Experimental Study on PM$_{2.5}$ Purification Characteristics of Different Filter Units in Enclosed Environments

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ABSTRACT

Many epidemiological studies have shown that long-term exposure to high PM$_{2.5}$ concentrations can significantly increase the morbidity and mortality of different diseases. Air cleaners are effective in removing PM$_{2.5}$. In the present research, different filter units were tested to determine their PM$_{2.5}$ filtration efficiency. The filter face velocity was adjusted to 50%, 75%, 100%, 125%, and 150% of the corresponding rated airflow. The single-pass efficiencies, resistances, and cleaning efficiencies were simultaneously measured on every filter. In order to determine the clean air delivery rate (CADR) and cleaning energy efficiency (CEE) of different filter units, we designed a specific air cleaner that can replace different filter units in the test chamber. Our results showed that different filter units can effectively remove PM$_{2.5}$. The filtration efficiencies of electrostatic structure precipitators (ESP) and intense field dielectric (IFD) were close those of the sub-high efficiency glass fiber filter. In this case, filtration efficiency decreased when wind speed increased, whereas that of the fiber filter did not. Even when cleaners with different filter units were able to quickly remove fine particles, the highest CADR and CEE values were obtained when the IFD cleaner was used. In contrast, medium efficiency glass fiber cleaners displayed the smallest CADR and CEE values. The CADR and CEE values of the medium efficiency glass fiber cleaner were about 48.3% and 51.4% that of the IFD cleaner. The present study provides relevant data that will be useful in pandemic prevention and control in order to reduce the risk of infection in enclosed environments.

Keywords: PM$_{2.5}$, Filter units, Single-pass efficiency, Clean air delivery rate, Cleaning energy efficiency

1 INTRODUCTION

Long-term exposure studies have indicated that fine particulate air pollution represents the most important environmental health hazard (Zhao et al., 2015; Hu et al., 2017; Li et al., 2018). PM$_{2.5}$ displays fine particle size, powerful activity, and may eventually transport toxic and harmful substances (Pope et al., 2004).

Many epidemiological studies have shown that long-term exposure to high PM$_{2.5}$ concentrations can significantly increase the morbidity and mortality of different diseases, especially in people living in low and middle-income areas (Shang et al., 2013; Taylor et al., 1998). Ciencewicki and Jaspers (2007) reported that particulate matter in the air is responsible for the increased risk of virus transmission among humans, and higher environmental quality can reduce outbreaks of infectious diseases (Dutheil et al., 2020). Studies have shown that for every 1 µg m$^{-3}$ increase in
PM$_{2.5}$ average concentration, the likelihood of death of COVID-19 patients increases by 15%, patients with long-term exposure to high levels of air pollution were 20 times more likely to die from COVID-19 than others (Bilal et al., 2021).

Changes in lifestyle have caused that people spend more time indoors. It has been reported that, especially in developed countries, people spend between 80%–90% of their lives indoors (Wang, 2001). Since more than 55% of indoor fine particles are transported from the outside (Ozkaynak et al., 1996; Zwodzki et al., 2015), the most effective way to reduce health problems is to control the emissions of outdoor pollutants and reduce indoor PM$_{2.5}$ concentrations (Zheng et al., 2019; Du et al., 2011). PMs are mainly controlled by air filters in air conditioning systems of confined environments (Fisk, 2013). Some scholars in Korea's public buildings and the United States adjacent to the highway residential building test research shows that air filters and cleaners can effectively improve indoor air quality (Cox et al., 2018; Park et al., 2020b; Montgomery et al., 2015).

