Long-term performance of fibrous ventilation/air cleaner filter for particle removal

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Abstract. The performance of building ventilation systems and/or portable indoor air cleaners is greatly affected by the performance of the fibrous filters installed in them. The initial particle efficiency is generally used as a measure to evaluate the performance of the fibrous filters. However, with dust loading, the long-term performance of the filters might change, and the filters may become particle sources themselves and affect the performance of other systems. Previous studies on long-term performance were mainly based on theoretical analyses or laboratory experimental tests. This study investigates the long-term efficiency and pressure-drop change of various ventilation filters during real operation. No obvious efficiency decrease is observed, and it is inferred that the effect of dust loading on efficiency can be ignored. Secondary particle detachment is found to be possible in real applications, but its effect on the downstream concentration and indoor air can be made negligible with the use of an H-level filter. The pressure drop of the ventilation filter is also found to increase significantly.

1. Introduction
To evaluate the performance of fibrous filters, the initial particle efficiency is normally tested and reported. However, during the process of using, which is actually the dust loading on those filters, the practical filter efficiency may change[1, 2]. Generally, it was believed that dust-loading resulted in increased filtration efficiency for non-static filters[3, 4], but for the static filters, the charged polyolefin fibrous filters exhibited efficiency reductions[4]. For example, a study shows the long-term efficiency of electrically charged filters in a ventilation system reduced from 80%-100% to 35%-80% for particular particle diameter ranging from 0.219 µm to about 3 µm with time before the efficiency began to increase slightly again toward the end of the test[5]. Despite the changed efficiency, fibrous filters may emit particles as the dust loading, which turns to be a pollutant source. More dust emission from used bag-type fiberglass F7 filters than unused filters was discovered through sensory assessments[6]. And also the pressure drop may increase[5], leading to more energy consumption and noise. Therefore, it is important to determine whether the filter is still effective in keeping a low enough indoor concentration level and at the same time, energy saving and noiseless, therefore to guide the maintenance of these air cleaning systems or devices.

In summary, continuous monitoring of the long-term performance of filters, including the particle-removal efficiency and pressure drop, as well as comprehensive analyses of influencing factors are necessary. The monitoring of the long-term system efficiency and the cause analysis are also important. Hence, the objective of this study is to 1) investigate the practical development of ventilation filters’ particle-removal efficiency and pressure drop during operation; 2) determine the secondary particle detachment in real applications and its influence on the downstream concentration.
2. Methods
To simulate a ventilation filter challenged by ambient air, more realistically, a single-pass filter test duct was set up and installed across a window, for long-term operation, as shown in Fig. 1. An axial fan was used to draw the outdoor air through the tested filters.

![Figure 1. Schematic figure of single-pass filter test duct.](image)

The tested filter was uninstalled regularly to measure the amount of dust loading by using an electronic balance (D&T ES-E120B II) to measure the increase in the weight of the filter. The pressure drop was also recorded using a differential pressure instrument (TESTO 510). The test was terminated if the pressure drop increased to more than twice the initial value. A wireless PM2.5 concentration sensor (PMS 3003, PANTENG-W) was placed inside the test duct to monitor the downstream concentration continuously. Another sensor was placed outside the duct (i.e., atmosphere) to record the upstream concentration. In order to ensure the precision and consistency of the sensors, the two sensors were calibrated using a PM2.5 mass concentration tester DUSTTRAK (TSI, 8533) before use, by exposing them to the atmospheric PM2.5 concentrations for 70 h continuously. The data were recorded continuously and logged at intervals of one minute. The measurement range of the sensor was 0–500 μg/m³. The sensors were calibrated with DUSTTRAK (TSI, 8530), and the deviations of all sensors were < 5%. The filter mass efficiency defined by the upstream and downstream PM2.5 mass concentrations was used as the evaluation parameter in this study.

### Table 1. Test cases and filter information

| Test No. | Test Samples | Size | Operating Days (d) | Air Velocity (m/s) | Dust Loading (g/m²) | Initial Pressure Drop (Pa) | Pressure Drop Increase (Pa) |
|----------|--------------|------|--------------------|--------------------|--------------------|-----------------------------|-----------------------------|
| 1        | H13-Glassfiber | 300mm×195mm | 45                 | 1.22               | 11.90              | 105                         | 109                         |
| 2        | H13-PP        | m×30mm    | 65                 | 0.64               | 24.55              | 130                         | 251                         |
| 3        | F7-PP+PET     |          | 30                 | 1.50               | 22.00              | 73.5                        | 142                         |
| 4        | F7-PP         | 310mm×90mm | 23                 | 1.00               | 10.28              | 102                         | 127                         |
| 5        | G4-PP         | ×30mm     | 23                 | 1.87               | 13.53              | 66                          | 110                         |
| 6        | G4-Nonwoven   |          | 6                  | 2.67               | 4.57               | 67                          | 126                         |

