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Filter Quality of Pleated Filter Cartridges

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The performance of dust cartridge filters commonly used in dust masks and in room ventilation depends both on the collection efficiency of the filter material and the pressure drop across the filter. Currently, the optimization of filter design is based only on minimizing the pressure drop at a set velocity chosen by the manufacturer. The collection efficiency, an equally important factor, is rarely considered in the optimization process. In this work, a filter quality factor, which combines the collection efficiency and the pressure drop, is used as the optimization criterion for filter evaluation. Most respirator manufacturers pleat the filter to various extents to increase the filtration area in the limit space within the dust cartridge. Six sizes of filter holders were fabricated to hold just one pleat of filter, simulating six different pleat counts, ranging from 0.5 to 3.33 pleats cm^{-1}. The possible electrostatic charges on the filter were removed by dipping in isopropyl alcohol, and the air velocity is fixed at 100 cm s^{-1}. Liquid dicotylphthalate particles generated by a constant output atomizer were used as challenge aerosols to minimize particle loading effects. A scanning mobility particle sizer was used to measure the challenge aerosol number concentrations and size distributions upstream and downstream of the pleated filter. The pressure drop across the filter was monitored by using a calibrated pressure transducer. The results showed that the performance of pleated filters depend not only on the size of the particle but also on the pleat count of the pleated filter. Based on filter quality factor, the optimal pleat count (OPC) is always higher than that based on pressure drop by about 0.3–0.5 pleats cm^{-1}. For example, the OPC is 2.15 pleats cm^{-1} from the standpoint of pressure drop, but for the highest filter quality factor, the pleated filter needed to have a pleat count of 2.65 pleats cm^{-1} at particle diameter of 122 nm. From the aspect of filter quality factor, this study suggests that the respirator manufacturers should add ~0.5 pleats cm^{-1} to the OPC derived from the generalized correlation curve for pleated filter design based on minimum pressure drop.

Keywords: filter quality factor; optimal pleat count; pleated filter

INTRODUCTION

The best filter design requires consideration of not only the lowest pressure drop but also the highest collection efficiency possible. A dust respirator certification standard is dependent on the limited breathing resistance and minimal penetration of a specific diameter of challenge aerosol (NIOSH, 1996). With increased filtration area, the lower filter face velocity (the velocity vertical to the filter) will decrease both the penetration of small size challenge aerosol and breathing resistance. For more filtration area in the limited space, respirator companies usually folded or pleated the filter prior to packing it in the cassette. In this study, we asked two questions. How does the pleated filter affect the performance of dust cartridge including the pressure drop and the collection efficiency with different diameter challenge aerosols. How can the pleated filter satisfy the respirator certification standard when the diameter of the challenge aerosol is set to smaller size?

A pleated filter is generally believed to have a relatively low filter face velocity compared to a flat filter

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at the same approaching velocity. The resulting improvement of filtration is due to three factors: the loading capacity, the pressure drop and the collection efficiency. Loading capacity increases because the filtration area per unit base area increases. Filter face velocity decreases with increasing pleat count, which results in higher collection efficiency. Moreover, the lifetime of the pleated filter is prolonged as the number of pleat increases.

However, the behavior of the pressure drop of pleated filter is complicated and not dependent simply on the loading capacity. The total pressure drop of the pleated filter has three causes: the pressure drop across the filter, the viscous drag between the fluid and porous surface and the contraction and expansion of airflow through the pleated panels (Chen *et al.*, 1995; Lücke and Fissan, 1996; Caesar and Schroth, 2002). These components primarily govern the airflow profile through the zigzag-shaped pleated filter. Raber (1982) developed a model for triangular pleated filter using a finite element control volume concept with one-dimensional momentum conservation. Yu and Goulding (1992) and Chen *et al.* (1995) reported a semi-analytical solution and finite element numerical approximation to depict the flow field in the pleated channel. Recently, Subrenat *et al.* (2003) performed three-dimensional numerical simulations of flow in a cylindrical pleated filter. Based on these numerical simulations and their experimental results, Subrenat *et al.* concluded that as the pleat counts increase, the total pressure drop first reduces due to the decrease of filter face velocity and then rises because of an increase in the viscous drag between the pleat spacing. Therefore, when considering pressure drop, an optimal pleat count (OPC) should exist, and this OPC is current target of pleated filters designers. In addition, a semi-empirical model to derive this OPC based on pressure drop for a given pleat height and the pressure drop across the filter is developed by Chen *et al.* (1995, 1996).

