind pressure and no indoor source, the only difference between the two situations is the efficiency of central HVAC filtration system, 70% as calculated in Chapter 5 in Scenario 2 and 100% representing a HEPA filter in Scenario 3.

Figure 30 shows an apparent gap between two scenarios in all zone pollution levels, indicating the better filtration performance of HEPA, while the values are much higher than the suggested guideline. It reveals that even if a HEPA is applied to block almost 100% of the particles contained in the outdoor air supply, PM2.5 could get access into the indoor environment through infiltration and pose a serious hazard to human exposure. The minor difference between the two scenario data also implies that it is not necessary to use HEPA filters as the central HVAC filtration, which is in accordance with the conclusion drawn in Chapter 5. On the other side, the preponderance of HEPA gets minor when the ambient pollution level decreases. Considering the average outdoor PM2.5 concentration over the whole year, the cost performance of applying a HEPA as central filtration is barely satisfactory. The diversity of multi-zone values also provides a convincing proof that even if all the control parameters (mechanical ventilation rate, zone temperature, building enclosure, etc) are the same and the multi zones are ventilated with each other through big openings like doorways, windows and so on, the contaminant distribution is not even among the zones, driven by wind directions.

Group C

This comparison group is based on the uncertainty of indoor sources that was discussed in Chapter 5. Therefore, in Scenario 4 the slight source strength is applied concerning basic office equipments, while it is replaced by an intensive source strength, which may happen during peak hours or lunch time.

The comparison between Scenario 3 and 4 displays a fair increase, implying the dominance of ambient source on the indoor particle mass concentration. However, the indoor values are strikingly higher in Scenario 16 when the strength of indoor emission source increases. Another unexpected fact is that while Zone B remains the highest PM2.5 level among the four zones in all the other scenarios embodying the effect of the most frequent airflow infiltration, in Scenario 16 it shows the lowest contaminant concentration. This reverse trend also applies to the rest, suggesting the highest level in Zone D, which is often the most slightly polluted one.

This could be explained quantitively by mass balance. It is shown in the simulation data that the pressure difference and airflow mass rate through the envelope paths remain the same in the three scenarios, indicating the irrelevance between infiltration and indoor source strength. The mechanical ventilation rate is 0.54 kg/s in this case, bringing 29.83 microgram PM2.5 per second into the office environment after HVAC filtration. It is assumed that there is no indoor source in the initial state. As soon as the intensive emitter is applied, the transient mass balance could be estimated.

Taking Zone B as a reference, the airflow rates through Path B-1 and B-2 are 0.2168 kg/s (inward) and 0.0613 kg/s (outward), leading to a rate of 39.92 infiltrated and 6.55 exfiltrated fine particles. So the total fine particles induced from outside is 63.20 microgram per second. On the other hand, the generation rate of indoor emission is 89.7 microgram per second, around 1.4 time of the outside brought amounts. So the contribution of indoor generation to the increase of indoor particle level is apparent, while the ambient source also plays an important role.

In contrast, in other zones with exfiltration rather than infiltration airflows, the role of indoor source is even more significant. For example, Zone D is with 0.1220 kg/s exfiltration, taking 9.91 microgram particulate matter 2.5 out. So the total fine particles induced from outside is 19.92 microgram per second. The only particle generation source is the indoor emission with a rate of 89.7 microgram per second. Therefore, the indoor PM2.5 level rises after some time, and undoubtedly the indoor source is the determinant factor of the fine particle mass concentration in Zone D.

This indicates the enormous potential of indoor source in determining the indoor pollution level. Whether outdoor or indoor source dominates depends on the strength of indoor source and the ventilation conditions of the zone. It could also be inferred from this data that indoor purifiers are required to remove both infiltration induced particles and newly generated emissions, and the demand is more emerging with the increasing intensity of indoor sources.

Group D

This group includes four scenarios with redoubled unit leakage areas of the envelope. Other conditions such as wind pressure, HVAC filter efficiency and indoor sources are all kept the same. So Scenario 4, with the second strict airtight level, is selected as the criterion representing the actual case and to be compared with other scenarios as well. The values for unit leakage area are 0.7, 1.4, 2.8, 5.6 cm^2/m^2, respectively representing different classification levels (as explained in Table 11).

It could be seen from Figure 32 that with the increasing unit leakage area, the indoor contaminant level rises. In addition, the airflow chart of Group D shows a linear correlation between unit leakage area and airflow rate passing by. This trend is easily understood since larger leakage area would lead to more penetrated airflow mass, bringing more outdoor air into the zones. Because of the higher PM2.5 level outside, closer connection with the ambient undoubtedly increase the indoor particle mass concentration. Furthermore, the quantitive relationship between decreased airtightness and indoor PM2.5 level would be elaborated through a sensitivity test in section 6.4.2.

Group E

Group E is a part of the mechanical ventilation rate comparison. The comparison involves two steps. First, given a constant air supply rate, the return rate is adjusted to differentiate the depressurized, equilibrated and pressurized space. This is done in group E1 and E2 individually with two different air supply rates to validate each other. Then, the impact of air exchange rate is explored by combing group E1 and E2. For a comprehensive output, the six scenarios are compared together to see which ventilation strategy is the most appropriate way.

In Group E1 and E2, as shown in Figure 33, the trend line keeps declining with the decrease of air return rate (air supply rate is kept constant). The values below the graph also give a proof, showing a remarkable drop in both E1 and E2. This consistency reveals that air infiltration happens least in a pressurized zone, while the most preferable situation inducing leakage and ambient particles is depressurization.

Group F

Instead of a line chart, the bar diagram explains the comparison result better in this group. The six series with diverse legends represent six tactics: pressurization with low AER (Scenario 4), equilibrium with low AER (Scenario 8), depressurization with low AER (Scenario 9), pressurization with high AER (Scenario 10), equilibrium with high AER (Scenario 11), depressurization with high AER (Scenario 12).

The evaluation of each strategy on the indoor PM2.5 concentration level could be interpreted from the length of each bar. The best one with the lowest particle mass concentration for the four zones is the same, pressurization with high AER scenario. The superiority of pressurization has already been discussed in Group E. Compared to the standard case Scenario 4, a higher air exchange rate acts in refreshing the air of the space frequently, replacing the existing air with conditioned fresh air, thus diluting the contaminant level in the ventilation zone and removing the contained particles with the exhaust air. It could be speculated that depressurization with low AER performs worst.

However, from Figure 34 it is surprising that for most zones the indoor PM2.5 concentration level is higher in Scenario 12 than in 9. The difference between Scenario 11 and 8 is relatively not obvious, since the trends in the four zones are not consistent. It could only concluded from the graph that pressurization with high AER is the most favorable mode, followed by pressurization with relatively low AER.

It should be highlighted that in Figure 37 showing the unit infiltrated airflow mass, Path C-2 and D-1 presents reverse trends. Take D-1 as an example, in a pressurization case the airflow is a negative value representing exfiltration. In contrast, in a equilibration situation the sign switches to positive, representing infiltration from ambient, though the absolute value is minor. This is due to the force of wind pressure. With the increase of air return rate, the formation of a depressurized zone draws more air from the ambient, which leads to a larger infiltration rate. This explains the trend on the leeside. On the windward side it is also applicable for the reverse airflow trend of Path D-2, the increases of positive infiltration strength with the increase of air return rate, and the decreases of negative exfiltration strength on the two crosswind sides.

