SELECTION OF AIR FILTERS FOR RESIDENTIAL FRESH AIR IN CHINA BASED ON THE CONTROL OF $PM_{2.5}$

by

Xin ZHANG**, Yuesheng FAN, Jiaxin ZHANG, Huan WANG, Shuxuan WEI, and Wanqing YU

School of Building Services Science and Engineering,
Xi'an University of Architecture and Technology, Xi'an, Shaanxi, China

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Efficient filtration provides a healthy and comfortable residential environment. Based on the performance testing for filter materials commonly used in China, the mass balance equation of controlling the indoor $PM_{2.5}$ concentration was set up, and the filter selection criterion was discussed. An optimal section was suggested by taking into account the economic cost, filter price, and indoor air quality.

Key words: *fresh air, residential building, $PM_{2.5}$, combined performance*

Introduction

Air quality problems have become increasingly prominent now, which are harmful to people's physical and mental health. Some studies showed that $PM_{2.5}$ could cause some diseases related to the human lung, and cardiovascular [1-3], and the polluting particulate matters are widely appeared [4, 5], therefore a good indoor environment is extremely longed for. With the outbreak of 2019-nCoV epidemic in the world [6], fresh air systems have become one of the necessary ways to protect public health, the selection and replacement of filters have been becoming remarkably important [7].

However, people are now paying more attention to the filtration efficiency [8], air filtration systems [9], different materials [10-12], and the matching energy of consumption problems [13]. Although some results had been achieved, research on selecting air filters in fresh air was not enough (GB/T 18883-2002). Systematic replacement of air filters has become an urgent issue to ensure normal work and life now. But the economic cost of replacement and working costs are two factors that restrict the selection. Most of the air-conditioning systems were adopted to combine two-stage or three-stage filters. The coarse filter and Sub-HePa filter, or the coarse filter and medium-efficiency filter and Sub-HePa filter were generally used [14]. People rarely consider the issue on filter replacement. However, there is a long opening period and replacement frequency in moist air, the selection and matching filter materials were in chaotic condition [7], the cost of replacement was almost fewer. So, the research of the existing combination filters in residential refreshing air was even more rarely.

This paper is to solve those problems based on the performance testing of the commonly filter materials in China. The residential fresh air was taken as an example to calculate the filter efficiency.

* Corresponding author, e-mail: 2601084634@qq.com

Methods

The simplified model diagram of fresh air with two-stage or three-stage combined filters on the existing market was illustrated in fig. 1.

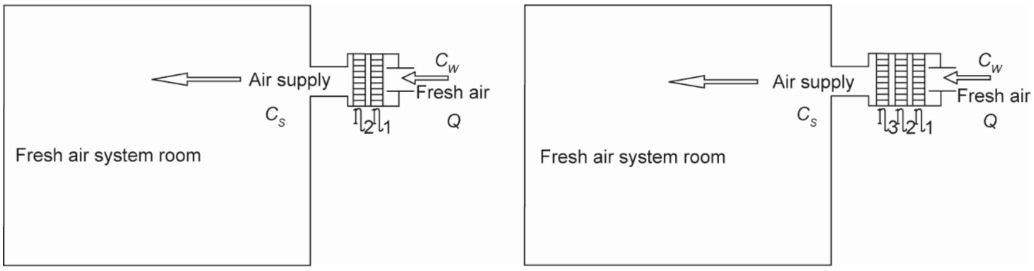

Figure 1. A simplified model diagram of the fresh air

The mass balance equation of indoor $PM_{2.5}$ concentration control in fresh air is [7]:

$$QC_W[1-(1-\eta_1)(1-\eta_2)\times(1-\eta_3)] = QC_S \tag{1}$$

where Q [m^3h^{-1}] is the air supply volume, η_1 – the weighting efficiency of coarse filters, η_2 – the weighting efficiency of medium efficiency filters, η_3 – the weighting efficiency of high efficiency filters, C_W [μgm^{-3}] – the mass concentration of outdoor $PM_{2.5}$, C_S [μgm^{-3}] – the mass concentration of $PM_{2.5}$ in fresh air.