The present optimization process used in designing filters assumes that pressure drop across the filter is dominating the filter quality factor and neglects the importance of collection efficiency of pleated filter. Although Lücke and Fissan (1996) proposed an integration of simplified penetration equation weighting with the velocity field to model filter quality factor, the experimental data were not provided to verify this approach. The main purpose of this work is to search for the OPC based on a more comprehensive optimization criterion, normally referred to as 'filter quality factor' (q_f), an indicator combining the measurements of penetration rate (P) and pressure drop (Δp). The definition of q_f is expressed as follows:

$$q_f = \frac{-\ln P}{\Delta p}.$$

Experimental methods

The experimental setup, as shown in Fig. 1, can be divided into three components: a particle generation system, a filter holder and a particle size spectrometer (Scanning Mobility Particle Sizer, SMPS 3934, TSI Inc., St Paul, MN, USA). In the particle generation system, the test agent, polydisperse liquid dicotylphthalate (DOP), was produced by a constant output aerosol generator (TSI 3075). By passing the aerosol output through a neutralizer (TSI 3077), the Boltzmann charge equilibrium was established. After

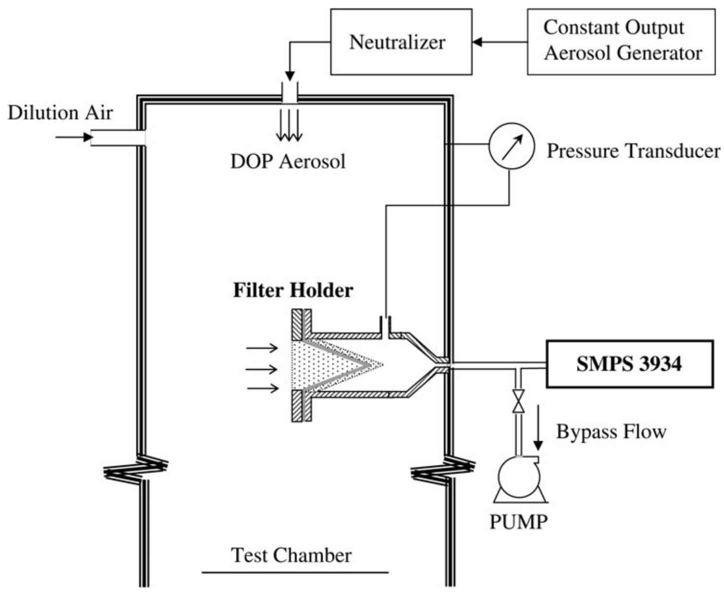


Fig. 1. Schematic diagram of the experimental system setup.

drying with purified air, the test aerosols are introduced into the test chamber to challenge a melt-blown fibrous polypropylene (PP) filter.

The main filtration-related properties of the tested filters were filter thickness of 1.5 mm, packing density of 0.15 and fiber diameter of 30 μm. From a preliminary test, the collection efficiency of the PP filter was found to be highly unstable apparently due to static electricity. As a result, the filters were dipped in isopropyl alcohol (IPA) to remove possible electrostatic charges and deposited DOP particles before performing the air resistance and aerosol penetration tests. In addition, to minimize the variation among filter strips, one filter strip is repeatedly tested after cleaning with IPA. The filter strip is discarded when either the air resistance or aerosol penetration values were 5% off the original values. The filter strip is embedded in a filter holder, as shown in Fig. 2, for fixing its pleat shape during the experiments.