Group G

In this group, four scenarios with different temperature difference between the indoor environment and ambient are included. Two are with a negative temperature difference (warmer interior, cooler exterior), while the other two are cooler interior and warmer exterior. The indoor control temperature is higher in Scenario 4 than in Scenario 13, while in Scenario 14 the interior environment is warmer than in Scenario 15. It could be interpreted from Figure 35 that all the four trend lines are kept almost horizontally, showing a negligible decrease. This could be understood as that the temperature difference between interior and exterior has little influence on the indoor PM2.5 level.

6.4.2 Sensitivity analysis

To quantitatively explore the determinant factors on the indoor contaminant concentration, a sensitivity analysis is conducted selecting the unit leakage area, air exchange rate, ratio of air supply to return rate, and the temperature difference between interior and exterior as the criteria. Therefore, Scenario 4, 5, 6, 9, 10, 13, 18, 19, 20 are involved composing comparison group H.

Scenario 4 is set as the baseline for the four parameters. Within a certain range, the sensitivity of each factor is calculated as follows.

Unit leakage area			
Range	0.7 (-50%)	1.4 (100%)	2.8 (+100%)
Values	86.71	128.65	166.22
Difference value	-41.94		37.57
Unit D-value	-0.8388		0.3757
Air exchange rate			
Range	0.27 (-50%)	0.54 (100%)	1.08 (+100%)
Values	147.96	128.65	105.44
Difference value	19.31		-23.21
Unit D-value	0.3862		-0.2321
Ratio of air supply to return rate			
Range	0.7 (-22%)	0.9 (100%)	1.1 (+22%)
Values	100.03	128.65	163.07
Difference value	-28.62		34.42
Unit D-value	-1.3009		1.5645
Temperature difference			
Range	-30 (50%)	-20 (100%)	-10 (+50%)
Values	129.25	128.65	128.01
Difference value	0.6		-0.64
Unit D-value	0.012		-0.0128

Table 13. Sensitivity of each parameter to indoor PM2.5 level in Zone B.

To avoid deviation and minimize the possibility of abnormal data, the sensitivity of each factor in the other zones are also taken into account to guarantee the reliability.

Unit leakage area			
Range	0.7 (-50%)	1.4 (100%)	2.8 (+100%)
Values	74.18	108.78	143.89
Difference value	-34.6		35.11
Unit D-value	-0.692		0.3511
Air exchange rate			
Range	0.27 (-50%)	0.54 (100%)	1.08 (+100%)
Values	120.19	108.78	93.70
Difference value	11.41		-15.08

Unit D-value	0.2282		-0.1508
Ratio of air supply to return rate			
Range	0.7 (-22%)	0.9 (100%)	1.1 (+22%)
Values	82.28	108.78	148.22
Difference value	-26.5		39.44
Unit D-value	-1.2045		1.7927
Temperature difference			
Range	-30 (50%)	-20 (100%)	-10 (+50%)
Values	109.56	108.78	107.96
Difference value	0.78		-0.82
Unit D-value	0.0156		-0.0164

Table 14. Sensitivity of each parameter to indoor PM2.5 level in Zone A.

Unit leakage area			
Range	0.7 (-50%)	1.4 (100%)	2.8 (+100%)
Values	69.12	101.78	137.65
Difference value	-32.66		35.87
Unit D-value	-0.6532		0.3587
Air exchange rate			
Range	0.27 (-50%)	0.54 (100%)	1.08 (+100%)
Values	112.09	101.78	88.98
Difference value	10.31		-12.8
Unit D-value	0.2062		-0.128
Ratio of air supply to return rate			
Range	0.7 (-22%)	0.9 (100%)	1.1 (+22%)
Values	76.81	101.78	144.65
Difference value	-24.97		42.87
Unit D-value	-1.135		1.9486
Temperature difference			
Range	-30 (50%)	-20 (100%)	-10 (+50%)
Values	102.61	101.78	100.90
Difference value	0.83		-0.88
Unit D-value	0.0166		-0.0176

Table 15. Sensitivity of each parameter to indoor PM2.5 level in Zone C.

Unit leakage area			
Range	0.7 (-50%)	1.4 (100%)	2.8 (+100%)
Values	68.09	98.21	129.64
Difference value	-30.12		31.43
Unit D-value	-0.6024		0.3143
Air exchange rate			
Range	0.27 (-50%)	0.54 (100%)	1.08 (+100%)
Values	102.76	98.21	87.94
Difference value	4.55		-10.24
Unit D-value	0.091		-0.1027
Ratio of air supply to return rate			
Range	0.7 (-22%)	0.9 (100%)	1.1 (+22%)
Values	74.43	98.21	146.20
Difference value	-23.78		47.99
Unit D-value	-1.0809		2.1814
Temperature difference			
Range	-30 (50%)	-20 (100%)	-10 (+50%)
Values	99.14	98.21	97.22
Difference value	0.93		-0.99
Unit D-value	0.0186		-0.0198

Table 16. Sensitivity of each parameter to indoor PM2.5 level in Zone D.

The Tornado diagrams of each zone could be achieved shown as follows.

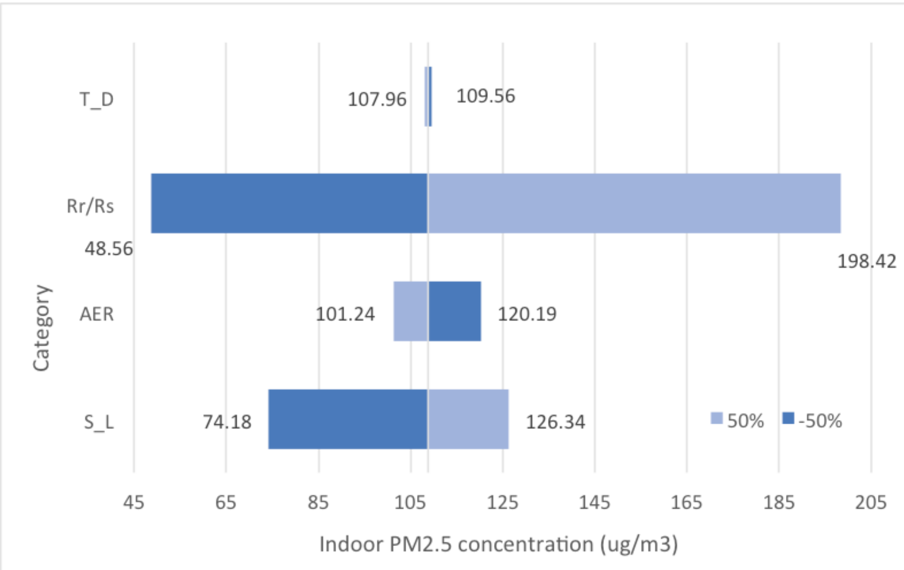


Figure 39. Tornado diagram of the sensitivity analysis in Zone A.

