Study on Performance of Cabin Air filters Under Different Work Conditions

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Abstract: The in-vehicle air quality has increasingly attracted the attention of people. Hence, air filter performance under actual work conditions demonstrates remarkable significance. It is verified that the electrostatic adsorption can dramatically enhance the fractional efficiency of small-particle pollutants without increasing the pressure loss; as regard a lack of fractional efficiency test on the filter during the whole life cycle in current standards, the paper studied the tendency of filter’s fractional efficiency variation in the whole life cycle and discovered that fractional efficiency of small particles decreased first after increase due to the shielding of electrostatic charge; the tests on different air speed and area of filtered paper were carried out, showing that increasing the area of filtered paper can significantly lower the pressure loss and increase the filtration efficiency, which is of vital significance to provide the reference for further improving the performance of cabin air filter.

1. Introduction
As the “mask” of vehicle, air filter can block droplets, suspended particles and even harmful gas and bacteria and the like, which is able to reduce the entry of harmful substances into the vehicle to a great extent. The in-vehicle air quality has drawn increasingly more attention, which is of vital importance to further research on the air filter. At present, electrostatic electret filter materials have been commonly used by air filter, including polypropylene(PP), polyethylene(PE), spunbonded filter material and polytetrafluoroethylene(PTFE), etc. The most commonly used filter material is PP, characterized by low density, sound tensile property, good abrasion resistance, excellent chemical resistance, mildew resistance and barely free from moisture absorption and extremely low moisture regain, etc.[1].

However, with the duration of cabin air filter utilization and change of environmental factors, the electrostatic effect will gradually be weakened with a decline of fractional efficiency. The main reasons comprise the following aspects such as the compensation of electric charge in the atmosphere, the conduction or drift of its own electric charge as well as neutralization of the electric charge carried by filtered aerosols and chemical reaction of filter materials, which are shown in relevant researches of scholars. Jiang[1] in Tianjin University studied the impact of different aerosols, air flow rate and temperature and humidity on fractional efficiency. Tang[2] in South China University of Technology improved the dust-holding performance of electret filter material by using charged particles, proposed a composite electret filter material and superfine fiber layer to obtain an idea of new filter materials. Walsh
and Stenhouse[3] studied the properties of electrostatic charge on the fibre after dust-holding. Experiment showed that the filter with static electricity had a larger dust-holding volume than that of traditional filter. In the existing standards such as GB/T 32085.1-2015[4], QC/T 998-2015[5] and CAC-PV18-019:2020[6], the fractional efficiency test on air filter was only an initial filtration efficiency, with an insufficient understanding in the fractional efficiency variation of air filter during the whole life cycle, especially affected by weakened electrostatic effect. The environmental temperature of air filter also had an impact on its performance. In the existing standards such as QC/T 998-2015[5], the technical requirements of temperature resistance were only about observing if filter material after temperature treatment is separated or unglued from the outer frame, as well as the dimensional deviation of the air filter’s length, width and height, etc. without conducting performance tests on the air filter after temperature treatment concerning its initial pressure loss, fractional efficiency and dust-holding capacity, etc. Considering different air speed used by air filter and different size of air filter produced by manufacturers, whether the filter performance is different remains to be studied. Relevant studies on aforementioned issues are of vital importance to provide the reference for improving the performance of air filter.

2. Electrostatic Electret Material

During the process of traditional mechanical filtration, large particles should be intercepted through interceptive, gravity and inertia effect, and smaller particles should be intercepted through diffusing effect, while relatively large particles are the most difficult to be intercepted. One solution is to make the mesh hole as small as possible, but the pressure loss will increase sharply. The disadvantage of applying it to the air filter lies in an increase of filter power consumption, and a consumption of oil and electricity. The second solution is to apply electrostatic adsorption same as mask to the air filter. Electrostatic electret material is the material that makes PP melt-blown cloth charged with static electricity to maintain such a state for a long time. If particles pass through the hole, it will be adsorbed by charged static electricity, thus enhancing greatly the fractional efficiency without improving the pressure loss. Electrostatic adsorption plays a crucial role in the filtration of 0.1 μm~0.4 μm particles that are not easy to be intercepted in mechanical filtration.

To further verify the ability of electrostatic electret material to enhance particle fractional efficiency, three materials are selected for fractional efficiency test and pressure loss test, with the materials as respectively no-static electret, low static electret and high static electret.