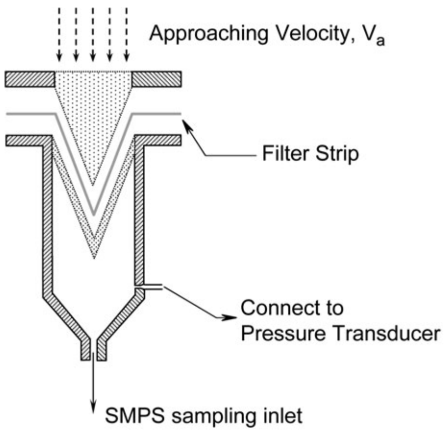
Typically, commercially available pleated filters have two types of pleat configuration: the rectangular shape and the triangular shape. In the present study, the triangular pleat configuration is chosen and the holders were fabricated to hold just one pleat of filter. With different designated gap spacing (W), the filter holders simulated pleated filters of different numbers of pleats per centimeter, as shown in Fig. 2. The length of the filter (L) is 1.0 cm for all holders. Moreover, in order to avoid any other particle loss due to electrostatic attraction, the filter holders were made of conductive aluminum.

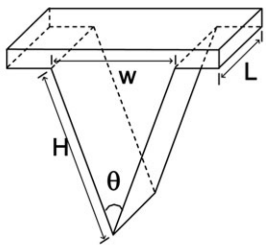
The SMPS is used to measure the particle concentrations and size distributions from 30 nm to 820 nm upstream and downstream of the pleated filter. A differential pressure transducer calibrated against an inclined manometer is connected to the testing filter holder to monitor the pressure drop across the filter at a sampling rate of 1 Hz, and the data were transmitted to and recorded by a computer. For pressure drop measurements, six different pleat count filter holders (0.5, 1.0, 1.5, 2.0, 2.5, 3.33 pleats cm^{-1}) with two different pleat heights (H = 2.1 and 3.5 cm) were used. The tests were performed at a fixed approaching velocity of 100 cm s^{-1}.

RESULTS AND DISCUSSION

Pressure drop

Pressure drop is the present optimization criterion when searching for the OPC of pleated filter. By minimizing the pressure drop across the filter, the energy consumption caused by the pleated filter, normally the major cost, can be curtailed to the lowest possible. Figure 3 presented the experimental results of pressure drop for two different pleat heights, and both curves showed a typical U-shape. However, the characteristics of these two curves were slightly different. For instance, the minimum pressure drop is 2.8 cm H_2O for the 2.1 cm pleat height filter at 2.15 pleats cm^{-1} and 1.7 cm H_2O for 3.5 cm pleat height filter at 1.73 pleats cm^{-1}, respectively. This discrepancy is highly dependent on pleat height. In the pleated filter of greater pleat height, the long flow channel reduced the face velocity while increased the viscous drag. As a result, for the pleated filter with 3.5 cm pleat height, the left side of the curve, the filter dominated regime, is shifted downward, but the right side, the viscosity dominated regime, is lifted upward. Therefore, the pleat count for minimum pressure drop became smaller, so did the corresponding pressure drop across the filter. These pressure test





W, cm	Pleat Count, 1/cm	θ, degree	
		H = 2.1 cm	H = 3.5 cm
0.3	3.33	8.2	4.9
0.4	2.50	10.9	6.6
0.5	2.00	13.7	8.2
0.67	1.50	18.3	11.0
1.0	1.00	27.6	16.4
2.0	0.50	56.9	33.2

Fig. 2. Schematic diagram of the filter holder.

results were in good agreement with previous studies (Yu and Goulding, 1992; Chen *et al.*, 1995).