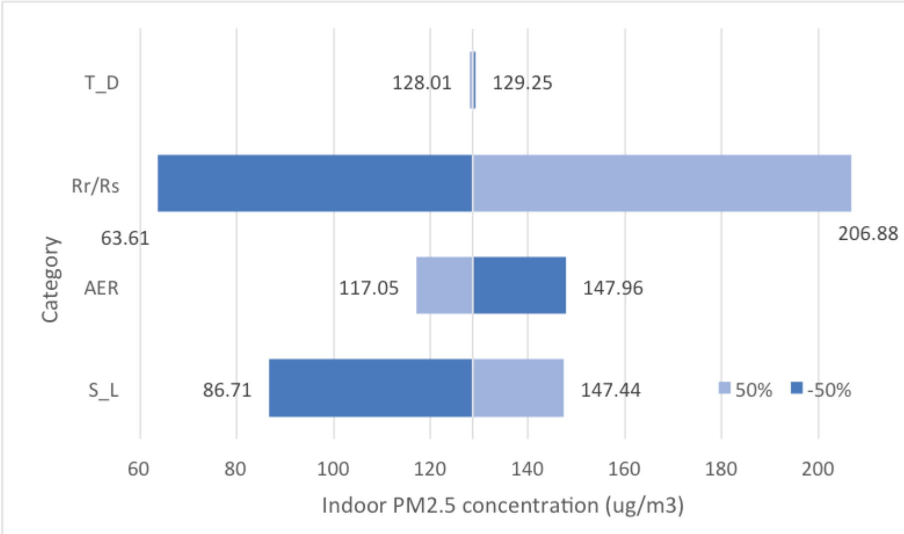


Figure 40. Tornado diagram of the sensitivity analysis in Zone B.

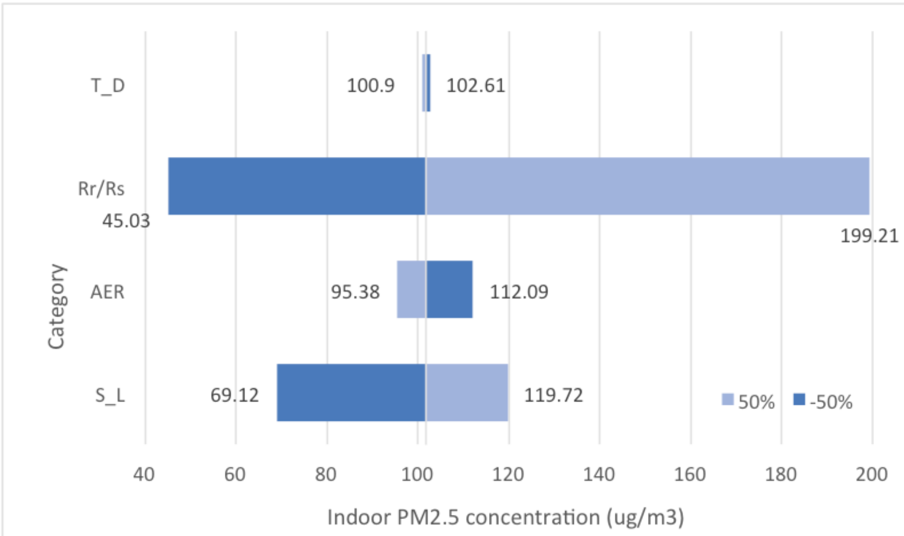


Figure 41. Tornado diagram of the sensitivity analysis in Zone C.

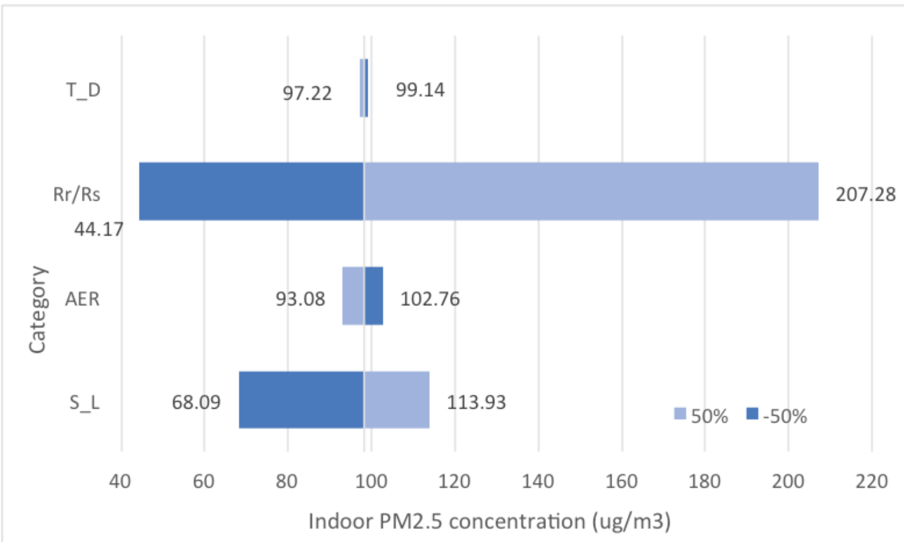


Figure 42. Tornado diagram of the sensitivity analysis in Zone D.

All the four tornado diagrams manifest the similar trends. On the ground of the single-dimentional sensitivity analysis, it could be interpreted that the rate of air supply to return rate dominates in deciding the indoor PM2.5 mass concentration. Within the range of 0.45 to 1.35 the corresponding change of particle level is remarkable in both directions. It should be mentioned that the baseline criteria for the ratio is 0.9, suggesting that with the increase of air return to supply ratio, both equilibrium and depressurization situations are included. In the other direction, given a certain air supply rate, the less return airflow, the better it performs to prevent infiltration. However, the pressure difference should be overcame by stack effect or other approaches, which should be taken into consideration.

The other factor affecting indoor PM2.5 level prominently is the airtightness of the envelope. In this case, the building is assumed to be careful sealed (the second class as shown in Table 9), representing the often case for lots of newly built high-rise office buildings. Based on this criterion, the more airtight the exterior enclosure is, the better it is to separate ambient pollutants and provide a well-conditioned interior environment. Less infiltration is also beneficial for energy saving, decreasing the heating and cooling demands effectively. Therefore, the airtightness of building enclosure is of significance. On the other hand, if the envelope is not airtight sufficiently, the situation is a little bit different. The increase of leakage factor would lead to more infiltration undoubtedly and induce more airborne contaminants into the indoor environment, while the amplitude of variation is not as obvious as that of increasing airtightness. In that case, the impact of a leaky envelope could be compared to the effect of decreasing the ventilation rate.

The air exchange rate of a building makes a little contribution to affecting the indoor PM2.5 level. As the baseline of the comparison meets the minimum ventilation rate standard of an office building, the decreasing values do not suggest a practical case. On the other hand, increasing AER would facilitate the ventilation of the space and therefore dilute the contaminant concentration, as explained in section 6.4.1.

By contrast, the influence of temperature difference between interior and exterior is minor. It could be seen from the tornado diagrams that the fluctuations induced by temperature variations are minor. It suggests the rationality of neglecting the role of interior control temperature.