Extensive research has been performed on purification performance of PM by air filters and cleaners. Stuart (1983) proposed that electrostatic technology increases the operational efficiency of dust removers and improves the dust removal process. Alistair (1992) proposed a predictive efficiency Equation for mixed aerosol populations using effective migration rates and verified the performance of electrostatic air filters. Xu et al. (2009) conducted a study to determine if the air cleaners improve respiratory health. Zuraimi et al. (2011) evaluated the effectiveness of portable air cleaners in removing sodium chloride particles from the air. In this case, sodium chloride was used to simulate influenza viruses. These researchers used indoor air quality balance models to assess the effectiveness of air cleaners for controlling particulate pollution, which in consequence reduces residents’ exposure and risk of infection. Kim et al. (2012) developed a new method that involves Fourier Transfer Infrared measurements and CADR calculations to determine the gas removal performance of indoor air cleaners using a closed test chamber. Pei and Ji (2018) studied the effect of outdoor dust on HEPA fiber filters performance in a residential primary air system. Fang et al. (2019) performed a health risk assessment of toxic VOCs inhalation during evening sleep. In addition, they determined the effectiveness of indoor air cleaners for VOC removal. Park et al. (2020a) tested the antiviral performance of air filters using a liquid medium where infectious virus particles were dispersed. Bluyssen et al. (2021) quantified the “air purification” effect of an ambulant high-efficiency particulate filtration system in a sense experience room. Buising et al. (2022) studied the airflow characteristics, transmission, and removal of aerosols using portable air purifiers in clinical spaces in COVID-19 hospital wards.

However, most of the filter unit research focuses on a single filter unit, and few studies have compared the PM$_{2.5}$ removal performance of different filter units. In the present investigation, different filter units were collected and analyzed to perform comparative studies on filter performance. The particle removal performance of different air purifiers was studied.

## 2 METHODS

### 2.1 Air Filters Tests

Different air filter units were tested using an air filter test board of a purification laboratory. Filters included electrostatic structure precipitators (ESP) filter unit, intense field dielectric (IFD) filter unit, high efficiency poly tetra fluoroethylene (PTFE) air filter, sub-high efficiency air filter, and medium efficiency air filter. The experimental test board (Fig. 1) which was based on a Chinese Air Filter Standards (GB/T 14295:2019) was used to determine PM single-pass removal efficiency, wind resistance, and PM$_{2.5}$ cleaning efficiency, among others. A potassium chloride solution was used to generate aerosol particles. The test filter unit was placed between the upstream and downstream sampling points. Before the assay, the air supply temperature of the air duct on the test bench was controlled at (23 ± 5)°C, and the relative humidity at (45 ± 10)% to reduce the influence of ambient temperature (Pei et al., 2021).

The fan powers the test board. The filtered indoor air flows into the plenum, and the fine particles processed by the aerosol generator which can remove charge distribution on aerosols enter the injection sample chamber. The aerosol particles are thoroughly mixed with purified air in the injection sample chamber and move towards the exhaust bellows. Mixed airflow purified
**Fig. 1.** Schematic diagram of air filter test board.

**Table 1.** Experimental instruments and test items.

| Instrument                              | Test item                      | Precision                  |
|-----------------------------------------|--------------------------------|----------------------------|
| TSI Dust Trak II. 8532 Meter            | PM$_{2.5}$ mass concentration  | ± 0.1%; ± 1 µg m$^{-3}$    |
| TSI HY-AG-8108 Potassium Chloride Aerosol Generator | Experiment dust               | --                         |
| TSI 9306-V2 Particle Counter            | PM$_{2.5}$ number concentration| > 0.3 µm: 50%; > 0.45 µm: 100% |
| Grimm 1.109 Aerosol Particle Size       | PM$_{2.5}$ mass concentration  | ± 5%                       |
| Spectrometer                            | PM$_{2.5}$ number concentration|                           |
| FD-CG01 Smoke Generator                 | Experiment dust               | --                         |
| 8716B1 Electrical Parameter Tester      | Power consumption             | ± 0.1 W                    |

by the test filter passes through the exhaust bellows and is cleaned one more time at the end of the test board. The cleaned air is discharged from the exhaust outlet to complete the indoor air purification cycle. The measuring instruments and test items used in this study are shown in Table 1.

### 2.2 Particle Size Distribution of Potassium Chloride Aerosols

The fan of the air filter test board was turned on and air flow was adjusted according to evaluation results of different test filters. Later, the power supply of the HY-AG-8108 potassium chloride aerosol generator and electric heater was initiated. The aerosol generator is shown in Fig. 2(a). The temperature of the electric heater was set at 90°C. When the temperature reached the proper conditions, the compressed air and the liquid peristaltic pump were switched on. The atomizing nozzle produced tiny drops of potassium chloride aerosol inside the drying cylinder. During this process, heated and antistatic diluted air was injected from the bottom of the drying cylinder. Airflow was mixed with atomized aerosols, and the mixture was dried to form solid salt aerosol particles that were later released from the bottom of the drying cylinder. A Grimm 1.109 aerosol spectrometer was used to determine aerosol concentrations at the upstream sampling point. A 5% change in PM$_{2.5}$ concentration indicated that aerosol levels reached equilibrium (time = 0). The aerosol particle size spectrometer was set to 6-s sampling intervals, and the sampling time was 20 minutes. In this study, the average value of 200 groups of data was obtained. Data proved the polydispersity of solid potassium chloride particles, which sizes were between 0.25 µm and 10 µm.