Considering the currently commonly used filter units in ventilation systems in the market, filters of three efficiency levels (G level for pre-filtration, F level for medium efficiency, and H level for high efficiency filter) were selected for test. Different filtration materials were also considered. As PP (or plus PET) material and glass-fiber are the mostly applied material in the existing product, those two material was selected for each filtration level filter if possible. For G level filters, nonwoven material was also considered. Six batches of test was conducted through 2016 -2018. The tested filters, operation period, air velocity, dust loading and pressure drop increase at the end of each test was listed in Table 1.
3. Results

3.1. Long-term filter efficiency during life-time

Fig. 2 shows the daily average PM2.5 removal efficiency of each tested filter and upstream PM2.5 concentration (indicated by the triangle symbol in the figure) during operating time. The corresponding dust loading is also indicated on the top axis. For all the other filters except G4-nonwoven, the PM2.5 removal efficiency fluctuated during operating time, but no evident unidirectional change trend was indicated. The fluctuation extent of lower efficiency filters was wider than higher efficiency filters. For H13-Glassfiber and H13-PP filters, in more than 80% of the test period, the efficiency fluctuated in 70%-90% and 60%-82%, respectively. For F7-PP+PET and F7-PP filters, in more than 60% of the test period, the efficiency were 50%-97% and 24%-83% respectively, which fluctuated in a wider range than higher efficiency (H rating) filters. For G4-PP filter, in more than 60% of the test period, the efficiency is 25%-54%, which was much lower. For filter G4-Nonwoven, the removal efficiency dropped immediately to below 10% after only one day’s operating. Therefore, except G4-Nonwoven, there was no significant unidirectional efficiency change during the operating time despite the big fluctuation, even though their pressure drop had increased for almost 2 times compared to the initial value (as shown in Table 1). Besides, low efficiency occurred when upstream particle concentration was low, which means the fluctuation is related to upstream particle concentration, and this will be discussed in more details in later section.

3.2. Filter efficiency vs Dust loading

The efficiencies of H13 filters were stable until the end of the test. Except for upstream PM2.5 concentration < 50µg/m³, the efficiencies of F7-PP+PET, F7-PP and G4-PP were stable too, but dispersed in a wider range compared to H rating filters. The efficiency of G4-Nonwoven decreased rapidly after dust loading of 1g/m².

For H13 filters, there were only a few low efficiencies even when upstream air was very clean. Filters F7-PP+PET, F7-PP, G4-PP and G4-Nonwoven had obvious negative efficiency when upstream PM2.5 concentration was below 50µg/m³. For G4 filters, the negative efficiency started from the early stage of dust loading and for F7 filters, this phenomenon occurred a bit later, when the dust loading was about
1g/m². which means that the accumulation and detachment process of dust for fibrous filters happens as long as there is dust loading, but not only occurs until a certain dust accumulation amount.

In summary, the long-term efficiency of filters except G4-Nonwoven had no evident unidirectional change along with dust loading. On one hand, the accumulated dust affects the average fiber diameter and filter solidity, which act like additional short “fibers” having a diameter of average mass of the loading dust, so the efficiency could increase with dust loading. On the other hand, the effectiveness of the electrostatic charges on the fibrous filters reduced with dust loading. And detachment of particles also decrease the efficiency of filters. Those factors counteract with each other, resulting in relatively stable long-term efficiency for the same upstream particle concentration. However, efficiency indicated evident fluctuation under different upstream particle concentration, which will be discussed in next section.

3.3. Filter efficiency vs Upstream particle concentration

As shown in Fig.3, the relationship between the filter efficiency and the upstream particle concentration is plotted. The darkness of the colour represents different dust loading stage, which is divided into 5 stages, respectively 0-5g/m², 5-10g/m², 10-15g/m², 15-20g/m², 20-25g/m². Darker symbols represent higher concentration. The red line represents that the upstream PM2.5 concentration of 100µg/m³. It can be seen that for filters F7-PP+PET, F7-PP and G4-PP, when upstream PM2.5 concentration was < 100µg/m³, the efficiency increased evidently with the increase of upstream particle concentration. For filters H13-Glassfiber and H13-PP, when upstream PM2.5 concentration was about < 20 µg/m³, the efficiency increased with the increase of upstream particle concentration, and when upstream PM2.5 concentration > 20 µg/m³ and < 100µg/m³, the efficiency decreased slightly. At lower upstream concentration, the downstream concentration became more sensitive to the particle detachment, therefore leading to lower efficiency.