6.4.3 Indoor filtration demands

In each simulated scenario, the minimum purification demand of PM2.5 removal is also calculated. The removal rate value is adjusted until the concentration levels in all zones satisfy the limit, keeping a decimal. Considering the possibility of deviation, a certain error bar with the range of 0.1 kg/s is kept. The statistics of the indoor filtration rate is shown in the scatter diagram.

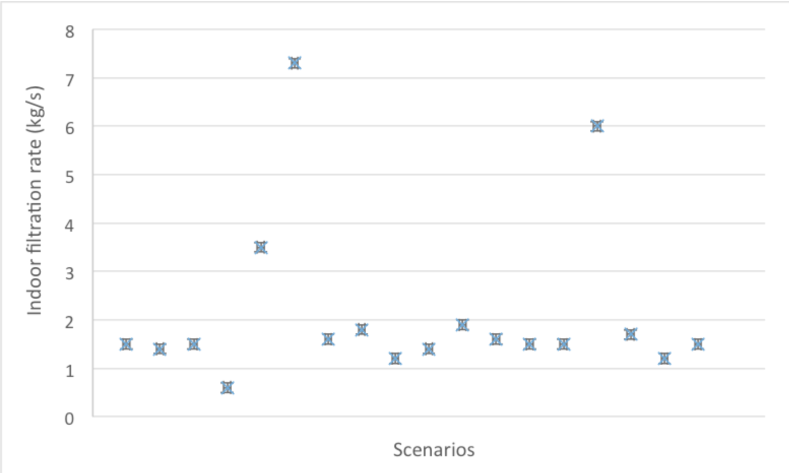


Figure 43. Statistics of the required minimum indoor air purification rates.

The distribution shows an intensive trend that for most cases the indoor purification demand is around 1.5 kg (1.25 cubic meter) air per second, regardless of the pressure mode, air ventilation rate or control temperature of the zone. The only fluctuation appears in Scenario 5, 6, 7, where the infiltration factor of the envelope varies. The correlation between leakage area and purification demand is shown in Figure 44. The scatters are fitted with a correlation factor 0.99, indicating the linear dependence of the parameters.

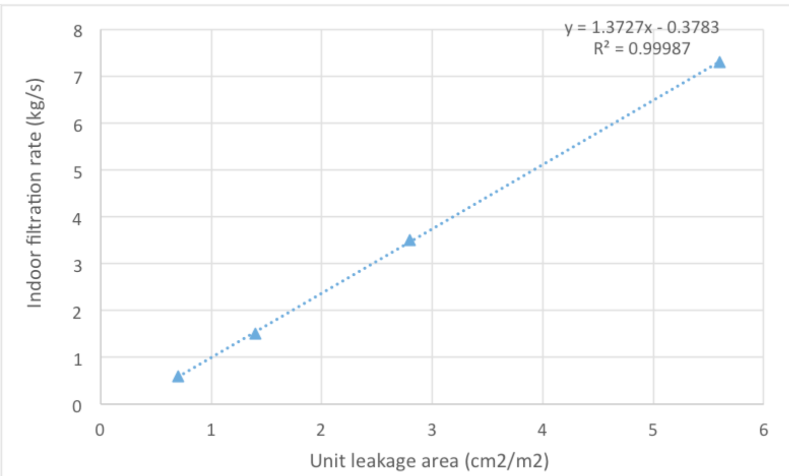


Figure 44. Fitted curve of the correlation between leakage area and filtration demand.

The high coefficient of determination of the fitted formula suggests the positive linear correlation between leakage area and minimum filtration rate. It is striking that through the infiltration factor of building enclosure does not play the most outstanding role in deciding the interior PM2.5 level, it does influence the filtration demand a lot. In contrast, other factors such as ventilation pressure ratio, which indoor particle concentration is most sensitive to, do not affect the required purification rate apparently.

This could be explained by the mass balance of airborne particles. In the case of a leaky envelope, fine particles penetrate the enclosure and access the indoor environment constantly. As shown in the airflow diagram of comparison group D (Figure 36), a double leaky facade would induce double airflow mass, containing double fine particles. Once the particles get inside, they must be removed by indoor filters to remain the qualified PM2.5 level. As the infiltration airflow is continuous, the demand for penetrating particle removal also doubles. On the other hand, if the air supply rate keeps constant while increasing the return rate to form an equilibrated or even depressurized zone, the infiltration strength gets higher bringing more fine particles in. Meanwhile, the increased return rate would also take more particles out, and thus neutralize with the infiltrated particles. As a result, the removal load of indoor filters is kept within the certain range rather than keeping growing.

The data of indoor filtration demand demonstrates the efficiency requirements of indoor filters. For most scenarios, the minimum purification rate is 1.0 to 2.0 kg/s. This value increases with the reduction of envelope airtightness level. In case of a pressurized building with good sealing envelop and sufficient AER ventilation, the indoor purification demand is around 1.6 kg/s (1.3 cubic meter air). Considering the volume of the analyzed zone (840 cubic meter), the purification rate is 5.6 h^{-1}. This value reflects the maximum indoor filtration demand, since an extreme ambient mass concentration level is adopted.

7 Conclusions and Recommendations

7.1 Conclusions

- **What determines the indoor PM2.5 concentration level?**

The pollution level in indoor environments is a combination product of outside PM2.5 concentration, building ventilation mode, indoor sources and sinks.

Whether outdoor or indoor source dominates in indoor PM2.5 concentration depends on the amounts of airborne particles generated by indoor sources and brought inside by ventilation. In case of intensive indoor sources, if the space is well ventilated with sufficient inward airflows either through mechanical air supply or infiltration, the net transferred rate of particle mass induced from ambient would be positive and larger than the emission rate, and outdoor source dominates. Conversely, if the zone is poorly ventilated or pressurized too much leading to serious exfiltration, particles brought into the indoor environment might be less than new particles generated by indoor emissions, or even resulting an outward airflow rate, then indoor source will be the dominant factor.

- **What is the relationship between indoor and outdoor PM2.5 level?**

The relationship between indoor and outdoor PM2.5 mass concentration could be indicated by a ratio I/O. Typically, without intensive indoor source, I/O is a value less than 1, suggesting that the indoor pollution level is often lower than ambient. The more frequent a building is ventilated with outside, the higher I/O. However, if the strength of indoor emission is quite high (e.g. smoking, cooking, etc), I/O could be a value much higher than 1.

- **What approaches can help to ameliorate indoor particles?**

The main principles are pollution resource control, attenuation through ventilation and air purification. From the point of building design, passive and active approaches include:

(1) Selecting less polluted sites.
(2) Separating long exposure areas with intensive emission sources.
(3) Improving the air tightness of building envelop.
(4) Choosing an appropriate ventilation mode and rate.
(5) Applying air filtration and purification systems.

- **What kind of purifiers can remove airborne fine particles effectively?**

For commonly adopted purifiers, fibrous media filters, ionizers and water scrubbers are the only effective technologies in airborne particle removal. Fibrous media filters capture fine particles physically by diffusion and impaction, and the effectiveness depends on the particle size and filter classification. Ionizers adsorb particles through electrostatic adherence, but it could only work as enhancement in combination with other technologies due to the low efficiency. Water scrubbers, typically applied in heavily polluted industries, are rarely used in office environments considering the cost performance and potential risk of secondary pollution.