Particle concentration can be calculated by the following Eq. (1) and the normalized concentration of potassium chloride aerosol is shown in Fig. 2(b).

$$C = N_i/N_{50a}$$  

where $C$ is the normalized concentration; $N_i$ corresponds to the average concentration of particles in a certain particle size segment (pc L$^{-1}$); $N_{50a}$ represents the particle concentration of median particle diameter (pc L$^{-1}$).
Fig. 2. Aerosol generator and normalized concentration of potassium chloride aerosol.

Table 2. Filter efficiency level and rated velocity for test.

| Test filter          | Efficiency level | Rated velocity |
|----------------------|------------------|----------------|
| ESP filter unit      | Sub-high efficiency | 1.0 m s\(^{-1}\) |
| IFD filter unit      | Sub-high efficiency | 1.0 m s\(^{-1}\) |
| PTFE air filter      | High efficiency   | 0.45 m s\(^{-1}\) |
| Glass fiber air filter | Sub-high efficiency | 1.0 m s\(^{-1}\) |
| Glass fiber air filter | Medium efficiency   | 1.5 m s\(^{-1}\) |

2.3 Resistance Test

In this experiment, the air filter was installed in the static pressure chamber to ensure no leakage was present at the installation frame. Later, fan was turned on and different surface velocities were achieved by adjusting the parameters of the differential pressure transmitter. The surface velocity corresponds to the ratio of air volume passing through the air filter vertically to the cross-section area. Rated velocity values of 50%, 75%, 100%, 125%, and 150% for different tested filters were selected as the test wind speed. When aerosol concentrations stabilized, resistances were recorded under different wind speeds using the differential pressure transmitter. Later, ESP, IFD, high efficiency PTFE air filter, sub-high efficiency glass fiber air filter, and medium efficiency glass fiber air filters were replaced and tested. The rated velocity varied as efficiency of the filters also varied (Yit et al., 2020). Table 2 displays efficiency level and rated velocity of the tested filters.

2.4 Single-pass Efficiency Test

Before experiments were performed, upstream aerosol mass concentration was maintained between 150 and 750 \(\mu\)g m\(^{-3}\). In addition, downstream aerosol concentration was kept above 100 pc L\(^{-1}\). Upstream and downstream aerosol concentrations were simultaneously monitored using a TSI Dust Trak II 8532 Meter and a Grimm 1.109 aerosol particle size spectrometer, respectively. During the experiment, the Grimm 1.109 was used at the upstream and downstream test board sampling points, and the average values were measured more than six times. The aerosol particle size spectrometer first measured and recorded aerosol concentrations at the downstream sampling points; subsequently, aerosol concentrations were recorded at the upstream sampling points. Automatic restarts and re-tests were performed every time the instrument changed position. Air volumes were adjusted to 50%, 75%, 100%, 125%, 150% of rated airflow for...
different filter units. Finally, after filter replacement, assays were performed as indicated. Counting efficiency was calculated using Eq. (2), which is from the Air Filter Standards (GB14295:2019).

\[
E = \left(1 - \frac{N_2}{N_1}\right) \times 100%
\]  

where \( E \) is the counting efficiency of a certain particle size segment; \( N_1 \) corresponds to the average concentration of a certain particle size segment on the upwind side (pc L\(^{-1}\)); \( N_2 \) represents the average concentration of a certain particle size segment on the downwind side (pc L\(^{-1}\)).

Eq. (3) was used to compute PM\(_{2.5}\) cleaning efficiency, which is also from the Air Filter Standards (GB14295:2019).

\[
E_{PM_{2.5}} = \left(1 - \frac{C_{PM_{2.5},2}}{C_{PM_{2.5},1}}\right) \times 100%
\]  

where \( E_{PM_{2.5}} \) is PM\(_{2.5}\) cleaning efficiency of the corresponding filter; \( C_{PM_{2.5},1} \) indicates the average PM\(_{2.5}\) mass concentration at the upstream sampling site (\(\mu g\) m\(^{-3}\)); \( C_{PM_{2.5},2} \) represents the average PM\(_{2.5}\) mass concentration at the downstream sampling site (\(\mu g\) m\(^{-3}\)).

