Dust Loading Performance of the PTFE HEPA Media and its Comparison with the Glass Fibre HEPA Media

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ABSTRACT

HEPA filter media have been used in many fields to maintain super clean air in an indoor environment. Due to their much lower initial resistance, PTFE HEPA media has increasingly attracted the interest of researchers. Solid KCl particles loading experiments were conducted to examine the dust loading performance of PTFE media and compare it with that of glass fiber media. The experimental results provided insights into the surface deposition mode of particles captured by PTFE media. A new resistance growth coefficient, k_2, was defined to reflect both the instantaneous growth rate of the dynamic pressure drop and the dust loading stage of HEPA media. In addition, a method of evaluating the energy consumption of HEPA media was developed by calculating the average pressure drop during laboratory dust loading experiments. Based on the results, PTFE overall is more energy efficient than glass fiber except in circumstances of heavy loading or infrequent maintenance.

Keywords: Surface filtration; Resistance growth coefficient; Average dynamic pressure drop.

INTRODUCTION

High Efficiency Particulate Air (HEPA) filters have been used in many fields to maintain a super clean indoor air environment for various purpose, such as clean rooms for producing semiconductor and LCD panel, nuclear power plants, bio-pharmacy and food processing and production facilities.

Characterized by two parameters, filtration efficiency and pressure drop, HEPA media essentially determine the filtration performance of HEPA filters. Traditional glass fiber has been commonly used as HEPA media. Recently, the polytetrafluoroethylene (PTFE) HEPA media, which are usually applied to industry in dedusting for the removal of large particles in exhaust gas, have emerged as an alternative and gradually gained certain percentage of the market share because of their much lower initial pressure drop as compared to that of glass fiber at the same efficiency level.

During the service life of HEPA media, their filtration efficiency and pressure drop increase simultaneously as dust is being loaded into the media. However, while the efficiency may be considered as unchanged due to its very high initial efficiency at > 99.95%, special attention should

be paid to the rise of pressure drop which directly leads to an increase in energy consumption of a ventilation system and determines the lifespan of a HEPA filter.

Studies have been conducted on both filtration theory and modeling of dynamic pressure drop for various HEPA media. A widely accepted filtration theory divides a dust loading procedure into three stages (Brown, 1993): The first stage refers to depth filtration during which particles deposit inside a medium and build "dendritic dust fiber". For the second stage or transition stage, with the clogging of the medium, particles will gradually not be able to deposit into the medium but only on its surface. At the third stage of filtration or surface filtration, "dust cake" will be formed by the collected particles on medium surface.

There are a number of models to describe the pressure drop of HEPA filters and HEPA media loaded with solid particles from the perspective of depth filtration, surface filtration and both (Carman, 1956; Happel, 1959; Bergman and Taylor *et al.*, 1978; Rudnick and First, 1978; Novick and Monson *et al.*, 1992; Thomas and Penicot *et al.*, 2001). Among them, Novick's semi-empirical model is the most popular one which assumes the total pressure drop as the sum of the initial pressure drop and the pressure drop caused by loaded dust as follows,

$$\Delta P = \Delta P_0 + K_2 \frac{VM}{A} \qquad (1)$$

where ΔP is the dynamic pressure drop of a HEPA medium,

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ΔP_0 the initial pressure drop of the HEPA medium, K_2 an empirical specific pressure drop coefficient, V the filtration face velocity, M the collected particle mass and A the filtration surface area. In addition, the effects of various factors on the dynamic pressure drop of HEPA media, such as face velocity, temperature, humidity, concentration and size distribution of test aerosol have also been investigated (Gupta and Novick *et al.*, 1993; Cheng and Tsai, 1998; Joubert and Laborde *et al.*, 2011; Wang and Lin *et al.*, 2016).

However, there has been very limited research available in open literatures that focused on the dust loading performances of PTFE HEPA media. Barhate and Ramakrishna (2007) experimentally studied the effect of the PTFE media production process on its filtration performance. Park (2012) investigated the performance of the PTFE media when they are used in bag filters. No information on the performances of the PTFE HEPA media in terms of filtration efficiencies and pressure drop has been available and the total energy consumption level during their entire service life as compared to the glass fiber HEPA media remained unclear.

Therefore, this paper aims to experimentally study the filtration performance of the PTFE HEPA media when loaded with solid particles and to compare their dust loading performance with that of glass fiber HEPA media, so as to obtain a better understanding of the energy consumption performances of the two kinds of HEPA media.

EXPRIMENTAL SETUP AND EXPERIMENTS DESIGN

All experiments in the current study are conducted in an indoor filter media experimental setup which is schematically shown in Fig. 1. As seen, it consists of an aerosol generation section, a filter medium test section and an air flow rate control section.

Ambient air is firstly compressed by an air compressor, dried through a refrigerant dryer and filtered by a high efficiency filter. Then, the compressed clean air is separated into two streams, one passing through an aerosol generation bypass pipe, the other a dry air bypass pipe under the control of electronical valves. Polydisperse solid particles used in dust loading experiments come from the KCl solution and are generated through a nebulizer in the aerosol generator before being dried by the dried air from the dry air bypass pipe. The concentration and size distribution of the aerosol are controlled by the inlet pressures of two air streams and the concentration of KCl solution.

The filter medium under test is fixed on a pneumatic holder with an effective area of 100 cm². Static pressure sample holes and aerosol sample pipes are set in the upstream and downstream of the holder. The pressure drop of the filter medium is measured and recorded by an electronic differential manometer and the concentration and size distribution of the aerosol used in experiments can be captured by an aerosol spectrometer.

In the flow rate control section, a nozzle flow meter measures the flow rate of the air passing through the filter medium on a real time basis, so that a variable frequency fan can dynamically adjust the flow rate to make it around its set-point value. Excessive air that does not flow through the filter medium will be exhausted but may be utilized as upstream sample aerosol to avoid the fluctuation of air flow rate passing through the filter media.