![Figure 1 Fractional efficiency of three materials](image_url)

Figure 1 showed the curve of fractional efficiency of three materials. No-static material displayed the lowest fractional efficiency, with the particles less than 1 μm filtered at a fast growth rate. It can be seen from the curve that fractional efficiency of particles in full size was improved by electret, with the most remarkable effect manifested by particles less than 1 μm.

Low static and high static material curves displayed a downward trend in the fractional efficiency of
0.2 μm–0.3 μm particles. The reason was that particles of smaller size were easier to be adsorbed by the filter mesh under the impact of electrostatic adsorption. That is to say, 0.2 μm particles were easier to be adsorbed than 0.3 μm particles, with the electrostatic adsorption effect dampened for particles larger than 0.3 μm. The total effect of electrostatic adsorption and mechanical filtration first resulted in a decline of fractional efficiency before an increase, with the lowest efficiency shown by the size of 0.3 μm.

Figure 2 Pressure loss of three materials
Figure 2 displayed the pressure loss of three materials under different air speed. The three curves almost coincided, suggesting that the pressure loss of air filter won’t be enhanced by electrostatic electret.

3. Superimposed Pollutant Test
As the pressure loss of current standard and threshold of fractional efficiency target the brand-new air filter, namely initial pressure loss and initial fractional efficiency, there is an insufficient understanding of the air filter’s pressure loss and fractional efficiency during the whole life cycle. To probe into the changes accompanied by pollutant accumulation, air filter equipped by high static electret material is used as the test object. Pressure loss and fractional efficiency are measured once, twice and thrice......until the fractional efficiency variation of particles in full size levels off.

3.1. Superimposed Pollutant Test Under High Air Speed
The air speed is 300 m³/h selected as per GB/T 32085.1-2015, with the concentration of 15 mg/m³.

Figure 3 Superimposed pollutant test under the air speed of 300m³/h
Figure 3 displayed the test result of air filter under the air speed of 300 m$^3$/h and concentration of 15 mg/m$^3$. Fractional efficiency variation of particles in various sizes tended to be gentle after 10 tests, hence there was no need in sustaining the test. Pressure loss of air filter increased with the number of tests increasing, which meant an exponential increase during the dust-holding process. Due to an increasingly higher fractional efficiency, the dust intercepted by the filter mesh was higher than that of last time, making the blockage of mesh hole and increase of pressure loss more serious. The curve was drawn by selecting the fractional efficiency of three typical particle sizes, respectively 0.3 μm, 2.5 μm and 10 μm. As shown in the figure, the efficiency of 10 μm particles remained at 100% without any changes. All 10 μm particles can be mechanically intercepted because the maximum mesh hole was smaller than 10 μm. Fractional efficiency of 2.5 μm particles has been on the rise, reaching 100.00% in the 5th test and levelling at 100% afterwards. Fractional efficiency of 0.3 μm particles demonstrated a slightly downward trend in the 1st to 2nd test, gradually went up afterwards and kept stable in the 9th test.

An analysis was made on the reason for efficiency decline of 0.3 μm particles. While measuring initial efficiency, the electrostatic charge of the filter mesh was the strongest, and the particles can directly contact with the filter mesh, when electrostatic impact played a crucial role in the fractional efficiency of 0.3 μm particles; with the number of tests increasing, particles were gradually accumulated on the filter mesh, with the particle layer gradually shielding the electrostatic charge. Electrostatic adsorption effect was on the decline with the number of tests increasing during the dust-holding process; mechanical filtration was gradually on the rise with the dust-holding process playing a major role. The total effect of electrostatic adsorption and mechanical filtration gradually declined in the 1st to 2nd tests, gradually rose after the 3rd test and ultimately reached a stable level.

2.5 μm particles will also be generally affected by electrostatic adsorption and mechanical filtration, with the former having a relatively small impact, and there was no case of lowered efficiency caused by weakened electrostatic adsorption.