![Figure 3](image)

Figure 3. The relationship between PM2.5 removal concentration and upstream particle concentration of (a) H13-Glassfiber, (b) H13-PP, (c) F7-PP+PET, (d) F7-PP, (e) G4-PP and (f) G4-Nowove

To evaluate the influence of particle detachment on the overall filter performance, the occurrence of negative efficiency and corresponding downstream concentration was summarized. It can be seen from Fig.4 that the occurrence of upstream PM2.5 concentration < 50µg/m³ accounted for 32%-51% of the test time period, means that there is a significant percentage of time that the ambient concentration is low enough to make the particle detachment taking effect even in Tianjin, which even though is a
seriously “polluted” city in China. For H13 filters, the period that negative efficiency occurred only accounted for <1% of the test period, during which period the highest downstream PM2.5 concentration was 5µg/m³. For F7 filters, the negative efficiency occurred for 26%-30% of the time, during which period the highest downstream PM2.5 concentration was 60µg/m³. For G4 filters, the period that negative efficiency occurred accounted for 29%-34%, during which period the highest downstream PM2.5 concentration was 91µg/m³. Compared to high efficiency (H13) filters, the negative efficiency happens for a much longer time for medium and low efficiency (F7 and G4) filters. At the same time, the downstream PM2.5 concentration caused by negative efficiency was also higher with lower efficiency filters. Therefore, for F and G class filters, when the upstream air was clean, the particle detachment from the used filters will happen very possibly (the negative efficiency occurred for 52%-67% of the time when the upstream PM2.5 concentration was < 50 µg/m³), leading to negative efficiency and filters themselves became particle resources.

However, in air cleaners and ventilation systems, there are filter sets including G, F and H class filters installed, with the filtration of H-class filters, the impact for indoor air caused by secondary particle detachment was negligible.

![Figure 4. Negative efficiency caused by secondary particle detachment](image)

3.4. Long-term filter pressure drop

In addition to efficiency, pressure drop is another important measure of filter performance, which influences the energy consumption, noise, and so on. In this work, in the real challenge with ambient air, the dust loading during operation was obtained for the tested filter as shown in Fig.5(a). A linear correlation was observed for all the tested G, F, and H-rated filters. Although the ambient dust concentration varies from time to time, with the concentration level experienced in this study, which can also be considered the normal ambient condition in real applications, this linear relationship can be used to predict the operation time and dust-loading amount. Among the six filters, the two H-13 filters exhibited the lowest dust-loading rates.

The pressure drops at different dust loadings were also measured and plotted as shown in Fig.5(b), from the accelerated test in duct with controlled airflow. The rate of pressure-drop increase of the filter with dust loading was mainly related to the filter material properties and operating airflow. A linear correlation was observed for all the tested filters in the current study, which agreed well with the results in the literature, although the slope of the linear relationship could be different depending on the different filtration media. This linear relationship can be used to predict the pressure-drop increase. Overall, filters of higher filtration rating had larger pressure drops for the same dust loading. They also exhibited higher increase rates.
Figure 5. (a) Tested dust loading of each filter during operation and (b) pressure drop with dust loading.

The pressure drops during operating are presented in Fig.5(a) and (b). It is observed that, for the tested filters, after 60 days of continuous operation, the pressure drop increased to more than double the initial value, which could result in reduced air flow, increased energy consumption, and noise.

As mentioned above, the pressure drop of the filters could increase significantly even though their efficiencies were relatively stable. Therefore, the life spans of the filters could be determined from the pressure-drop increase, instead of from the efficiency change. For real applications, the manufacturers could conduct pre-tests on their filters to obtain the relationship between the pressure drop and dust loading, thereby helping users to estimate the pressure-drop increase according to the ambient air quality (dust-loading status), and thus determine the maintenance schedule for the filters.

4. Conclusions

This study investigated the long-term performance and influencing factors of fibrous ventilation/air-cleaner filters and analysed the secondary particle detachment as well as the system efficiency of the air cleaners and ventilation systems. The long-term efficiencies of the H and F-rated filters were found to fluctuate within a certain range, and no obvious decrease was observed during the lifetime. The relationship between the efficiency and dust loading could be ignored.

Even though negative efficiencies were observed for the F-class and G-class filters when the upstream air was clean, secondary particle detachment had little influence on the performance of the H-class filters. The impact on indoor air, caused by secondary particle detachment, was negligible. The pressure drop of the ventilation filter could increase significantly even though the efficiency was relatively stable. A method was proposed to obtain the relationship between the pressure drop and dust loading, which could help users to estimate the pressure-drop increase according to operation time, which in turn, would help determine whether the filters should be replaced or not.

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