### 2.5 Decay Test

Decay test was conducted in a float flat glass with stainless steel frame chamber that volume is about 30 m\(^3\) (3.5 \(\times\) 3.4 \(\times\) 2.5 m) with a dedicated HVAC system for simulating realistic room environmental conditions. Air cleaners were assayed using a 30 m\(^3\) test chamber (Fig. 3(a)). Fig. 3(b) displays the air cleaner design that was used to replace the filter unit.

![Schematic diagram of the test chamber](image)

**Fig. 3.** Schematic diagram of the test chamber: Instructions of (a): 1) Stirring fan; 2) Circulating fan; 3) Cleaner for test; 4) TSI 9306-V2 particle counter; 5) Smoke generator; 6) Air filter; 7) Test chamber air supply valve; 8) Constant temperature and humidity air supply; 9) Air duct reversing valve; 10) Test chamber constant temperature and humidity conditioning return air; 11) Exhaust port; 12) Exhaust window; 13) Test door; 14) Exterior cabin constant temperature air conditioning inlet; 15) Exterior cabin constant temperature conditioning return air outlet; 16) Door outside cabin; 17) Sampling port and injection port; 18) Regulated power supply.
In order to perform the decay test, the following steps were performed: (1) The cleaner was placed at the center of the test chamber (see 3 in Fig. 3(a)) and the machine was corrected; (2) the sampling port was connected (see 17 in Fig. 3(a)) to the TSI 9306-V2 particle counter (see 4 in Fig. 3(a)), and the injection port (see 17 in Fig. 3(a)) with the smoke generator (see 5 in Fig. 3(a)); (3) Subsequently, the cleaner was turned on to purify the test chamber. When particle concentration in the test chamber was below $1.0 \times 10^3$ pc L$^{-1}$, the control device was switched on to set up temperature and relative humidity to the proper value. Temperature was controlled at $(25 \pm 2)^\circ C$ and the relative humidity at $(50 \pm 10)\%$. (4) The air cleaner and control device were turned off, and the stirring fan (see 1 in Fig. 3(a)) and circulating fan (see 2 in Fig. 3(a)) turned on. Subsequently, a cigarette was placed in the smoke generator before this was switched on. When the smoke concentration in the test chamber reached about $1.6 \times 10^6$ pc L$^{-1}$, the valve of the smoke conveying pipe was closed. The stirring fan worked for 10 more minutes to disperse the PMs. The circulating fan remained working all the time. (5) After the stirring fan stopped rotating, the TSI 9306-V2 particle counter was used to measure the initial particle concentration ($t = 0$). (6) Particle concentrations were measured every 2 minutes for 20 minutes.

After steps 1 to 4 were completed, the air volume of the tested cleaner was adjusted to the maximum value. The TSI 9306-V2 particle counter was used to measure the initial particle concentration. Time zero indicated the moment when the cleaner started working. After every measurement, step 6 was repeated. After filters were replaced, tests were performed as indicated. The power consumption of different cleaners was determined at the maximum airflow using the 8716B1 electrical parameter tester. At the end of the assays, all devices were turned off.

The attenuation constant $k$ can be obtained using the Eq. (4), which is from the Air Cleaner Standards (GB18801:2015).

$$-k = \frac{\sum_{i=1}^{n} t_i \ln C_i - \frac{1}{n} \left( \sum_{i=1}^{n} t_i \right) \sum_{i=1}^{n} \ln C_i}{\sum_{i=1}^{n} t_i^2 - \frac{1}{n} \left( \sum_{i=1}^{n} t_i \right)^2}$$

where $k$ is the decay constant (min$^{-1}$); $t_i$ is the time corresponding to the sampling point $i$, (min); $\ln C_i$ indicates the natural logarithm of the particle concentration corresponding to the sampling point $i$; and $n$ is the sampling frequency.