3.2. Superimposed Pollutant Test Under Low Air Speed
During the practical utilization process, the pollutant density of atmospheric particles was usually below 100 μg/m$^3$. Restricted by the dust concentration stability of test equipment, superimposed test registered a concentration of 15 mg/m$^3$. High concentration test caused the dust rapidly accumulated on the filter mesh, and mechanical interception effect was fast on the rise, covering up the reduction process of electrostatic adsorption effect. The test air speed was lowered to be 30 m$^3$/h, the minimum speed for test equipment, with the concentration remaining at 30 m$^3$/h in order to further probe into the fractional efficiency variation of air filter under an operation state of low dust volume and the impact of electrostatic adsorption on fractional efficiency. Lowering air speed can reduce the dust quality in the test process each time. Under the air speed of 30 m$^3$/h, the dust volume of each test was only 10% of the test with the air speed of 300 m$^3$/h. Therefore, the operation state of air filter was simulated under normal large air speed and low concentration.

Figure 4 showed the test results of cabin air filter at the flow rate of 30 m$^3$/h and the concentration of 15 mg/m$^3$. The fractional efficiency at different particle sizes changed little after 40 times of stack, and thus further tests were unnecessary. The pressure loss, however, showed a straight upward trend. As the dust generation at the flow rate of 30 m$^3$/h through 40 times of stack was equal to that at the flow rate of 300 m$^3$/h through 4 times of stack, the dust holding process can be further broken down. The fractional efficiency curves of three typical particle sizes, i.e. 0.3 μm, 2.5 μm and 10 μm, were drawn. It shows that the fractional efficiency at the particle size of 10 μm kept at 100.00%, while that at particle size of 2.5 μm changes little in the first 15 times of stack, and then began to decline to the lowest at the 22nd time of stack, followed by increasing to the 29th time of stack and keeping unchanged after that. The fractional efficiency at the particle size of 0.3 μm changed little in the first 17 times of stack, and then began to decline to the lowest at the 22nd time of stack, followed by increasing to the 35th time of stack and keeping unchanged after that.
The reasons for the change of fractional efficiency at the particle sizes of 2.5 μm and 0.3 μm are as follows. When measuring the initial efficiency, the electrostatic interaction in the filter screen was the strongest, and particles can touch the filter screen, and therefore the electrostatic interaction determined the fractional efficiency of small particles. With the stack of test times, particles accumulated on the filter screen, and the electrostatic interaction was gradually shielded by particles, making the electrostatic adsorption weaker with the dust holding progressing. The mechanical filtration, however, gradually dominated with the dust holding progressing. The combined effect of electrostatic adsorption and mechanical filtration gradually decreased in the early tests but increased in the middle tests and finally kept almost unchanged.

It can also be seen that the fractional efficiency of 2.5 μm particles had a smaller reduction than that of 0.3 μm particles. Although under the combined action of electrostatic adsorption and mechanical filtration, the electrostatic adsorption had less influence. Despite of the dropping process, the mechanical filtration effect on 2.5 μm particles was stronger than that on 0.3 μm particles, and the fractional efficiency recovered faster.

Compared with the test results at the flow rate of 300 m³/h and the concentration of 15 mg/m³, it can be seen that the fractional efficiency of 0.3 μm and 2.5 μm particles at the flow rate of 300 m³/h did not decrease significantly, or even kept unchanged; the fractional efficiency, however, decreased considerably at the flow rate of 30 m³/h. The reason is that the dust generation in each test at the flow rate of 300 m³/h is equivalent to 10 times that under 30 m³/h. In the process of the second and third tests, the fractional efficiency had actually fallen for a certain period of time, which, however, was covered by the overall data in the case of a large total dust generation, resulting in an insignificant drop in fractional efficiency, indicating that the higher dust generation in the laboratory does not reflect the true fractional efficiency changes of the Cabin air filter throughout the life. Under a low concentration of pollutants in the real atmosphere, the electrostatic electret material will experience a decrease of fractional efficiency with the attenuation of the electrostatic charge and the shielding of dust.

4. Tests on Air Flow Rate and Filter Paper Area
The performance of Cabin air filter depends on the flow rate and the filter size. The two independent variables reflect essentially the air volume per unit area of filter paper.

4.1. Effect of Air Flow Rate
The pressure loss of filter element will exert considerable influence on the fuel consumption of automobile, air volume and noise of air conditioner. The above tests showed that the fractional efficiency of particles at the flow rate of 30 m³/h was higher than that at 300 m³/h. In order to further investigate the fractional efficiency of Cabin air filter and then provide more rational recommendation for the user,
the initial pressure loss and fractional efficiency of Cabin air filter were tested at the flow rate of 30 m³/h, 50 m³/h, 100 m³/h, 150 m³/h, 200 m³/h, 250 m³/h, 300 m³/h, 350 m³/h, 400 m³/h, 450 m³/h, 500 m³/h, 550 m³/h, 600 m³/h, 650 m³/h, and 700 m³/h, respectively.