Biological absorption is an alternative technology being developed to fit indoor environments. It has been proved that plants are native sinks for fine particles, although the removal efficiency is far from sufficient. Hence, botanical biofilters such as biowalls, green facades, moss mats and so on could make a great contribution in improving the filtration performance of greenery.

- **Is it essential to use a central filter or an individual indoor purifier?**

Yes, both central HVAC and indoor filtration are required. For office buildings with mechanical ventilation, the filtration of fine particles during HVAC processes is a crucial consideration, since it works in purifying intake air, ensuring fresh supply and minimizing the indoor purification loads. An individual indoor purifier is essential to remove unintended particles induced by infiltration and indoor emission. It is impossible to control indoor PM2.5 concentration and provide qualified air without either one of the filtration systems.

- **What is the filtration demand and requirement for purification systems?**

For HVAC filtration, it was pointed out that a HEPA filter is not necessary since it does not ensure qualified indoor air due to infiltration and indoor sources. Oppositely, a HEPA could bring along other problems like the concern of secondary pollution or frequent maintenance. Instead, a medium grade fine filter with a higher efficiency of 70% is adequate. This could be realized by applying a filter with a higher grade of MERV 13.

For indoor purification, it was proved that in case of the most serious ambient pollution level, with the premise of fair sealed enclosure, the filtration rate capacity of indoor purifiers should meet the requirement of 5.6 h^{-1}. This demand increases with the drop of envelope airtightness level.

- **What sort of strategies of building design have a direct impact on indoor PM2.5 level?**

From the point of building engineering, air infiltration through envelop and air exchange through mechanical ventilation system are the two vital considerations in indoor PM2.5 control. As infiltration is induced by pressure and temperature difference, envelop airtightness level, building pressure mode, interior control temperature are all concerned.

In case of a careful sealed enclosure, the indoor PM2.5 level is quite sensitive to the envelope leakage area, together with the pressurization ratio. However, if the airtightness grade is not high enough, for example in an average-classified building or even a leaky house, the significance of leakage area decreases. In that case the role of leakage factor is similar to the air exchange rate of the building.

It is for certain that an increased AER leads to more frequent airflow ventilation supplying fresh air, and helps to lower indoor contaminant level. However, the maximum airflow velocity is also limited in indoor environments for human comfort. The high energy consumption is another defect of a high AER. Therefore, it is advised that the air exchange rates of office buildings should be determined based on the minimum ventilation demand, energy budget and related airflow standards. Within the allowable range, a high air exchange rate is favorable for both indoor PM2.5 control and human health.

Temperature difference between interior and exterior, was indicated to be of no significance. The influence of interior temperature seemed to follow a random pattern. As a result, there is no need to control the indoor temperature deliberately for infiltration prevention, as the affection could be ignored. However, the impact of adjusting indoor temperature on energy saving is prominent.

- **Which parameter is the most dominant one?**

Air infiltration is overwhelming in deciding indoor PM2.5 level compared to mechanical air ventilation. Among all the influencing factors, pressurization is the most effective strategy in air infiltration and contaminant penetration control. The more pressurized a zone is, the better it performs in preventing air infiltration. However, the air return rate should not be designed extremely lower than supply rate, since the imbalance must be offset through other paths such as chimney effects. Excessive pressurization would also lead to difficulty in indoor access and other problems.

- **What could be done to improve the indoor air quality concerning fine particles?**

First, it is essential to apply a fine filter with a higher efficiency than 70% as the HVAC central filtration process before air supply. Indoor purifiers are required as well, while the removal rate depends on infiltration rate. In case of well sealed building enclosure and no intensive indoor sources, the capacity of indoor purifiers should meet 5.6 h^{-1}.

Next, pressurization strategy is always appreciated and highly recommended in mechanical ventilation mode, and the specific ratio of air supply to return rate should be controlled within a certain range, depending on the specific airflow design and test results. On the other hand, the airtightness level is another crucial indicator in PM2.5 concentration control, as the air infiltration rate increases in linear with the envelop leakage areas. As a result, the facade should be strictly sealed during design and construction phases. Moreover, within the allowable range (not exceeding the maximum design guideline of indoor airflow standard), a high air exchange rate is preferable, while energy consumption and human comfort should also be considered.

It is dispensable to concern about interior temperature to prevent infiltration, though it is also suggested to monitor the control temperature in consideration of energy consumption reduction. The strategy metric is illustrated in Figure 45.

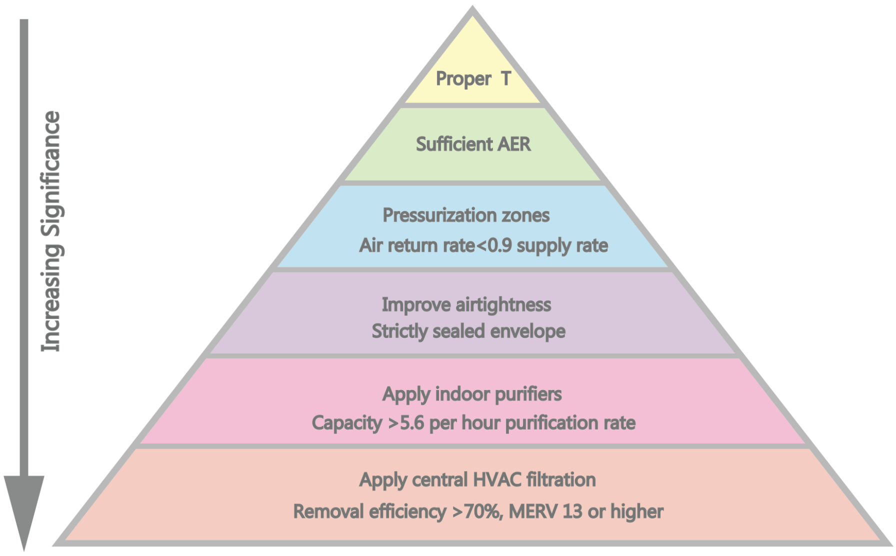


Figure 45. Hierarchy metrics of indoor PM2.5 control strategies.

7.2 Recommendations

It has been concluded that air infiltration through building envelope is the main cause of unintended increase of indoor PM2.5 concentration level. As a result, it is more crucial to monitor the infiltrated air rather than improving the filtration process of the mechanical ventilation system. The main measures include minimizing the leakage paths, creating a relative positive pressure space, and pre-filtering the infiltrated air.