We calculated the CADR of different cleaners using Eq. (5), which is also from the Air Cleaner Standards (GB18801:2015).

$$Q = 60 \times (k_e - k_n) \times V$$

where $Q$ indicates the CADR (m$^3$ h$^{-1}$); $k_e$ is the total decay constant (min$^{-1}$); $k_n$ the natural decay constant (min$^{-1}$); $V$ corresponds to the test chamber capacity (m$^3$). In addition, Eq. (3) was used to determine $k_e$ and $k_n$.

### 2.6 Quality Assurance

When we use Grimm 1.109 for a counting efficiency test, we first test the concentration of the downstream sampling point, the average value of the test data is called downstream data 1, and then measure the concentration of the upstream sampling point, the average value of the test data is called upstream data 1, counting efficiency $E_1$ can be obtained by substituting downstream data 1 and upstream data 1 into Eq. (2). Next, measure the concentration of the downstream sampling point, the average value of the test data is called downstream data 2, and the efficiency $E_2$ can be obtained by substituting downstream data 2 and upstream data 1 into Eq. (2). When the difference between $E_1$ and $E_2$ is greater than the threshold, the set of data will be discarded, and the test will be performed again. The size of $E_1$ is different, and the threshold is also different. The range and threshold of $E_1$ are shown in Table 3. For example, when the filtration efficiency of a certain particle size of $E_1$ is lower than 40%, the absolute value of the difference between $E_2$ and $E_1$ needs to be less than 30%$E_1$, otherwise, the set of test data will be discarded.
2.7 Criteria
The generating aerosol used for the efficiency test was a 10% potassium chloride solution. KCl purity was not less than 99.5%, according to the Air Filter Standards (GB14295:2019) and the Chemical reagent potassium chloride Standards (GB646:2011). Cigarette smoke was used as the dust source of particulate pollutants according to the Air Cleaner Standards (GB18801:2015). Moreover, we only counted the number of particles above 0.3 μm.

2.8 Statistical Analysis
For statistical analysis, we sent all recorded data to a private computer. Origin software was used to perform data fitting and linear regression analysis, and Excel was used to calculate and analyze CADR.

3 RESULTS AND DISCUSSION

3.1 Filter Characteristics
The relationship between velocity and resistance of the air filter is shown in Fig. 4. Resistance and wind speed data for each air filter were fitted by a curve fitting method. As Fig. 4 shows, the wind speed of the filter was approximately linearly correlated with the resistance, and the results are the same as those of Mohammad et al. (2020). The determination coefficient depends on $R^2$, which stands for the fitting goodness. According to the fitting results, the determination coefficients of ESP and IFD filter units were greater than 93%. Nevertheless, those corresponding to the sub-high efficiency filter, high efficiency filter, and medium efficiency filter were greater than 99%. The low fitting ESP and IFD coefficients were probably due to the voltage breakdown (Hilal Kurt and Salamov, 2020) that occurred during the operation process. This breakdown leads to resistance fluctuations. The resistances followed the order ESP < IFD < medium efficiency filter < sub-high efficiency filter < high efficiency filter. Data in Fig. 4(a) to Fig. 4(e) indicated that, because of different structures and dust collection properties, the resistances of ESP and IFD increased relatively slowly with the increase in wind speed. In contrast, that of fiber filter increased more rapidly as wind speed increased. At the same wind speed, ESP and IFD resistances were similar. However, that corresponding to IFD was slightly greater than that of ESP because of the IFD’s honeycomb dust collecting unit.

Classification counting efficiencies for each filter are shown in Fig. 5. With the increase of particle size, the classification counting efficiency increases. The highest filtration efficiency was observed in the PTFE filter, while that of the medium efficiency glass fiber filter was the lowest. The filtration efficiency of sub-high efficiency glass fiber filter was between those of IFD and ESP. According to our results, tested filters displayed filtration efficiencies for particles above 1.0 μm of more than 95%. Thus, they were effective in purifying PM2.5 generated by a potassium chloride solution. It was also determined that smaller particle sizes resulted in a reduced filtration efficiency in ESP and medium efficiency glass fiber filters. When the particle size was larger than 2.0 μm, ESP filtration efficiency was higher than that of the sub-high efficiency glass fiber filter. In addition, when the particle size was less than 0.5 μm, the filtration efficiency of the medium efficiency fiber glass filter decreased rapidly to values of less than 90%. Similar results were obtained for ESP.