An electronic balance is used to weigh the filter media before and after a dust loading experiment. A scanning
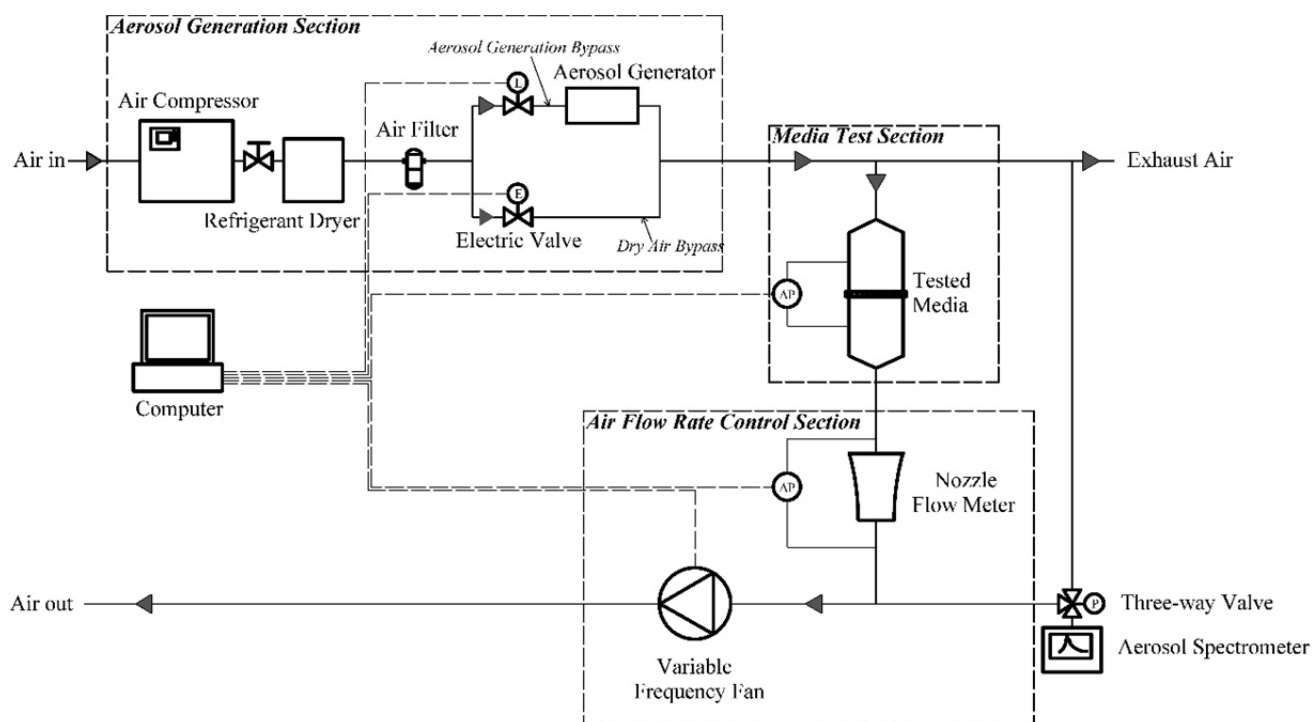

Fig. 1. Schematic diagram of the experimental setup.

electron microscope (SEM) is also used to obtain the inner micro view of the loaded filter media.

Before a dust loading experiment for each of the tested HEPA media, its mass and initial pressure drop are firstly measured. Then the aerosol generation bypass is put into operation under the setting parameters and the HEPA medium loaded at experimental aerosol of a constant concentration and a constant flow rate, during which the pressure drop through the loaded medium is measured and recorded every 3 minutes. When the pressure drop reaches 900 Pa, an experiment is ended, and the mass of HEPA medium was weighed again by using the electronic balance and the micrographs captured with SEM after experiments.

Four kinds of HEPA media, two glass fiber media from Manufacturer I and two PTFE media from Manufacturer II as detailed in Table 1, were tested in this study. For H14 PTFE medium, its experiments on dust loading pattern under different conditions were carried out at three KCl aerosol concentrations and three face velocities to investigate the effect of varied concentrations and face velocities on the loading process of PTFE media. On the other hand, for the comparison experiments of dust loading performances between glass fiber media and PTFE media, two PTFE and two glass fiber media were loaded with KCl solid particles under the same operation conditions.

The arrestance efficiency of the four kinds of HEPA media is very close to 100%. Therefore approximately all the upstream aerosol particles can be captured by the media, and hence a "dust loading time-pressure drop" curve can be converted to a "dust loading mass-pressure drop" curve for subsequent analysis and discussion, at a constant upstream aerosol concentration.

RESULTS AND DISCUSSIONS

Aerosol Used in Experiments, Four Kinds of HEPA Media and their Initial Pressure Drops

The size distribution of ambient aerosol that had been filtrated by a F7 filter medium was monitored to ensure that the experiment aerosol size distribution is similar to that in a real life operation environment. Fig. 2 shows the size distribution of filtrated ambient aerosol in both counts ratio scatters and cumulative ratio curve, which suggests that over 95% of the particles penetrated F7 media distribute in the size range of less than 0.5 μm. The concentration of KCl solution and the pressure of compressed clean air used in the aerosol generator were adjusted to simulate the above aerosol size distribution. The size distribution of the generated aerosol with a 20 g L^{-1} concentration and a 80 kPa pressure can be seen in Fig. 2, which agrees well with the

Table 1. Characteristics of tested filter media.

Filter medium	Material	Class[a]	Manufacturer	Thickness (mm)	Basic weight (g m^{-2})	Solidity
A	Glass fiber	H14	I	0.43	74.85	0.070
B	PTFE	H14	II	0.39	91.37	/[b]
C	Glass fiber	U15	I	0.43	77.92	0.072
D	PTFE	U15	II	0.39	91.42	/[b]

[a] It's classified based on EN 1822-1:2009 High efficiency air filters (EPA, HEPA and ULPA) -Part1: Classification, performance testing, marking.
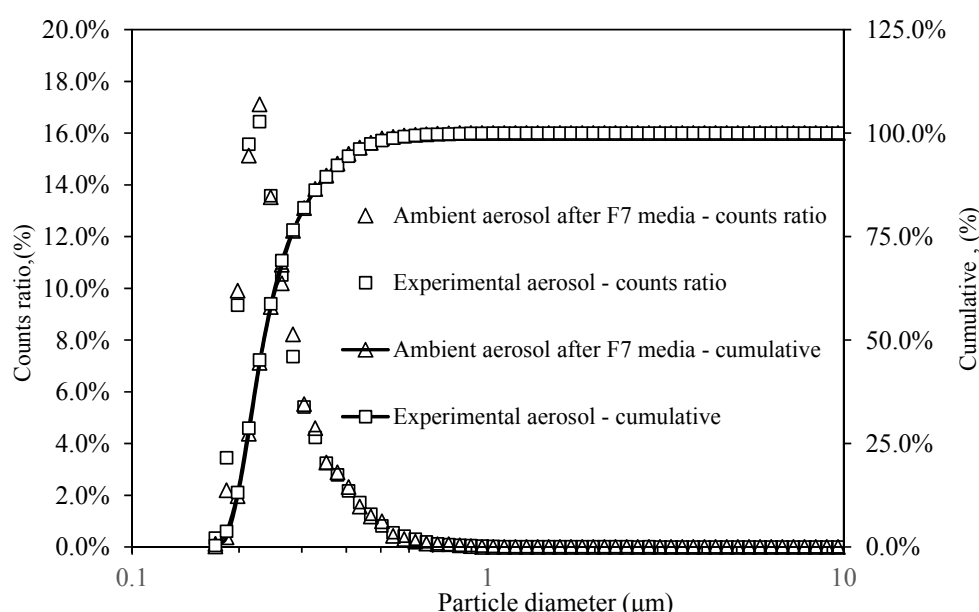[b] The solidity calculation method is not applicable to PTFE media due to its sandwich structure.