Since the pressure drop model developed by Chen *et al.* (1996) is currently used for pleated filter design, this model is used to compare and validate the pressure drop measurements carried out in the present study. In Chen's work, the ratio of the total pressure drop (ΔP) and the pressure drop across the filter medium (ΔP_{m}) is shown as a non-dimensional pleating parameter, which depends on the approaching velocity and the variable of $2/(W \times \Delta P_{\mathrm{m}})$, where W is the gap spacing of the pleat. Normally, by plotting the non-dimensional pleating parameter against $2/(W \times \Delta P_{\mathrm{m}})$, the correlation curve (approaching velocity dependent) can be used to estimate pressure drop. In this work, the approaching velocity is fixed at 100 cm s^{-1}. Hence, as shown in Fig. 4, the data points of two different pleat heights fell on the same trajectory, indicating that the measurements agreed well with the semi-empirical model developed by Chen *et al.*, (1996).

Aerosol penetration

Penetration rate is an important performance indicator for evaluating the pleated filter. However, the collection efficiency of pleated filter is rarely considered in the optimization process, probably due to the fact that aerosol penetration experiments are more complicated and time consuming than the air resistance tests. Due to the difference in flow distribution through the filter between flat filter and pleated filter, the aerosol penetration curves were slightly different, as shown in Fig. 5. With the approaching velocity (to the pleated filter, 1.0 pleats cm^{-1}, pleat height 2.1 cm) fixed at 100 cm s^{-1}, the filter face velocity (perpendicular to the filter) is estimated to be 23.8 cm s^{-1}. In Fig. 5, for particles <0.5 µm, the pleated filter obviously has a higher penetration rate than the flat filter does. This implied that the face velocity in the pleated filter is greater than calculated assuming uniform flow. This higher aerosol penetration apparently is due to the dead zone in the pleated filter, especially where the viscous drag dominated. For particles >0.5 µm, aerosol penetration through pleated filter is lower than the flat filter because of higher inertial impaction. By increasing the face velocity through the flat filter from 23.8 cm s^{-1} to 31.3 cm s^{-1}, the aerosol penetration curve was a good match with the pleated filter, further supporting our suggestion of non-uniform flow.

The crossover point at ~0.5 µm shown in Fig. 5, also appeared in Fig. 6, which showed the effect of pleat count on the aerosol penetration as a function of particle size. The filter face velocity in the pleated filter increased with decreasing pleat count. Hence, as pleat count decreased, the penetration curve shifted upward for particles <0.5 µm because of shorter retention time and less filter materials for aerosol deposition by diffusion. For particles >0.5 µm, aerosol penetration decreased with decreasing pleat count, due to higher inertial impaction. This

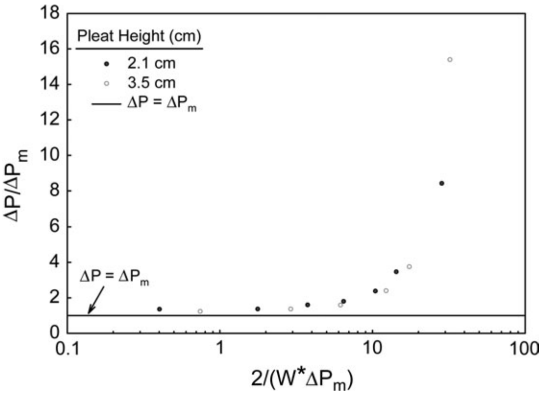


Fig. 4. Correlation curve for approaching velocity at 100 cm s^{-1}.

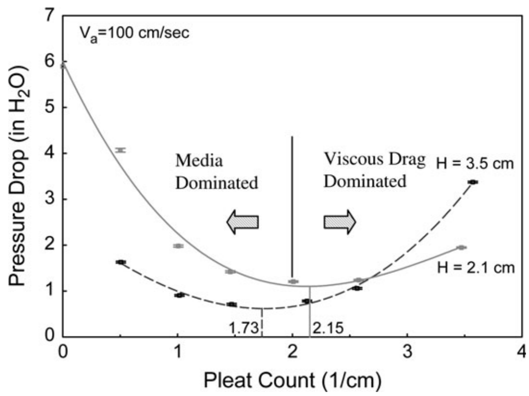


Fig. 3. Pressure drop as a function of pleat count.