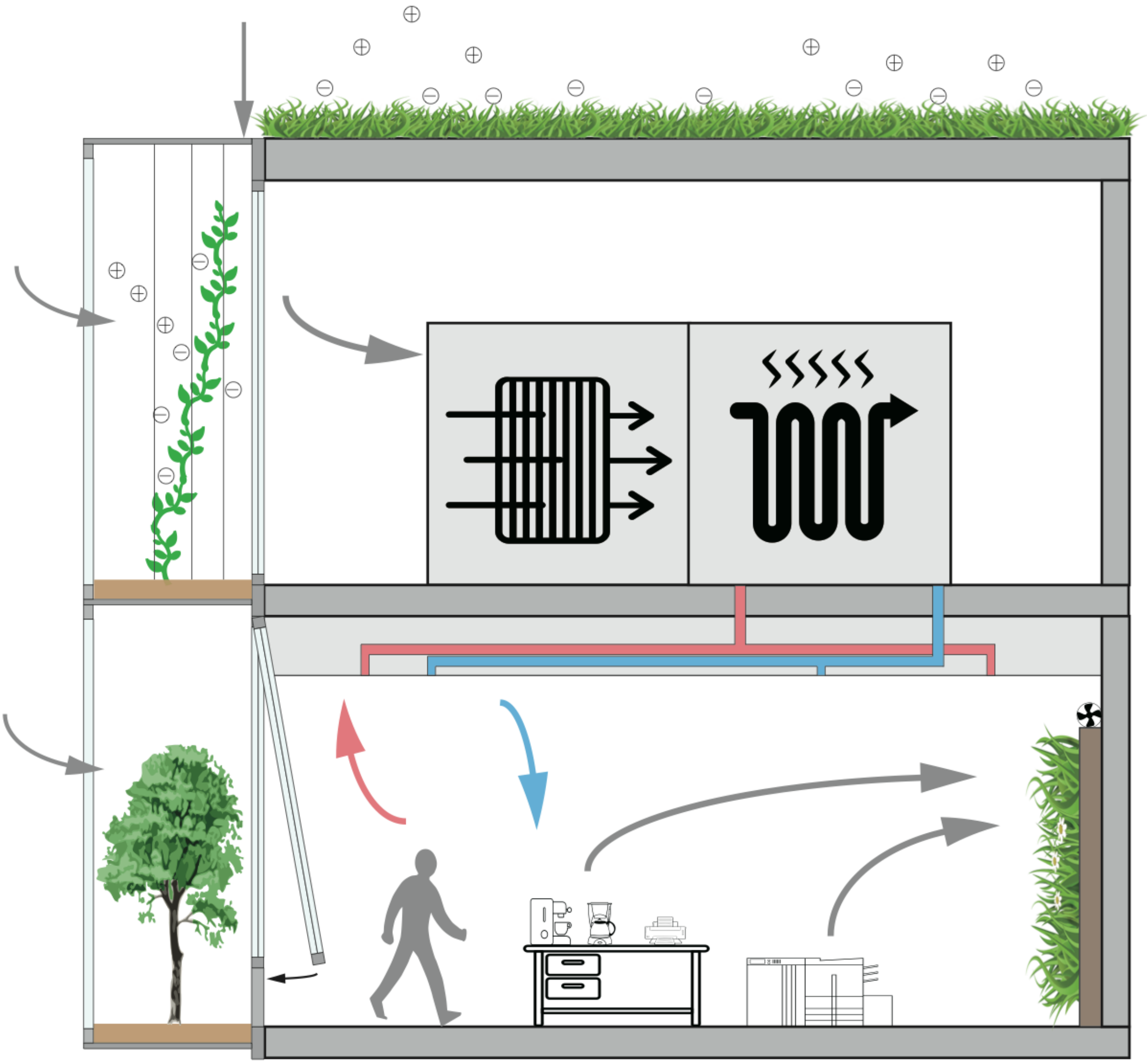


Figure 46. Filtration system design of high-rise office buildings.

Combing the conclusions drawn in Chapter 3 and 4, the suggested filtration applications are shown in Figure 46. The grey arrows represent heavily polluted air containing a great mass of PM2.5. The blue arrow indicates qualified supply air, and the red one suggests the exhaust airflow. For a mechanical ventilation system, the ambient air goes into the building through air inlets on the rooftop level. The negatively charged moss mats serve as a green roof and pre-filter the ambient air before getting access into the building. Then the air passes the central HVAC room containing a filtration process. After that the filtrated air is supplied to each room, and later exhausted through the air return ducts. Meanwhile, ambient air also penetrates the building envelope into the indoor environment. For most high-rise office buildings, a double facade system is adopted. Botanic pre-filters, like crawling vines on negatively charged grills or greenery species, are placed in the cavity between the glass layers. The inner layer of the facade is openable for washing the deposited particles on leaf surfaces or plant maintenance after work hours. In addition, capable indoor purifiers like biowalls or others are applied for removing new particle generations emitted by electronic devices as well as infiltrated PM2.5. A fan system is included to ensure the circulation of indoor airflows.

Suggestions for further researches include:

(1) Building airtightness improvement technologies

Since a strictly sealed enclosure is always recommended to prevent infiltration for infiltration prevention and energy saving as well, the development and study of improving facade airtightness is a main concern in building technology field.

(2) Specific air filter efficiency estimation & evaluation

It was pointed out that the indoor purification demand does not vary a lot with the change of air exchange rate, pressure mode or interior temperature. The only influencing factor is the leakage area, with a positive linear correlation of minimum filtration load. For careful sealed buildings, the filtration rate capacity of indoor purifiers should be higher than 5.6 per hour. This requirement grows with the decrease of envelope airtight level. Thus either fiber media filters or botanical biofilters should be tested to certificate the qualification when being applied as indoor purification tools. Such sorts of experiments and research are required to quantify the efficiency as well as to evaluate the technologies.

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Appendixes

A. Supplemental data

Table S1 Statics of PM2.5 Concentration in Shanghai from April 2015 to March 2016