Fig. 2. Size distribution of the filtrated ambient aerosol and aerosol generated in experiments.

size distribution of aerosol filtrated by F7 media. This indicates that this experimental aerosol can accurately reflect the dust loading performance difference between glass fiber HEPA media and PTFE HEPA media in a real life operation environment.

Fig. 3 shows the external appearances and SEM images of both H14 glass fiber medium and H14 PTFE medium. A glass fiber HEPA filter medium is usually white with a fluffy windward side as shown in Fig. 3(a) and a compacted leeward side. However, a PTFE medium has a three-layer composite structure with two layers of base material and one layer of sandwiched PTFE membrane. The windward and leeward base material are the same and designed with grids to strengthen the intensity of filter media as seen in Fig. 3(b).

Figs. 3(c) and 3(d) are the SEM photos of H14 glass fiber medium and PTFE membrane inside the H14 PTFE medium, respectively. By comparing the microstructure of these two media, it can be seen that for the PTFE membrane, its fiber diameter is much smaller, with therefore a much denser structure as compared to those of glass fiber HEPA media. This leads to a much lower initial pressure drop for a PTFE medium at the same filtration efficiency level.

Table 1 lists the detailed parameters and the EN 1822

class of the four kinds of filter media used in the experiments. U15 glass fiber medium has a higher basic weight and solidity than those of H14 glass fiber medium at a higher filtration efficiency. However, the basic weights of the PTFE medium at different classes are approximately the same, because the quality of effective PTFE membrane accounts for a small percentage of the mass of PTFE media.

The initial pressure drop curves of the four HEPA media at unloaded condition were measured and plotted in Fig. 4. As seen, the initial pressure drops of all media are linearly related to the face velocity, following Darcy's law. The ascendancy in initial pressure drop of PEFE HEPA media is obvious because the initial resistance of H14 glass fiber medium is about twice as much as that of H14 PTFE medium, and is even greater than that of U15 PTFE medium. For the glass fiber media, the initial pressure drop for U15 is greater than that of H14 by over 40%, because for a glass fiber filter medium, high filtration efficiency is achieved by increasing its solidity or the thickness, which definitely leads to an increased resistance.

Dust Loading Performance of PTFE Media at Different Loading Face Velocities and Aerosol Concentrations
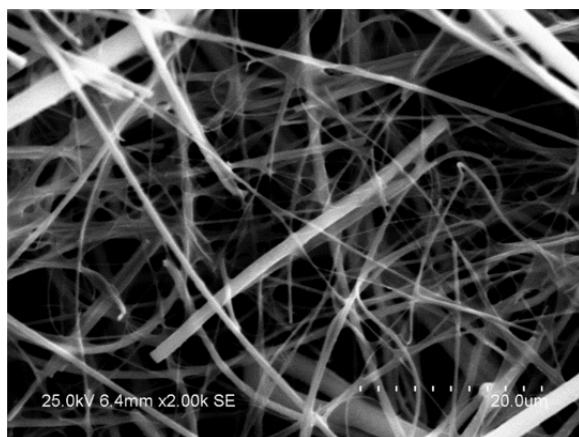
Dust loading experiments for H14 PTFE media at different loading conditions were carried out to reveal the effect of
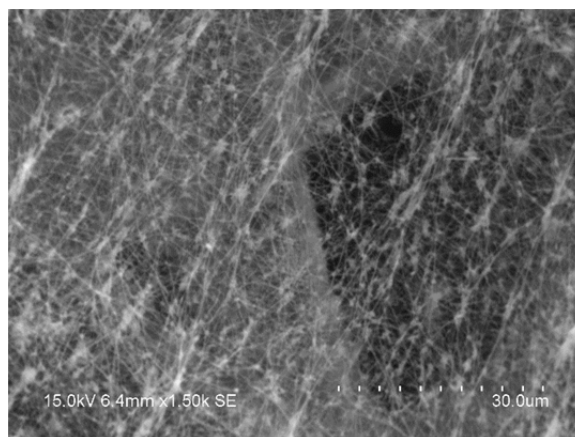

(a) Surface photo-Glass fiber HEPA media

(b) Surface photo-PTFE HEPA media

(c) SEM image-Glass fiber HEPA media

(d) SEM image-PTFE HEPA media

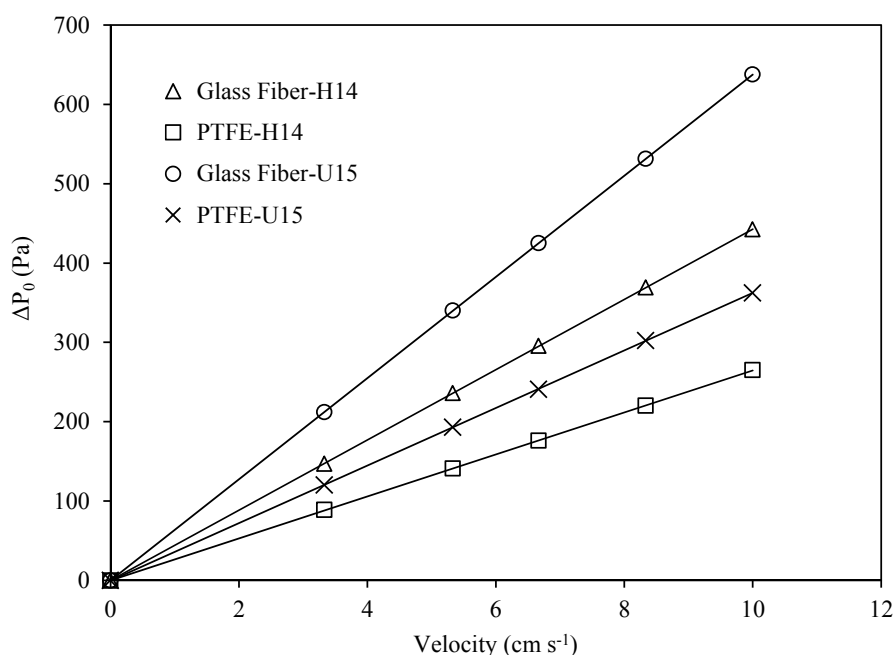**Fig. 3.** Surface photos and SEM images of tested filter media.