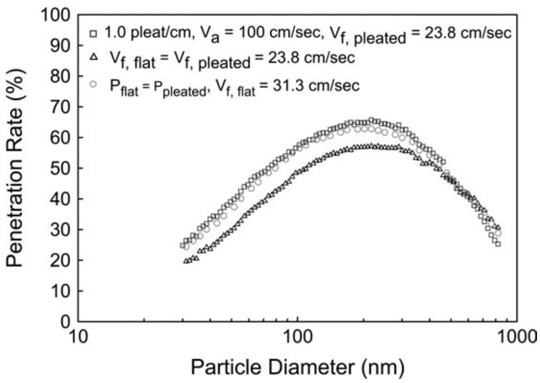


Fig. 5. Penetration curves: 1.0 pleats cm^{-1} filter at approaching velocity of 100 cm s^{-1}, flat filter at face velocity equal to the mean face velocity of 1.0 pleats cm^{-1} filter.

behavior illustrated that reducing filter face velocity by increasing pleat count cannot always guarantee high collection efficiency, which is a strong function of particle size. Therefore, it is essential to include the penetration rate when determining the OPC for pleated filter.

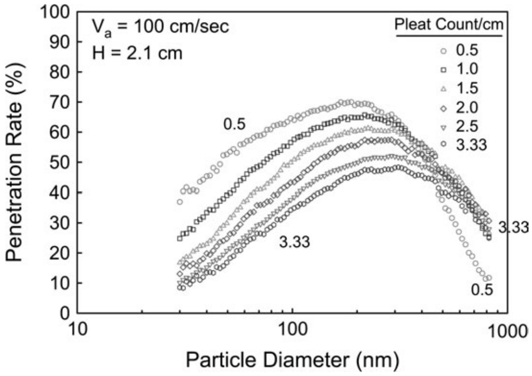


Fig. 6. Penetration curves for different pleat counts, ranging from 0.5 to 3.33 pleats cm^{-1}, with an approaching velocity fixed at 100 cm s^{-1}.

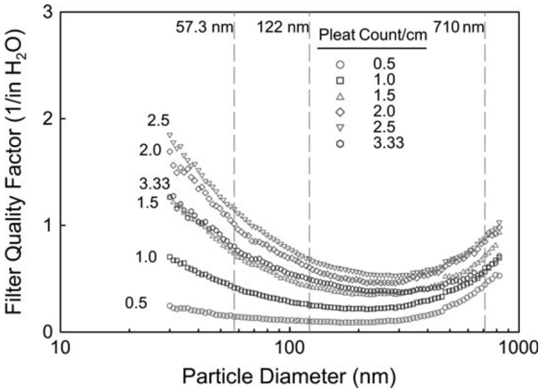


Fig. 7. Filter quality factor curves for different pleat counts, ranging from 0.5 to 3.33 pleats cm^{-1}, with an approaching velocity fixed at 100 cm s^{-1}.

Filter quality factor

The filter penetration is affected by particle size as well as pleat count. However, pressure drop is a function of pleat count only. Thus, for a given pleat number, the filter quality factor simply depends on the penetration rate. The relation between the filter quality factor and particle diameter is shown in Fig. 7. The filter quality factor increased with increasing pleat count, shown in Fig. 7, apparently due to more filter material and therefore more surface for aerosol deposition. Nevertheless, this increasing trend reversed for pleat count greater than 2.5 counts cm^{-1}, indicating the presence of an OPC, from the prospective of filter quality factor. The difference between OPC based on filter quality factor and OPC based on pressure drop will be discussed in detail below.

To find the OPC for maximum filter quality factor, the comparisons of filter quality factor regarding to pleat count were made for three particle diameters at 57.3, 122 and 710 nm. As seen in Fig. 8, the pleat count for maximum filter quality factor were 2.62 pleats cm^{-1}, 2.65 pleats cm^{-1} and 2.46 pleats cm^{-1} for particle diameter at 57.3, 122 and 710 nm, respectively, while the pleat count for minimum pressure drop is 2.15 pleats cm^{-1}. Figure 8 showed that the OPCs based on filter quality factor varied with particle size, but they were all greater than the OPC based on minimum pressure drop by about 0.3–0.5 pleats cm^{-1}, for the PP filters tested in the present study.