(Source: U.S. Department) $(Unit : \mu g / m^3)$

date	2015.4	2015.5	2015.6	2015.7	2015.8	2015.9	2015.10	2015.11	2015.12	2016.1	2016.2	2016.3
1	46.25	43.13	47.25	37.79	50.25	41.13	31.13	41.08	54.67	59.25	50.83	39.50
2	34.21	46.04	32.96	55.96	42.21	57.88	31.79	113.38	74.58	95.79	97.67	68.92
3	64.08	58.88	18.24	71.87	39.33	64.75	33.71	84.29	54.50	139.71	56.71	66.71
4	61.25	66.42	24.50	51.78	39.96	58.46	24.25	34.92	50.50	120.54	37.00	29.17
5	50.92	23.33	63.83	23.35	34.38	36.50	24.04	38.39	65.67	29.38	138.25	85.42
6	21.92	39.83	56.08	18.56	21.42	28.38	17.00	21.09	102.04	52.00	60.08	89.17
7	24.57	51.29	26.63	19.38	18.29	14.63	15.13	48.13	79.38	80.54	62.00	80.79
8	32.14	30.50	16.83	25.29	11.08	11.96	16.73	62.21	33.42	71.75	93.38	18.04
9	N	26.79	44.58	27.38	10.83	10.33	64.24	85.50	37.83	114.50	75.17	22.58
10	N	39.04	33.33	21.58	16.79	17.25	39.87	58.39	41.17	62.54	34.92	25.42
11	N	29.83	48.79	5.79	17.13	22.61	43.32	36.52	78.96	48.92	24.88	58.96
12	47.31	46.54	55.50	20.42	30.13	45.88	N	N	49.33	45.96	28.04	82.71
13	N	44.13	51.58	67.21	43.75	27.04	N	N	61.65	126.10	54.83	58.79
14	65.92	50.25	35.25	62.25	32.54	17.50	59.73	124.21	146.59	160.25	37.71	73.79
15	70.54	38.50	38.17	25.29	22.71	20.54	26.08	102.13	220.96	133.08	35.46	42.13
16	65.67	46.83	28.04	27.21	31.54	19.00	36.00	71.08	68.92	124.38	39.33	44.39
17	33.5	41.79	20.21	29.08	40.46	24.04	28.96	29.67	45.42	88.38	59.00	38.65
18	58.04	49.75	21.58	22.54	41.50	29.04	39.04	28.88	51.38	135.42	68.21	93.78
19	111.22	71.58	41.54	18.00	22.83	18.58	37.42	33.32	37.50	89.83	66.25	N
20	46.17	43.79	35.38	21.13	37.50	37.25	34.42	44.46	50.04	27.04	77.29	N
21	38.39	23.13	39.25	37.00	19.25	32.17	41.92	27.13	138.25	22.30	45.33	N
22	72.00	34.21	25.67	31.92	N	29.38	75.25	31.08	89.25	42.50	41.12	40.33
23	N	40.17	47.67	35.08	N	27.23	42.33	33.04	187.50	48.33	57.17	36.30
24	60.00	36.33	53.17	31.79	20.25	20.33	42.00	25.04	61.61	34.54	37.25	25.92
25	67.00	31.50	41.33	48.75	32.63	26.71	44.08	38.00	174.13	40.79	46.17	37.29
26	48.96	29.52	33.63	60.75	55.50	30.38	43.79	57.17	96.63	57.96	70.17	53.79
27	N	42.00	12.75	44.33	83.58	26.08	70.96	45.38	66.04	40.79	55.13	101.46

28	65.53	33.29	13.00	44.92	78.50	23.71	59.96	64.58	40.79	27.54	68.08	83.25
29	47.86	28.17	37.13	42.04	61.63	8.00	37.21	74.13	58.46	30.29	52.57	64.46
30	65.75	35.08	52.63	31.21	53.00	15.50	31.21	116.58	93.25	39.33		68.92
31		49.00		36.42	36.92		23.04		137.54	60.50		54.54
average	54.13	40.99	36.55	35.36	36.07	28.07	38.43	56.06	82.19	65.01	57.59	56.61

Table S2 WHO air quality guidelines and interim targets for PM (24-h concentrations)
(Source: World Health Organization)

	PM10 ($\mu g/m^3$)	PM2.5 ($\mu g/m^3$)	Basis for the selected level
Interim target-1	150	75	Based on published risk coefficients from multi-centre studies and meta-analyses (about 5% increase of short- term mortality over the AQG value).
Interim target-2	100	50	Based on published risk coefficients from multi-centre studies and meta-analyses (about 2.5% increase of short- term mortality over the AQG value).
Interim target-3	75	37.5	Based on published risk coefficients from multi-centre stud- ies and meta-analyses (about 1.2% increase in short-term mortality over the AQG value).
Air quality guideline (AQG)	50	25	Based on relationship between 24-hour and annual PM levels.

Table S3 EPA air quality index and aerosol density for PM (24-h concentrations)
(Source: US Environmental Protection Agency)

AQI	PM10 ($\mu g/m^3$)	PM2.5 ($\mu g/m^3$)	Air Quality Descriptor
0-50	0-54	0.0-15.4	Good
51-100	55-154	15.5-40.4	Moderate
101-150	155-254	40.5-65.4	Unhealthy for sensitive groups
151-200	255-354	65.5-150.4	Unhealthy
201-300	355-424	150.5-250.4	Very unhealthy

Table S4 Minimum Efficiency Reporting Value (MERV) classification for filters.
(Source: ASHRAE)

MERV Grade	Dust Spot Efficiency	Arrestance	Typical Controlled Particle Size	Typical Applications and Limitations
1	<20%	<65%	>10.0 pm	Minimal Filtration Residential Window A/C Units
2	<20%	65-70%		
3	<20%	70-75%		
4	<20%	75-80%		
5	<20%	80-85%	3.0-10.0 pm	Commercial Buildings Better Residential Industrial Workplace Paint Booth Inlet
6	<20%	85-90%		
7	25-30%	>90%		
8	30-35%	>90%		
9	40-45%	>90%	1.0-3.0 pm	Superior Residential Better Commercial Buildings Hospital Laboratories
10	50-55%	>95%		
11	60-65%	>95%		
12	70-75%	>98%		
13	89-90%	>98%	0.30-1.0 pm	General Surgery Hospital Inpatient Care Smoking Lounges Superior Commercial Buildings
14	90-95%	n/a		
15	>95%	n/a		
16	n/a	n/a		
17	n/a	n/a	<0.30 pm	Cleanrooms Radioactive Materials Pharmaceutical Man. Carcinogenetic Materials
18	n/a	n/a		
19	n/a	n/a		
20	n/a	n/a		

Table S5 Simulation data for different scenarios

Zone	PM2.5 level $(\mu g/m^3)$	Pressure (Pa)	Pressure difference through Path A-1, B-1, C-1, D-1 (Pa)	Airflow rate through Path (A-1, B-1, C-1, D-1) (kg/s)	Pressure difference through Path (A-2, B-2, C-2, D-2) (Pa)	Airflow rate through Path (A-2, B-2, C-2, D-2) (kg/s)	Modified level after applying indoor filtration $(\mu g/m^3)$
Scenario 1							
Zone A	34.46	-96.91	-5.58	-0.045	-5.58	-0.015	
Zone B	34.46	-96.91	-5.58	-0.045	-5.58	-0.015	
Zone C	34.46	-96.91	-5.58	-0.045	-5.58	-0.015	
Zone D	34.46	-96.91	-5.58	-0.045	-5.58	-0.015	
Scenario 2 (Minimum required indoor removal rate: 1.5 kg air per second)							
Zone A	108.15	-116.83	-30.66	-0.1362	59.34	0.0723	11.89
Zone B	128.13	-116.83	59.34	0.2168	-48.66	-0.0613	23.95
Zone C	101.11	-116.84	-48.65	-0.1839	-12.65	-0.0255	4.04
Zone D	97.52	-116.83	-12.66	-0.0766	-30.66	-0.0454	3.20
Scenario 3 (Minimum required indoor removal rate: 1.4 kg air per second)							
Zone A	87.31	-116.83	-30.66	-0.1362	59.34	0.0723	10.13
Zone B	110.98	-116.83	59.34	0.2168	-48.66	-0.0613	23.88
Zone C	78.97	-116.84	-48.65	-0.1839	-12.65	-0.0255	3.96
Zone D	74.71	-116.83	-12.66	-0.0766	-30.66	-0.0454	3.12
Scenario 4 (Minimum required indoor removal rate: 1.5 kg air per second)							
Zone A	108.78	-116.83	-30.66	-0.1362	59.34	0.0723	11.96
Zone B	128.65	-116.83	59.34	0.2168	-48.66	-0.0613	25.00
Zone C	101.78	-116.84	-48.65	-0.1839	-12.65	-0.0255	6.07
Zone D	98.21	-116.83	-12.66	-0.0766	-30.66	-0.0454	5.31
Scenario 5 (Minimum required indoor removal rate: 0.6 kg air per second)							
Zone A	74.18	-100.24	-47.25	-0.0902	42.75	0.0292	14.27