Fig. 4. Initial pressure drops of glass fiber/PTFE filter media.

face velocity and aerosol concentration on the loading process of PTFE HEPA media. The experimental results would also contribute to determining experimental parameters in the follow-up experiments where the dust loading performances between PTFE and glass fiber are compared.

During experiments, the face velocities were varied from 2.0 cm s^{-1} to 5.3 cm s^{-1}. The lower limit of velocity range was chosen because the media face velocity of plate HEPA filters installed in a Fan Filter Unit (FFU) and applied to a clean room is about 2.0 cm s^{-1}. But the upper limit is a rated value for the filter media test rigs in the laboratories in Mainland China. In order to eliminate the difference in the pressure drop caused by different face velocities, ($\Delta P - \Delta P_0$)/V against the mass of dust loaded per square meter was plotted in Fig. 5. As seen, the three curves at the three face velocities agreed well, indicating that different face velocities have no clear effect on the deposit mode of KCl particles in the PTFE HEPA media.

Fig. 6 shows the pressure drop increase for H14 PTFE medium when loaded with aerosol of different concentrations. KCl solution concentration and generation air pressure were adjusted to achieve three aerosol concentrations, among them, 13.8 μg L^{-1} was derived by 20 g L^{-1} concentration and 80 kPa pressure. It can be seen from the three overlapping curves that aerosol concentration will not influence the dust loading process of PTFE media either. The slight upward trend for 18.2 μg L^{-1} curve as compared to the other curves may be explained by the smaller average size of particles when increasing aerosol concentration by boosting pressure.

These two findings are consistent with the dust loading characteristics of glass fiber HEPA media studied by Thomas *et al.* (2001). Since both face velocities and aerosol concentrations have no effects on the dust loading performance for both glass fiber and PTFE HEPA media, 5.3 cm s^{-1} face velocity and 13.8 μg L^{-1} were used in the follow-up comparison experiments.

Dust Loading Performance Comparison between the PTFE HEPA Media and the Glass Fiber HEPA Media

Dust loading experiments for H14 and U15 glass fiber media, H14 and U15 PTFE media were conducted at 5.3 cm s^{-1} face velocity and 13.8 μg L^{-1} aerosol concentration. In Fig. 7, the SEM images for loaded H14 glass fiber medium and H14 PTFE medium are compared. Fig. 8 illustrates the "pressure drop-loaded dust mass/area" curves for the four HEPA media.

Earlier studies indicate that in the preliminary dust loading stage for a glass fiber HEPA medium, part of particles may deposit on the surface of medium while other can easily penetrate the surface fiber layer into the depth fiber layer due to the abundant space. However, as the growing dendritic dust fibers gradually fill the space among fibers, it becomes harder for particles to arrive at the depth of media. Then depth filtration turns into surface filtration and dense dust cake can be formed. As shown in the SEM photos for the loaded glass fiber medium in Figs. 7(a), 7(c), and 7(e), after a long time deposition, the dust particles captured by glass fiber media formed dendritic dust fibers inside the medium and a dust cake on the medium surface.

By contrast, the dust loading performance for the PTFE medium is very different from that for glass fiber medium. In Fig. 7(b), no dust layer can be found on the surface of PTFE medium. However, with an enlarged view shown in Fig. 7(d), it is seen that the upper coarse fibers of base material contributed little to filtrating particles because of its much larger diameter and lower solidity, so that most of particles deposited on the surface of PTFE membrane. Fig. 7(f) shows a profile SEM photo of loaded PTFE medium whose windward base material was removed. As seen, the PTFE membrane is extremely thin and effective
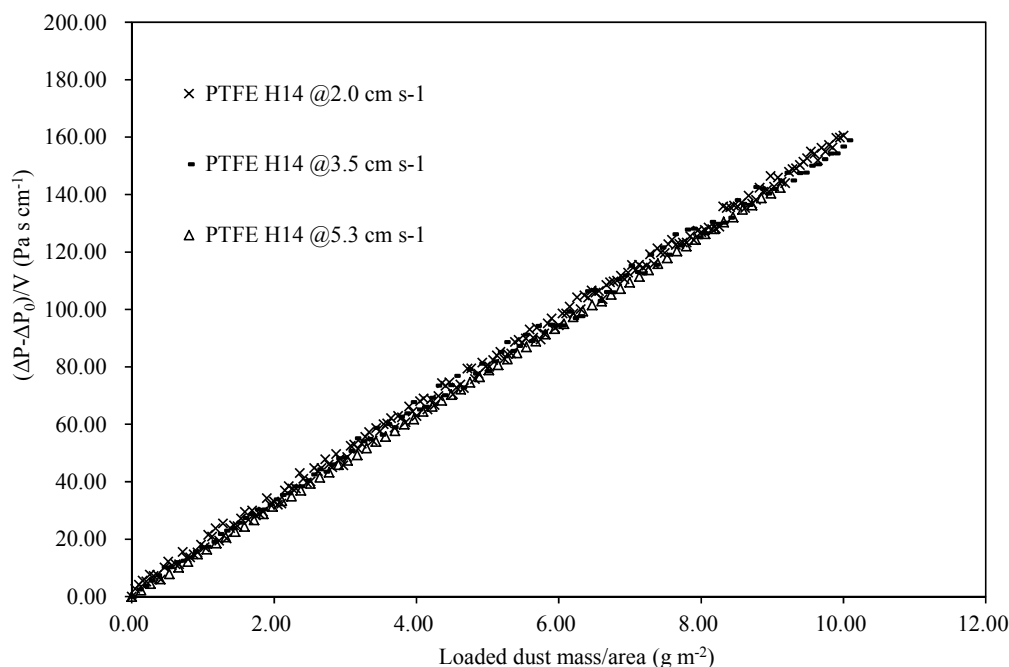
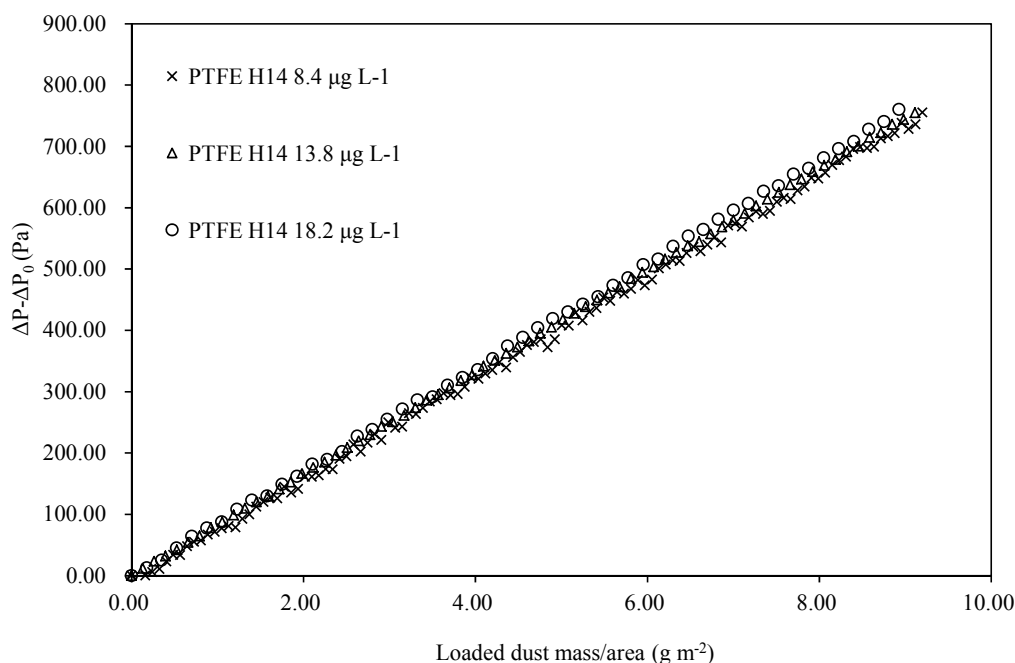**Fig. 5.** Effect of face velocity to dust loading process of PTFE HEPA media.