For filtration efficiency under using a two-stage combined with fresh air, the calculation formula is [7]:

$$(1-\eta_1)(1-\eta_2) = 1-\frac{C_S}{C_W} \tag{2}$$

For filtration efficiency under using a three-stage combined with fresh air, the calculation formula becomes [7]:

$$(1-\eta_1)(1-\eta_2)(1-\eta_3) = 1-\frac{C_S}{C_W} \tag{3}$$

Six kinds of different grades in filters (GB/T 14295-2008) were selected for the experimental testing. The specific features were shown in tab. 1.

Table 1. Experimental filter materials

Number	Symbol	Materials	Rmb (size)	Number	Symbol	Materials	Rmb (size)
1	G3	Polyester （PET）	28	2	G4	Polyester （PET）	35
3	F5	Non-woven fabric	65	4	F6	Non-woven fabric	70
5	H10	Polyester	86	6	H11	Polyester	100

Note: The unit prices are the average of the survey

The experimental system of filter performances was established as shown in fig. 2. Outdoor atmospheric dust was directly used as the dust source, which was more accordance with using conditions [15].

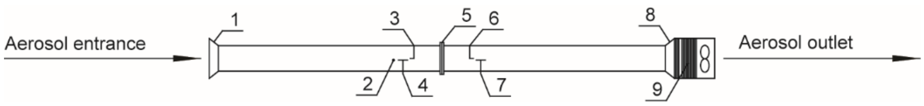

Figure 2. Experimental system; *1 – entrance, 2 – wind velocity measuring point, 3 – upstream static pressure probe, 4 – upstream acquisition point, 5 – filter materials, 6 – downstream static pressure probe, 7 – downstream acquisition point, 8 – gradual expansion, and 9 – soft connection*

The GRIMM1.109 Portable Aerosol Spectrometer was used to measure the mass concentration of $PM_{2.5}$ before and after the filters. Measuring range was 0.1-100.000 μg/m^3. The reproducibility was 5%. The HD2114P.0 Portable Micromanometer was used to test filter resistance. The measuring accuracy is ± (2% reading + 0.1 m/s). The pressure range is ±0.4% F.S. HD37AB1347 Indoor Air Quality Monitor was used to measure the velocity. The measuring accuracy range is ±3%. The test bench was built according to the specifications (GB50019-2015). To arrange measuring points complied with the rules of the specification. One set of data was gathered every five minutes, and the test results were averaged.

Experimental results

The filtration performances of different filter materials at different filtration velocities were shown in tab. 2. The relationship of peak filtration efficiency of $PM_{2.5}$ between filtration velocity and resistance was shown in tab. 3.

Table 2. Filtration performances of different filter materials

Grade	Symbol	Filtration velocity [ms^{-1}]	$PM_{2.5}$ The range of filtration efficiency [%]	The range of resistances [Pa]
Coarse filters	G3	1.0~2.6	1.6~22.3	19~91
	G4		1.1~24.2	35~128
Medium filters	F5	0.1~1.0	16.3~25.8	4~49
	F6		27.7~40.7	29~211
Sub-HePa filters	H10	0.02~0.25	63.8~82.7	62~191
	H11		80.1~97	114~365

Table 3. Relationship between peak filtration efficiency and filtration velocity

Grade	Symbol	Features		
		Peak filtration efficiency [%]	Filtration velocity [ms^{-1}]	Resistances [Pa]
Coarse filters	G3	22.3	2	64.5
	G4	24.2	2	90
Medium filters	F5	25.8	0.8	39
	F6	40.7	0.1	29.5
Sub-HePa filters	H10	82.7	0.02	63.5
	H11	97	0.02	116

The filtration velocity of G3~G4 filter materials that they were reaching the peak of filtration efficiency was at the edge of the filtration range of engineering application (GB/T 14295-2008). Therefore, when this grade in filter materials was used, it was recommended the filtration velocity of 2.0 m/s. The peak of filtration efficiency of F5 filter material was greater than that of the engineering application (GB50019-2015). It was recommended that when the filter material was applied. The filtration efficiency was a maximum when the filtration velocity was 0.8 m/s under the resistance was needed. The conclusion was consistent with the reference [16]. The filtration efficiency of F6 and H10~H11 filter materials was decreased with the increased of the filtration velocity. Because of that with the filtration velocity increased, the diffusion effect was also decreased. The particle sizes were smaller. The degree of attenuation of the diffusion effect was greater. Therefore, when high efficiency filters were selected, the filtration efficiency should be controlled in a smaller range of filtration velocity.