The aerosol penetration is dependent on aerosol size, so is the filter quality factor. Likewise, the OPC based on filter quality factor is expected to be a function of particle size. It is worthwhile to find the maximum OPC to avoid the occurrence of over-pleating. The OPC based on filter quality factor

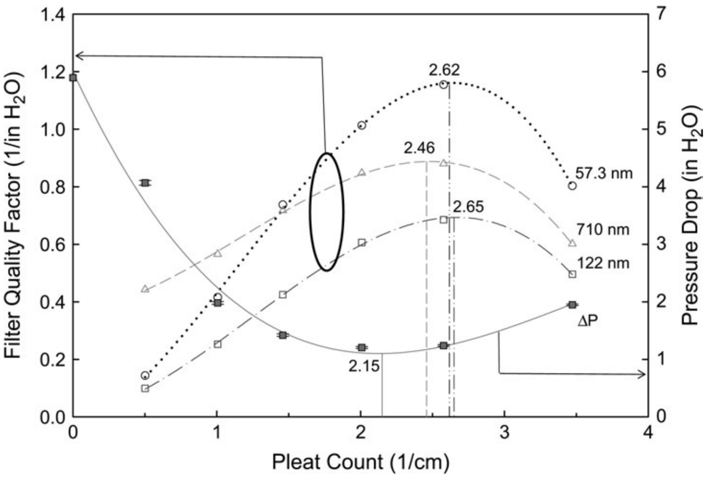


Fig. 8. Comparison of optimal pleat counts for maximum filter quality factor and for minimum pressure drop.

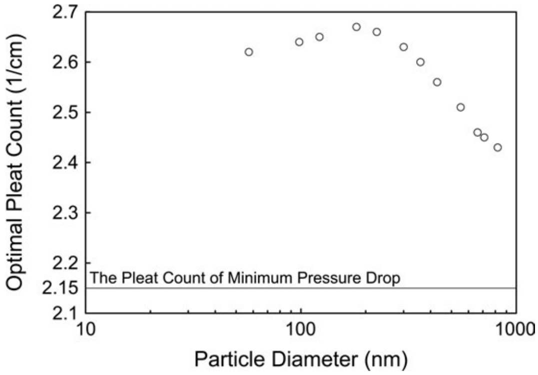


Fig. 9. Optimal pleat counts for maximum filter quality factor as a function of particle size.

can be obtained and plotted for each particle size, as shown in Fig. 9. The maximum pleat count occurred at ~150 nm with a pleat count of 2.67 pleats cm^{-1}. The aerosol size of the maximum OPC might be parallel to the most penetrating size (also referred to as collection minimum), but that consideration is not within the scope of this study.

CONCLUSION AND RECOMMENDATIONS

A series of single pleat filter holders (for different pleat count) made of conductive aluminum were fabricated to investigate the relationship between the OPC based on minimum pressure drop and the OPC based on maximum filter quality factor. Filtration efficiency always increased with increasing pleat count for particles >0.5 μm because of more filter materials and thus more surface and longer retention time for aerosol deposition by diffusion. This trend did not apply for particles >0.5 μm because the viscous drag might force some portions of the pleated filter to form a 'dead zone' and make particles travel faster. Under these conditions, inertial impaction becomes the dominant mechanism, especially for micrometer-sized aerosol particles. Similarly, filter quality factor first increased with increasing pleat count because of more filter materials but then the trend reversed as the pleat count further increased and viscous drag became the governing mechanism.

For the PP filter tested in the present study, the pressure drop measurements supported the conclusions of the non-dimensional analysis of Chen *et al.* The OPC based on minimum pressure drop is 2.15 pleats cm^{-1}. From the aspect of filter quality factor, it is advisable to add about 0.4–0.5 pleats cm^{-1} to the OPC derived from the generalized correlation curve for pleated filter design based on minimum pressure drop.

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