Fig. 6. Effect of upstream aerosol concentration to dust loading process of PTFE HEPA media.

so that particles deposit directly on the membrane rather than into it.

From the resistance curves for the glass fiber media HEPA in Fig. 8, it can be seen that the pressure drop of glass fiber media increases with the amount of particles deposited on it and an upward increasing trend is slow initially, but gradually accelerates at a constant speed, which is also consistent with the results in earlier studies. For the U15 glass fiber medium, the first stage of nonlinear resistance growth is much shorter due to its higher basic weight and solidity.

However, the pressure drop curves for the PTFE media are straight lines, which is different from those of glass fiber HEPA media. This suggests that the resistance of PTFE media increases uniformly and the filtration mode remains unchanged during the whole process of dust loading. From the above micro observation results for loaded H14 PTFE medium, it can be said that only one filtration mode exists in dust loading process for PTFE media, i.e., surface filtration.
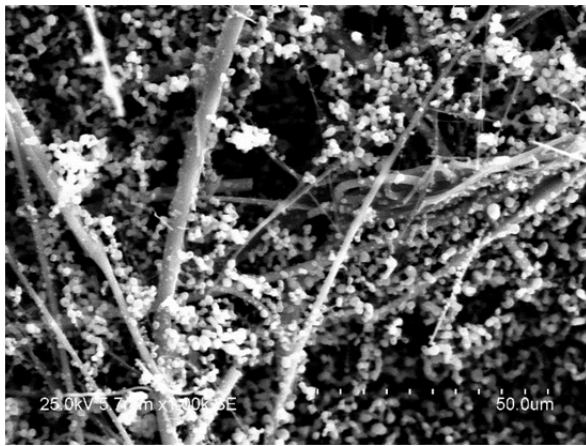
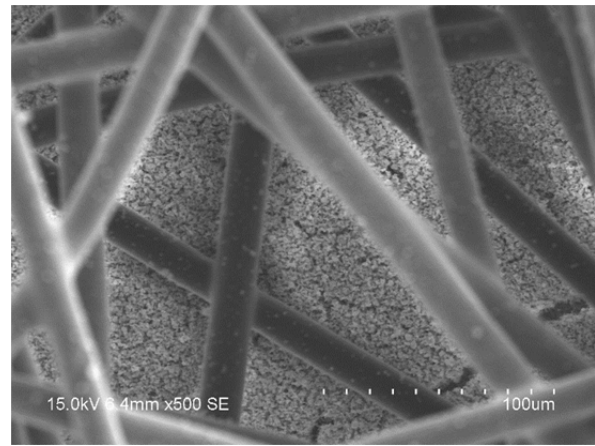It is worth noting from Fig. 8 that the resistance growth
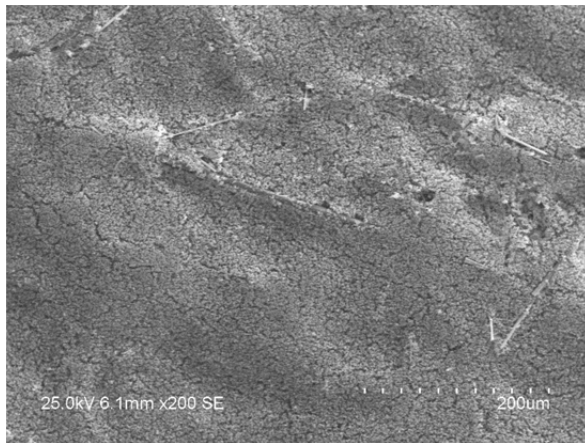
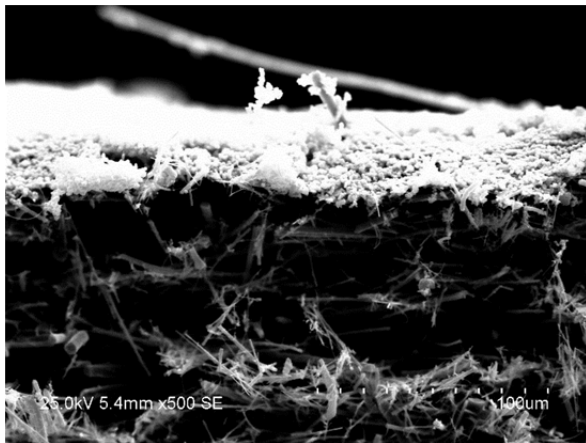(a) Surface of loaded glass fiber media
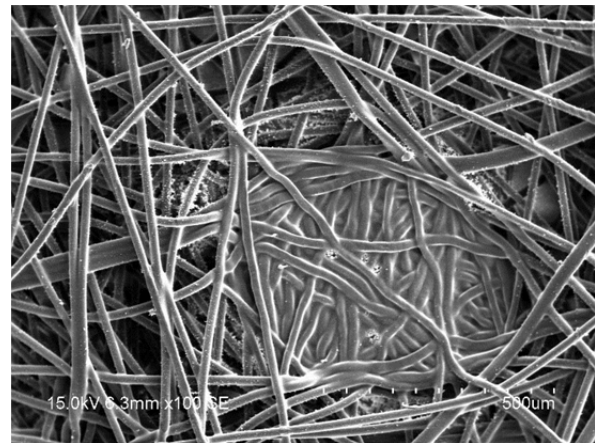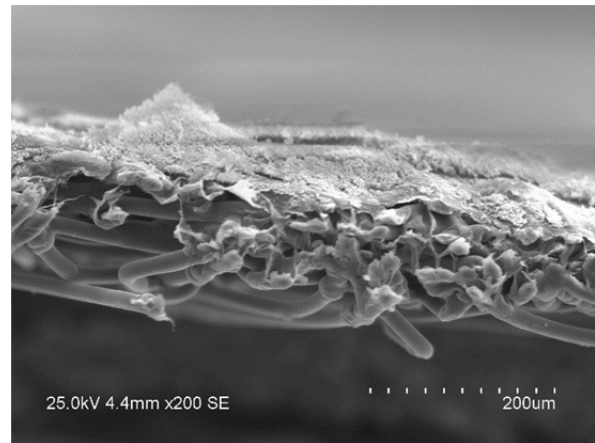
(b) Surface of loaded PTFE media