Zone B	86.71	-100.24	42.75	0.0876	-65.25	-0.0371	23.67
Zone C	69.12	-100.24	-65.25	-0.1113	-29.25	-0.0220	10.05
Zone D	68.09	-100.24	-29.25	-0.0661	-47.25	-0.0301	9.64
Scenario 6 (Minimum required indoor removal rate: 3.5 kg air per second)							
Zone A	143.89	-124.11	-23.38	-0.2284	66.62	0.1558	10.27
Zone B	166.22	-124.08	66.59	0.4673	-41.41	-0.1104	24.62
Zone C	137.65	-124.12	-41.37	-0.3310	-5.37	-0.0293	3.74
Zone D	129.64	-124.11	-5.38	-0.0879	-23.38	-0.0761	2.77
Scenario 7 (Minimum required indoor removal rate: 7.3 kg air per second)							
Zone A	173.24	-127.27	-20.22	-0.4157	69.78	0.3212	9.77
Zone B	192.46	-127.17	69.68	0.9626	-38.32	-0.2100	25.01
Zone C	169.52	-127.33	-38.16	-0.6283	-2.16	-0.0324	2.80
Zone D	156.95	-127.27	-2.22	-0.0988	-20.22	-0.1386	1.64
Scenario 8 (Minimum required indoor removal rate: 1.6 kg air per second)							
Zone A	133.93	-129.52	-17.97	-0.0963	72.03	0.0820	10.61
Zone B	150.60	-129.51	72.02	0.2459	-35.98	-0.0504	24.65
Zone C	127.48	-129.52	-35.97	-0.1511	0.03	0.0005	4.13
Zone D	123.20	-129.52	0.03	0.0015	-17.97	-0.0321	3.12
Scenario 9 (Minimum required indoor removal rate: 1.8 kg air per second)							
Zone A	148.22	-141.14	-6.35	-0.0490	83.65	0.0903	11.02
Zone B	163.07	-141.13	83.65	0.2710	-24.36	-0.0391	25.04
Zone C	144.65	-141.14	-24.35	-0.1173	11.65	0.0251	6.43
Zone D	146.20	-141.14	11.65	0.0752	-6.35	-0.0163	9.64
Scenario 10 (Minimum required indoor removal rate: 1.2 kg air per second)							
Zone A	93.70	-103.13	-44.36	-0.1732	45.64	0.0609	14.75
Zone B	105.44	-103.12	45.63	0.1828	-62.37	-0.0720	24.71
Zone C	88.98	-103.14	-62.35	-0.2161	-26.35	-0.0412	10.27
Zone D	87.94	-103.13	-26.36	-0.1235	-44.36	-0.0577	9.81
Scenario 11 (Minimum required indoor removal rate: 1.4 kg air per second)							
Zone A	133.64	-129.52	-17.97	-0.0963	72.03	0.0820	11.98

Zone B	143.90	-129.51	72.02	0.2459	-35.98	-0.0504	24.24
Zone C	129.20	-129.52	-35.97	-0.1511	0.03	0.0005	6.27
Zone D	127.76	-129.52	0.03	0.0015	-17.97	-0.0321	5.51
Scenario 12 (Minimum required indoor removal rate: 1.9 kg air per second)							
Zone A	160.75	-151.37	3.88	0.0368	93.88	0.0974	14.70
Zone B	167.41	-151.37	93.88	0.2921	-14.12	-0.0274	24.49
Zone C	157.13	-151.38	-14.11	-0.0823	21.89	0.0378	9.00
Zone D	160.34	-151.37	21.88	0.1133	3.88	0.0123	14.14
Scenario 13 (Minimum required indoor removal rate: 1.6 kg air per second)							
Zone A	107.96	-68.73	-30.08	-0.1369	59.92	0.0727	11.33
Zone B	128.01	-68.73	59.91	0.2182	-48.09	-0.0619	23.93
Zone C	100.90	-68.74	-48.08	-0.1856	-12.08	-0.0252	5.62
Zone D	97.22	-68.73	-12.08	-0.0756	-30.08	-0.0456	4.89
Scenario 14 (Minimum required indoor removal rate: 1.5 kg air per second)							
Zone A	107.01	29.14	-29.82	-0.1329	60.18	0.0688	11.53
Zone B	126.48	29.15	60.17	0.2064	-47.83	-0.0602	24.03
Zone C	100.11	29.14	-47.82	-0.1806	-11.82	-0.0243	5.88
Zone D	96.56	29.14	-11.82	-0.0728	-29.82	-0.0443	5.14
Scenario 15 (Minimum required indoor removal rate: 1.5 kg air per second)							
Zone A	106.18	75.96	-29.26	-0.1335	60.74	0.0692	11.57
Zone B	125.83	75.96	60.73	0.2076	-47.27	-0.0608	24.12
Zone C	99.24	75.95	-47.26	-0.1823	-11.26	-0.0239	5.90
Zone D	95.58	75.96	-11.26	-0.0718	-29.26	-0.0445	5.14
Scenario 16 (Minimum required indoor removal rate: 6.0 kg air per second)							
Zone A	674.09	-116.83	-30.66	-0.1362	59.34	0.0723	20.68
Zone B	593.86	-116.83	59.34	0.2168	-48.66	-0.0613	24.93
Zone C	702.38	-116.84	-48.65	-0.1839	-12.65	-0.0255	18.63
Zone D	716.81	-116.83	-12.66	-0.0766	-30.66	-0.0454	18.55
Scenario 18 (Minimum required indoor removal rate: 1.7 kg air per second)							
Zone A	120.19	-124.11	-23.38	-0.1142	66.62	0.0779	10.43

Zone B	147.96	-124.10	66.61	0.2337	-41.39	-0.0552	24.91
Zone C	112.09	-124.11	-41.38	-0.1655	-5.38	-0.0146	3.85
Zone D	102.76	-124.11	-5.3798	-0.0490	-23.38	-0.0381	2.85
Scenario 19 (Minimum required indoor removal rate: 1.2 kg air per second)							
Zone A	82.28	-88.36	-59.12	-0.2088	30.88	0.0473	14.54
Zone B	100.03	-88.36	30.87	0.1418	-77.13	-0.0827	24.61
Zone C	76.81	-88.37	-77.12	-0.2481	-41.12	-0.0550	10.25
Zone D	74.43	-88.37	-41.12	-0.1649	-59.12	-0.0696	9.72
Scenario 20 (Minimum required indoor removal rate: 1.5 kg air per second)							
Zone A	109.56	-161.77	-31.22	-0.1356	58.78	0.0718	11.91
Zone B	129.25	-161.76	58.77	0.2154	-49.23	-0.0608	24.89
Zone C	102.61	-161.78	-49.22	-0.1823	-13.22	-0.0151	6.05
Zone D	99.14	-161.77	-13.22	-0.0452	-31.22	-0.0452	5.30

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