Discuss and analysis

Outdoor $PM_{2.5}$ concentration

According to research [7] and some related comprehensive causes, the outdoor $PM_{2.5}$ concentration of non-guaranteed 10 days of 2017 was selected as the main research object of Xi'an. The outdoor $PM_{2.5}$ concentration was 260 μg/m^3. The indoor $PM_{2.5}$ concentration was 35 μg/m^3 (GB/T 14295-2008). The overall efficiency of the combination filters in fresh air was 86.54%. There are many types of filters which are combining two-stage or three-stage filters in the market. The overall filtration efficiency between 80% and 97% was selected as an alternative of combined filters in this paper, compared with different combined filters under the ample economic signals [17].

The $PM_{2.5}$ controls of two-stage combined filters

When combining two-stage filters were taken into using, the filter of G3 or G4 was as an initial effect, end efficiency by calculating need to be higher than 82.2%. According to the testing data and to combine in existing markets, the combined filters were G3 + H10, G3 + H11, G4 + H10, and G4 + H11, respectively, as shown in fig. 3.

The results showed the two-stage combined filters of the four combinations could achieve the needed effects. They were G4 + H11 > G3 + H11 > G4 + H10 > G3 + H10, respectively. Filtration efficiency between G3 + H10 and G4 + H10 combined with filters was rather low, only about 1% higher than the efficiency value which was satisfied the condition. Therefore, G3 + H11 and G4 + H11 could be used as the choice for two-stage combined filters. They also could meet the hygiene needs of indoor under the non-guaranteed 10 days. The figure also showed the combined effect of G4 + H11 had not much different from that of G3 + H11. They could reach 97.7%.

The $PM_{2.5}$ controls of three-stage combined filters

Same as above, G3 or G4 filter was as an initial effect. The F5 or F6 filter was as a medium effect. The end efficiency by calculating need to be higher than 87.1%. According to the testing data and to combine in existing markets, the combined filters were G3 + F5 + H11, G3 + F6 + H11, G4 + F5 + H11, G4 + F6 + H11, respectively, as shown in fig. 4.

The results showed the three-stage combined filters of the four combinations could also achieve the needed effects. They were G4 + F6 + H11 > G3 + F6 + H11 > G4 + F5 + + H11 > G3 + F5 + H11, respectively. They also could meet the hygiene needs of indoor un

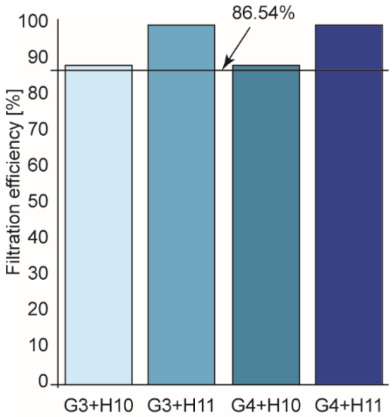

Figure 3. The filtration efficiency of two-stage combined filters

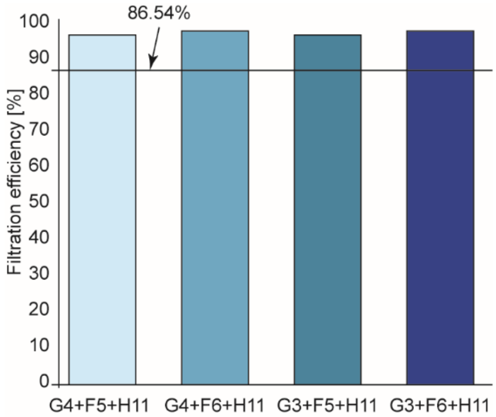

Figure 4. The filtration efficiency of three-stage combined filters

der the non-guaranteed 10 days. Filtration efficiency of four combined filters was about 11%~12% higher than the efficiency value which was given by calculated. The filtration efficiency of G4 + F6 + H11 was the best, which could reach 98.65%. It was 0.9% higher than that of filtration efficiency which was given by two-stage combined filters. So the three-stage combined filters were widely used in China.