(c) Depth of loaded glass fiber media

(d) Depth of loaded PTFE media

(e) Profile of loaded glass fiber media

(f) Profile of loaded PTFE media

Fig. 7. SEM images of H14 glass fiber/PTFE filter media after loading with KCl solid particles.

rates are not identical at the stage of surface filtration for the glass fiber and PTFE HEPA media at the same class, such as H14 glass fiber medium and H14 PTFE medium, even though the two media were loaded with the KCl aerosol of the same concentration and size distribution. A conjecture is therefore made that different surface situations in the glass fiber media and PTFE media lead to this difference: The surface of glass fiber media is potted, and the dust cake formed has a greater surface area and consequently

a lower resistance growth rate, while the surface of PTFE media is flat, resulting in a smaller surface area of dust cake formed, leading to a faster growth of resistance.

Eq. (1) mentioned in Introduction is Novick's semi-empirical model for the dynamic resistance of a HEPA filter media. In Fig. 9, the dust loading curve of glass fiber HEPA media is plotted with $\Delta P/V$ as y-axis and M/A as x-axis. Then the intersection point between the curve and the y-axis is the specific resistance, $\Delta P_0/V$ for the glass fiber HEPA media
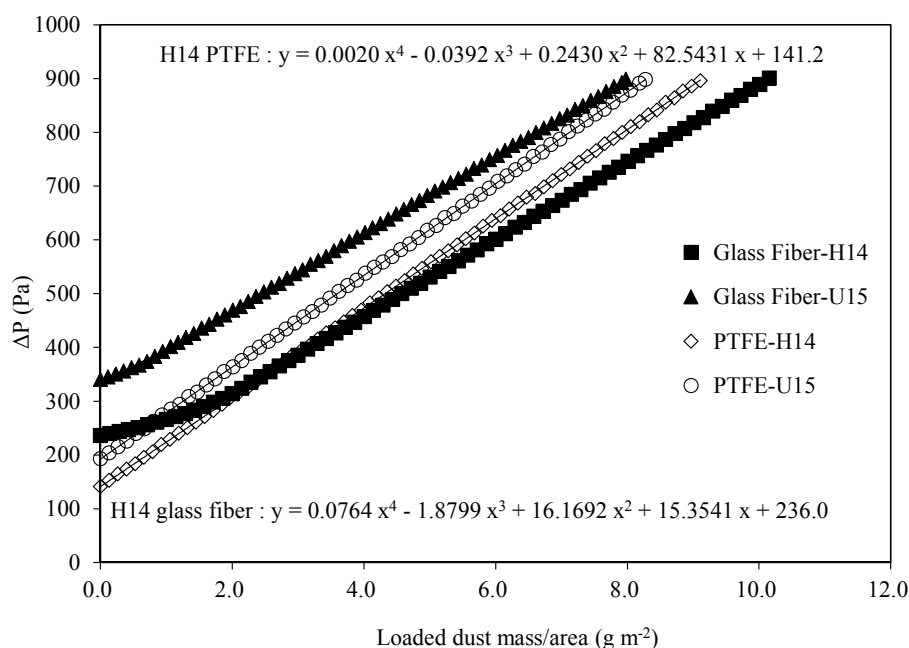
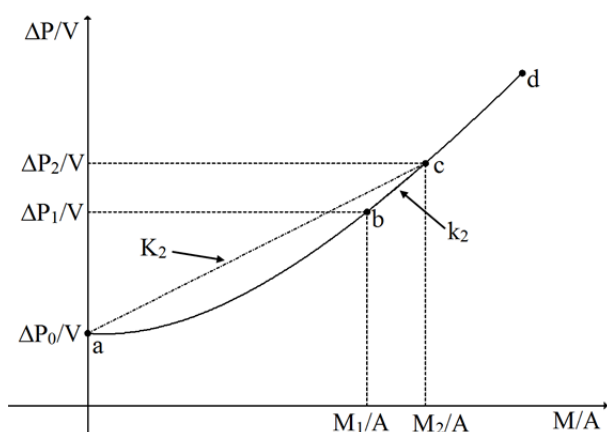**Fig. 8.** Pressure drop curves of four HEPA media during dust loading.

Fig. 9. Definition diagram of dynamic pressure drop coefficient k_2.

with no dust loaded. The curve a–b–c–d in Fig. 9 represents the change of the resistance of the media during the whole dust-loading process. Hence the slope of the line connecting a–c $(\Delta P_2 - \Delta P_0)A/(M_2 V)$ is K_2 in Eq. (1), reflecting the average increase rate of resistance prior to point c.