Figure 5 Effect of air flow rate

Figure 5 showed the initial pressure loss and fractional efficiency of electret material with high electrostatic density at various air flow rates. The initial pressure loss ramped with the flow rate increasing. The fractional efficiency curves of three typical particle sizes, i.e. 0.3 μm, 2.5 μm and 10 μm, were drawn. The fractional efficiency of 10 μm particle still kept at 100%, while that of 0.3 μm particle and 2.5 μm particle decreased with flow rate increasing. 0.3 μm particles had the largest drop in fractional efficiency. The air flow rate exerted greater influence on the smaller particles, thus making the fractional efficiency of smaller particles drop faster with flow rate increasing. The air flow rate inside the automobile cannot be too high to adversely affect the fractional efficiency of particles.

4.2. Effect of Filter Paper Area

Due to the different sizes of cabin air filter and the various effective filtration areas of filter, it is necessary to test the effect of filter paper area on the initial pressure loss and fractional efficiency, thus providing suggestions and data references for related car companies and accessories manufacturers. The pressure drop of the melt-blown material is extremely large when testing a small area of filter paper, which makes test difficult to complete, and therefore the filter paper without melt-blown material is used for the test. The tests were carried out at the air flow rate of 100 m³/h, and the filter paper was cut into squares with side lengths of 10 cm, 12 cm, 14 cm, 16 cm, 18 cm, 20 cm, 22 cm, and 24 cm, respectively. The initial pressure loss and fractional efficiency were tested.

Figure 6 showed the initial pressure loss and fractional efficiency at various filter paper areas. The pressure reduced exponentially with filter paper area increasing. The fractional efficiency curves of three typical particle sizes, i.e. 0.3 μm, 2.5 μm and 10 μm, were drawn. The fractional efficiency of 10 μm particle still kept at 100%, while that of 0.3 μm particle and 2.5 μm particle rose with filter paper area increasing. 0.3 μm particles had the largest rise in fractional efficiency. The filter paper area exerted greater influence on the smaller particles. The filter paper area actually affected the air volume per unit area of filter paper. The larger the area of the filter paper, the less air volume per unit area, that is, the smaller the air flow rate, the higher the fractional efficiency; and vice versa, which agrees with the conclusion drawn from the effect of air flow rate. The effective methods for reducing the pressure loss and improving the fractional efficiency include increasing the filter size and the filter paper area.
5. Conclusion

The lowest fractional efficiency of electrostatic electret material is observed at the particle size of 0.3 \(\mu\)m. The combined action of electrostatic adsorption and mechanical filtration makes the fractional efficiency reduces at first and then rises with particle size increasing.

The fractional efficiency of Cabin air filter throughout the service life reduces at first and then rises for small particles but rises all the way for large particles. The electrostatic effect is shielded by the accumulated dust, resulting in a drop in the fractional efficiency of small particles, and after that the leading role of mechanical filtration increases the fractional efficiency of small particles. Large particles are less affected by electrostatic effect, and thus the mechanical filtration takes the leading role all the way.

The fractional efficiency of all sizes of particles reduces with the air flow rate increasing, and the air flow rate exerts greater influence on small particles. The fractional efficiency rises with filter paper area increasing, and the filter paper area exerts greater influence on small particles. The pressure reduces exponentially with filter paper area increasing.

References

[1] Jiang MX. Research on the filtration performance of cabin air filter in different thermal and moist environment[D]. Tianjin University, 2009.
[2] Tang M. Study of filtration characteristics of electret filter media against PM2.5[D]. South China University of Technology, 2016.
[3] Walsh D C, Stenhouse J I T. (1997)The effect of particle size, charge, and composition on the loading characteristics of an electrically active fibrous filter material. Journal of Aerosol Science, 28(2):307-321.
[4] GB/T 32085.1-2015. Automobiles-Cabin air filter-Part 1: Test for particulate filtration [S]. China’s National Standard, 2015.
[5] QC/T 998-2015. The technical specification of automotive cabin air filter [S]. China’s National Standard, 2015.
[6] CAC-PV18-019:2020. CATARC mark certification implementation rules- filtration grade of automobile cabin air filter [S]. CATARC-cert.