The former is due to the low thickness and filling rate of the fiber layer, and some fine particles pass through the large pores, resulting in low filtration efficiency of the medium-efficiency fiber...
Fig. 4. The relationship between velocity and resistance of each air filter.
The latter is mainly due to the filtration mechanism. The ESP mainly relies on the electrostatic effect to filter the particles. It can be seen from Fig. 2 that the potassium chloride particles below 0.5 µm account for more than half of the total particles. When the ESP charging module does not apply charges to all the fine particles, it will flow to the dust collection module with the airflow, so that the uncharged particles cannot be collected.

Fig. 6 shows the PM2.5 cleaning efficiency of each tested filter. Data indicated that the cleaning efficiency was consistent with the classification counting efficiency. As shown in Fig. 6, cleaning efficiency for PM2.5 varied from 95.37% to 99.83%. Especially, the cleaning efficiency for PM2.5 of high efficiency PTFE filter ranged from 99.80% to 99.83%, with an average value of 99.82%. In addition, that for the medium efficiency filter varied from 95.37% to 95.54%, with an average value of 95.43%. It was found that PM2.5 cleaning efficiency of the high efficiency filter and sub-high efficiency filter did not display significant variations. On the contrary, those values corresponding to IFD, ESP, and medium efficiency filter presented noticeable variations. This phenomenon occurred because of voltage breakdown during the operation. Nevertheless, some fine particles passed through the large pores of the medium efficiency filter, which contained a thin fiber layer and small filling rate. As the purification test proceeded, the large pores were loaded with particulate matter, which improved the cleaning efficiency for PM2.5. For this reason, PM2.5 cleaning efficiency of the medium efficiency filter fluctuated.

The relationships between PM2.5 cleaning efficiency and wind speed are shown in Fig. 7. With the increase in wind speed, the purification efficiency of IFD and ESP decreased, whereas the filtration efficiency of fiber filters increased. Alistair (1992) obtained the same result by testing the purification efficiency of the ESP filter unit at different wind speeds. Elkamhawy and Jang (2020) conducted an experiment using a mixed air purification system with vegetation soil and ESP filter. Their results indicated that PM2.5 cleaning efficiency of the vegetation soil filter for 78.5% when the inlet wind speed was 0.15 m s\(^{-1}\). In addition, this value was 73.1% when the inlet wind speed was 3.0 m s\(^{-1}\). With increasing wind speed, ESP filtering efficiency decreased. Cui et al. (2017) tested the relationship between the primary filtration efficiency of the IFD filter unit and air volume. The filtration efficiency showed a decreasing trend with the increase in air volume, which was consistent with the experimental results. The filtration mechanisms of IFD and ESP are electrostatic effect (Ma et al., 2021). The lower the wind speed, the longer the time the electric field force acts on the dust. In consequence, the probability that particles will be captured increases, resulting in higher filtration efficiencies. At high velocities, some fine particles do not charge when they pass through ESP and IFD. For this reason, they cannot be adsorbed by the collecting...
Fig. 6. The Cleaning efficiency for PM$_{2.5}$ of different filter units.

As Fig. 7 indicates, when wind speed increased, the cleaning efficiency of ESP decreased faster than that of IFD. This occurred because discharge units present some differences. It was also determined that, at the same power, the charging voltage of ESP was lower than that of IFD. This indicated that the electrostatic adsorption capacity of ESP was weaker than that of IFD. Therefore, when wind speed increases, the cleaning efficiency of the ESP filter decreases at higher rates than those of IFD.

Sub-high efficiency and medium efficiency filters are made of fiber. Their filter mechanism is based on intercepting, inertia, and gravitational effects (Li et al., 2016; Bochkarev et al., 2021). The greater the wind speed, the higher the capture probability. Therefore, PM$_{2.5}$ cleaning efficiency increases. Since the PTFE filter density is high, when wind speed increases, the PM$_{2.5}$ cleaning efficiency remains.