Evaluation index of fresh air

The service life of the filters was calculated [18]:

$$T = \frac{P}{C_W\ Q\ t\ \eta} \tag{4}$$

where T [h] is the using time of filters, P [mg] – the dust holding capacity of filter materials, (coarse filters were 100000 mg, medium efficiency filters were 300000 mg, high efficiency filters were 500000 mg), C_W [mgm^{-3}] – the $PM_{2.5}$ concentration of filter inlet, Q [m^{3}s^{-1}] – the air volume of the filters, t [s] – the working time of filters, and η [%] – filtration efficiency of the filters.

The working energy consumption of the filters was calculated [19]:

$$E = \frac{q\ \mathrm{d}p\ t}{\eta\, 1000} \tag{5}$$

where E [kWh per year] is the energy consumption, dp [Pa] – the resistance, t [hour/year] – the working time, q [m^{3}s^{-1}] – the air volume, and η – the working efficiency of the fans, 70%.

It assumed to distribute outdoor airborne particulate matters did not change. Filtration efficiency of filters did not change any more. The dust accumulation amount before was 0. The daily time of fresh air was 24 hours, concentrating $PM_{2.5}$ before the filter was 0.26 mg/m^3. The filtration velocity of the residential fresh air was 4.0 m/s. The round pipe was DN150 mm. The working efficiency of the fan was 70%. According to the maximum of dust holding capacity of each grade in filters, the cycle time was one year, by formula, maximum working time and working energy consumption were shown in tab. 4.

Table 4. The prices of replacement of one year under combining filter

Types	Grade	Resistances [Pa]	Energy consumption [kWh per year]	Price of working [1.2 Rmb]	Price of replacement [Rmb]	Price of total [Rmb]
Two-stage combined filters	G3 + H11	180.5	159.6	192	2964	3156
	G4 + H11	206	182.1	219	3222	3441
Three-stage combined filters	G3 + F5 + H11	219.5	194.1	233	3027	3260
	G3 + F6 + H11	210	185.7	223	3137	3360
	G4 + F5 + H11	245	216.6	260	3284	3544
	G4 + F6 + H11	235.5	208.2	250	3391	3641

According to the relevant cost features of tab. 1, the prices of replacement of one year were taken into considering. The price sequence was:

$$G4 + F6 + H11 > G4 + F5 + H11 > G4 + H11 > G3 + F6 + H11 > G3 + F5 + H11 > G3 + H11$$

Price of G4 + F6 + H11 was the highest. It was 427 Rmb higher than that of the lowest of G3 + H11, so it could see the two-stage combined filters were more saving prices.

The prices of working cost of one year were taken into considering. The price sequence was:

$$G4 + F5 + H11 > G4 + F6 + H11 > G3 + F5 + H11 > G3 + F6 + H11 > G4 + H11 > G3 + H11$$

The overall running cost of three-stage combined filters was higher than that of the two-stage combined filters. Price of G4 + F5 + H11 was 68 Rmb higher than that of the lowest of G3 + H11, so the two-stage combined filters were more economical too.

From the total cost of all, the price sequence became:

$$G4+F6+H11 > G4 + F5 + H11 > G4 + H11 > G3 + F6 + H11 > G3 + F5 + H11 > G3 + H11$$

The total cost showed the same trend as the costs of replacement. The G3 + H11 of two-stage combined filters and the G3 + F5 + H11 of three-stage combined filters were the lowest in the same grade. The highest of G4 + F6 + H11 was 485 Rmb higher than that of the lowest of G3 + H11. All of the economic signals were taken into considering in using. The two-stage combined filters would have a big advantage in using and working.

Conclusions

The paper was based on the outdoor $PM_{2.5}$ concentration of non-guaranteed 10 days of Xi'an in 2017 to select the filter combination of the economic signals in residential fresh air. Some conclusions were followed. Between two-stage combined filters and three-stage combined filters were all had good filtration efficiency in using on the market in China. The price of three-stage combined fresh air filters was much higher than that of two-stage. From the total cost of all, the price sequence was G4 + F6 + H11 > G4 + F5 + H11 > G4 + H11 > > G3 + F6 + H11 > G3 + F5 + H11 > G3 + H11. The highest of G4 + F6 + H11 was 485 Rmb higher than that of the lowest of G3 + H11. The two-stage combined filters were more economical of all. Economic signals were one of the important factors which were to be considered in selecting filter schemes for practical engineering applications. It was more economical to employ the two-stage combined filters under the conditions of indoor sanitary. Nanofiber filters or shaped fiber filters are promising [20-23].

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