In order to more clearly reflect the instantaneous growth rate of pressure drop during the whole process of dust loading, k_2 which represents the slope at any point on the curve a–b–c–d is defined as $(\partial \Delta P/V)/(\partial M/V)$. For any dust loading interval b–c, the slope of the line connecting points b–c may be used to approximately represent k_2 in this interval, as follows,

$$k_2 = \frac{A(\Delta P_2 - \Delta P_1)}{V(M_2 - M_1)} \qquad (2)$$

Fig. 10 shows the curves for both K_2 and k_2 of H14 glass

fiber medium and H14 PTFE medium, respectively. From Fig. 10, it is seen that for H14 PTFE medium, K_2 and k_2 agree well and remain basically unchanged during the whole process, which corresponds to the surface filtration of PTFE media. However, for H14 glass fiber medium, k_2 firstly increases with an increase of dust capacity and then remains virtually unchanged after reaching a certain point which corresponds to a dust loading stages as analyzed earlier, while K_2 keeps increasing all the time. In comparison, k_2 can better reflect the change of filtration modes during a dust loading process. Besides, k_2 can also be applied to modeling the dynamic pressure drop at different filtration stages.

Average Pressure Drop Comparison between PTFE HEPA Media and Glass Fiber HEPA Media during a Dust Loading Period

So far there has not been international or regional standards to evaluate the dust loading performances of HEPA media. Manufacturers and end-users generally take loaded dust mass in practice as a key index to describe the durability of a HEPA filter. However, dust loading capacity only reflects the mass of the dust contained in a HEPA filter when reaches the final pressure drop under experimental conditions without taking the energy consumption performance into consideration. Therefore, it is worth studying the energy consumption level of HEPA filters according to the dynamic pressure drop during dust loading, which should be included as a part of performance comparison between glass fiber HEPA filters and PTFE HEPA filters.

The flow resistance of HEPA filters generally includes both HEPA media resistance and structure resistance. The structural resistance accounts for only small percentage of the total resistance and remains unchanged during its entire service life. Hence, energy consumption comparison between glass fiber HEPA filters and PTFE HEPA filters based on
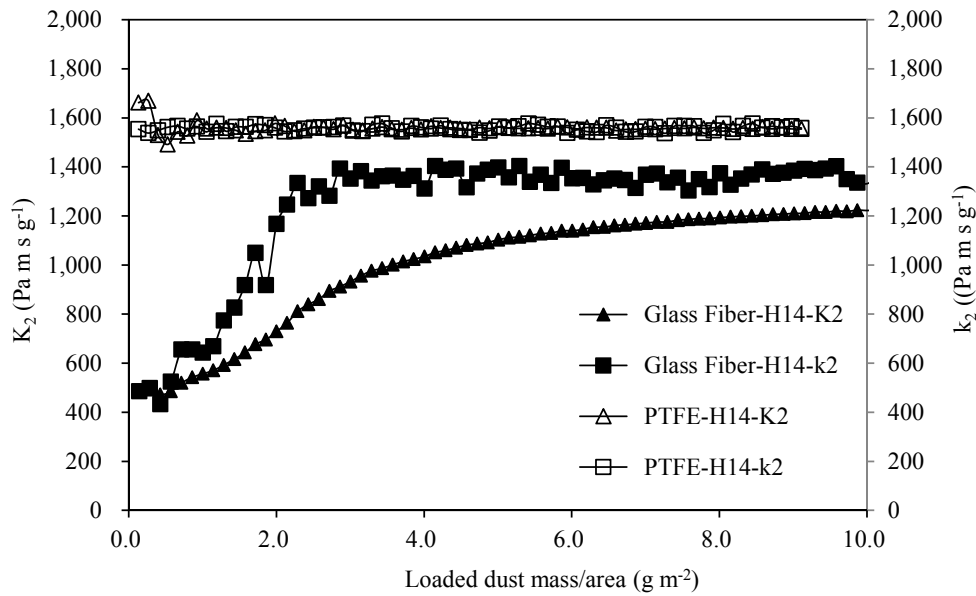
Fig. 10. Comparison between K_2 and k_2 of loading H14 HEPA media.

the dynamic resistance of HEPA media is acceptable.

According to the different operation modes of HEPA filters in practice, the maintenance of HEPA filters can be divided into two categories. The first mode is to replace HEPA filters according to time, such as annually, which is equivalent to the method based on the filter loaded dust mass because when comparing two filters used in the same environment, the same duration implies the same amount of dust mass loaded. Another mode is to replace HEPA filter when its resistance reaches a preset value of pressure drop.

The European Ventilation Association's standard, EUROVENT 4/11-2014 (EUROVENT, 2014), provides a method for calculating the energy consumption of filters for general ventilation based on laboratory test results. This method was applied to comparing the energy consumption performance between a glass fiber HEPA medium and a PTFE HEPA medium in this paper.

The energy consumption of a HEPA medium can be evaluated as follows,

$$W_t = \frac{q_v \int_0^t \Delta P dt}{\eta \cdot 1000} = \frac{q_v t \overline{\Delta P_t}}{\eta \cdot 1000} = \frac{q_v m \overline{\Delta P_m}}{\eta \cdot 1000} \qquad (3)$$

where W_t is the total energy consumption by a HEPA medium, q_v the rated air flow rate, ΔP the dynamic resistance, η the fan efficiency, t run time, $\overline{\Delta P_t}$ is time averaged resistance, m mass of loaded dust, $\overline{\Delta P_m}$ mass averaged resistance.

In order to calculate the mass averaged resistance, a polynomial fitting is made for the resistance curve of two HEPA media as shown in Fig. 8. The expression is as follows,

$$\Delta P(m) = a \cdot m^4 + b \cdot m^3 + c \cdot m^2 + d \cdot m + \Delta P_0 \qquad (4)$$

where $\Delta P(m)$ is media resistance at loaded mass m, a, b, c,

d the curve fit parameters. Then the mass averaged pressure drop can be evaluated as follows,

$$\overline{\Delta P_m} = \frac{1}{M} \int_0^M \Delta P(m) dm$$
$$= \frac{1}{5} a \cdot M^4 + \frac{1}{4} b \cdot M^3 + \frac{1}{3} c \cdot M^2 + \frac{1}{2} d \cdot M + \Delta P_0 \qquad (5)$$

where M is the final mass of dust loaded on the medium. From Eq. (5), it can be seen that the mass averaged pressure drop can be used in the comparison of the energy consumption performance between glass fiber media and PTFE media in the periodical replacement mode since other parameters in Eq. (3) are constant.