Fig. 7. The relationship between cleaning efficiency for PM$_{2.5}$ and wind speed.
3.2 Cleaner Characteristics

In the present investigation, air purifier performance of different filter units was tested. Fig. 8 displays the results for attenuation of cigarette particles concentration in different filter units. Data indicated that reduction in PM concentration was significant. However, the opposite was observed with natural decay as this parameter was not significant. It was also determined that the highest particulate concentration reduction rate occurred when the IFD cleaner was used. In contrast, the slowest decay rate was observed with the medium efficiency glass fiber cleaner. Moreover, the use of the ESP cleaner and high efficiency PTFE cleaner resulted in similar particulate concentration decline rates. As shown in Fig. 8, after 20 min of natural decay, PM concentration decreased about 8.9%. However, all tested cleaners were able to achieve a purification efficiency of more than 90% after 20 min.

CEE can be calculated considering the CADR and power consumption. CEE is an important index that evaluate the cleaners, which is calculated as the ratio of the CADR to the power consumption.

CADR values of different cleaners were calculated using Eq. (4) and Eq. (5). Table 4 shows the CADR and CEE data for cleaners tested in the present investigation. The larger the CADR, the better the PM removal effect and the shorter the time to remove particulate matter. When the particulate matter in the airtight cabin is purified to the same level, the larger the CADR, the shorter the purification time. And the larger the CEE, the smaller the power consumption is, the smaller the concentration of particulate matter is purified to the same level. It was found that CADR and CEE values followed the order IFD cleaner’s > high efficiency PTFE cleaner’s > ESP cleaner’s > sub-high efficiency glass fiber cleaner’s > medium efficiency glass fiber cleaner’s. CADR and CEE values displayed by the medium efficiency glass fiber air cleaner were 48.3% and 51.4% of those obtained with the IFD cleaner, respectively. Data in Fig. 8 and Table 4 show that

![Fig. 8. The decay of particulate concentration with time.](Image)

**Table 4. CADR and CEE of each cleaner.**

| Air cleaner            | CADR (m³ h⁻¹) | Power consumption (W) | CEE (m³ h⁻¹ W⁻¹) |
|------------------------|---------------|-----------------------|------------------|
|                        | Average       | Minimum               | Maximum          | Average       | Minimum               | Maximum          | Average       |
| IFD                    | 867.9         | 850.2                 | 898.5            | 206.6         | 206.5                 | 206.7            | 4.2           |
| ESP                    | 700.9         | 620.5                 | 730.4            | 206.6         | 206.5                 | 206.7            | 3.4           |
| Sub-high efficiency    | 574.2         | 520.6                 | 642.4            | 208.0         | 206.0                 | 210.0            | 2.8           |
| High efficiency        | 763.7         | 722.5                 | 814.4            | 197.6         | 197.5                 | 197.8            | 3.8           |
| Medium efficiency      | 420.0         | 398.3                 | 442.5            | 194.8         | 194.6                 | 195.0            | 2.2           |
PTFE cleaner displayed the highest CADR, even when the concentration attenuation curves of ESP cleaner and PTFE cleaner were similar.

4 CONCLUSIONS

The results of the present investigation indicated that resistances of different filter units at a given wind speed followed the order: ESP’s < IFD’s < medium efficiency filter’s < sub-high efficiency filter’s < high efficiency filter’s. With the increase in wind speed, the purification efficiency of IFD and ESP decreased, whereas that of fiber filter generally increased. At the tested wind speed, the purification efficiency of different filter units followed the order: high efficiency PTFE filter’s > IFD’s > sub-high efficiency filter’s > ESP’s > medium efficiency filter’s. IFD displayed low resistance and high efficiency for removing PM$_{2.5}$, and the filter wind speed should be controlled below 1.0 m s$^{-1}$. At a wind speed of 1.0 m s$^{-1}$, filtration efficiencies of ESP and IFD units were similar to those of the sub-high-efficiency glass fiber filter. However, ESP and IFD resistances were significantly lower than that of sub-high-efficiency glass fiber air filter. According to our results, when wind speed is lower than 1.0 m s$^{-1}$, IFD filter should be preferred. The same is suggested when wind speed is between 1.0 and 1.3 m s$^{-1}$. Data indicated that the use of cleaners with different filter units reduced PM concentrations. Moreover, CADR and CEE of IFD were significantly higher than those of sub-high efficiency glass fiber cleaners.

The present study provides relevant data that will be useful in pandemic prevention and control in order to reduce the risk of infection in enclosed environments.

ADDITIONAL INFORMATION AND DECLARATIONS

Conflicts of Interest
The authors declare no conflict of interest.

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