Fig. 11 shows the average pressure drop curves of test two H14 media under different loaded dust masses. It can be seen from Fig. 11 that the growth rate for average resistance of H14 glass fiber medium decreases slowly while that of H14 PTFE medium stays unchanged during the dust loading period. The average pressure drop of PTFE media is firstly less than glass fiber media but finally overtaken it when the loaded dust mass exceeds 6 g m^{-2} and the gap between them becomes wider after that. Thus it can be concluded that in the periodical replacement mode, the energy consumption advantage for H14 PTFE media is obvious at low dust loading or short-term use conditions, otherwise H14 glass fiber will be more energy efficient.

If the corresponding dynamic resistance of the loaded dust mass in Fig. 11 is used as the x value, the average resistance curves of the two HEPA media can be plotted as shown in Fig. 12. Over the whole process of dust loading, the average pressure drop for H14 PTFE medium is consistently lower than that of H14 glass fiber medium although the gap is not too big. Therefore, H14 PTFE medium will lead to less energy consumption in the operation mode of setting a final resistance.
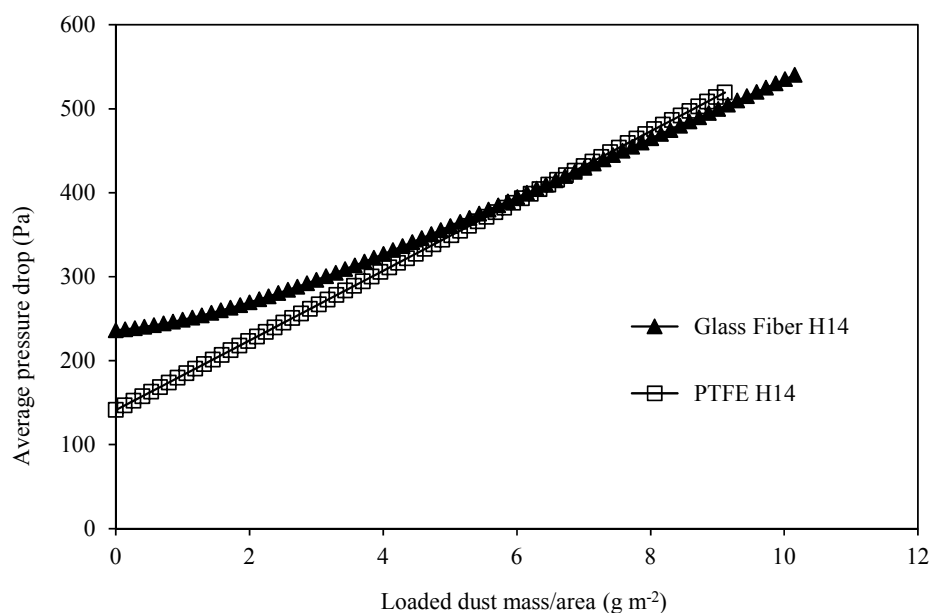
Zhang et al., Aerosol and Air Quality Research, 18: 1921–1931, 2018

Fig. 11. Average pressure drop comparison of glass fiber HEPA media and PTFE HEPA media when evaluated by loaded dust mass.
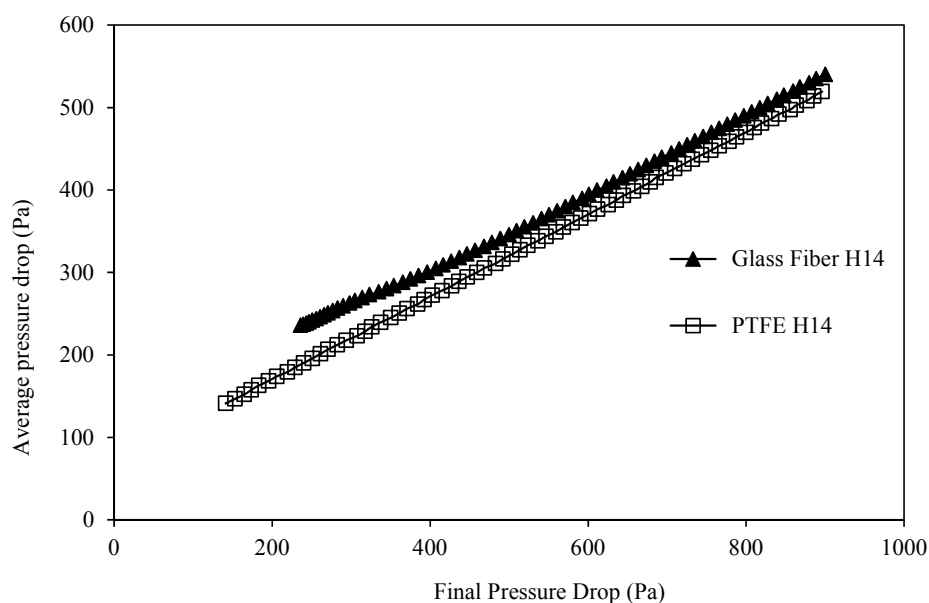

Fig. 12. Average pressure drop comparison of glass fiber HEPA media and PTFE HEPA media evaluated by final pressure drop.

For U15 media in Fig. 8, since the dynamic resistance of PTFE medium is always lower than that of U15 glass fiber medium, according to the average resistance calculating method above, it is clear that PTFE media is more energy efficient based on modes of either periodical replacement or setting a final pressure drop.

CONCLUSIONS

This paper systematically investigates the characteristics of PTFE HEPA media and their dust loading performance in comparison with that of glass fiber media. The internal membrane of PTFE media is constructed using very fine fibers, resulting in a much lower initial pressure drop than for glass fiber media in the same class. Dust loading experiments under different loading conditions were carried out, and the results reveal that the face velocity and aerosol concentration have no effect on the loading process of PTFE HEPA media. Microscopic observations of the loaded PTFE media indicate that due to the special sandwiched structure, filtration of the deposited dust occurs on the surface. The resistance growth coefficient k_2 was defined to reflect both the instantaneous growth rate of the dynamic pressure drop and the dust loading stage of HEPA media,

which can also be applied to theoretical modeling of the dynamic pressure drop at different stages. Finally, a method of evaluating the energy consumption of HEPA media was developed by calculating the average pressure drop during laboratory dust loading experiments. The energy efficiency of PTFE HEPA media and glass fiber HEPA media was also assessed based on their performance in two modes: periodically replacing the media and setting a final pressure drop. The results reveal that in general, PTFE is more energy efficient than glass fiber except in circumstances of heavy loading or infrequent maintenance.

ACKNOWLEDGMENTS

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