行政院國家科學委員會專題研究計畫成果報告
國科會專題研究計畫成果報告撰寫格式說明
Preparation of NSC Project Reports

計畫編號：NSC 90-2320-B-002-191
執行期限：90 年 08 月 01 日至 91 年 07 月 31 日

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一、中文摘要

在一般的過濾理論當中，氣流與濾紙通常都呈現垂直的情形，但在香煙濾嘴過濾微粒的機制顯然與此現象不同，因為氣流與濾嘴方向幾乎是平行的。並且在過去的研究中主要是針對微粒的重量，而針對粒徑方面的研究是相當有限的，因此在這個計劃中將針對垂直與平行方向濾嘴的過濾特性加以探討。

醋酸纖維濾紙是香煙濾嘴裡常見濾材，也是此計畫拿來測試的濾材。為了降低實驗的變異，因此在實驗時將濾嘴放進一個體積固定的立方體中，並且在測試垂直與平行方向的過濾特性時使用同一塊濾紙，在這個過程中濾嘴的填充密度 0.1 增加到 0.16。微粒的產生主要由定量輸出霧化器及超音波霧化噴嘴分別產生小於 0.8μm 及大於 0.8μm 的多粒徑分布，在濾嘴上下游的微粒濃度的量測上，小於 0.8μm 的微粒使用電移動度掃描分徑器量測，大於 0.8μm 的微粒則使用氣動微粒分徑器，濾嘴的壓降則用 U 形壓力計量測。

實驗結果顯示氣流與濾嘴方向平行與垂直的過濾機制並不完全相同。平行方向濾嘴的壓降比垂直的小，這表示氣流與濾嘴方向平行時氣流流線較平順，另外巧合的是在微粒的貫穿率方面平行方向比垂直方向有較高的貫穿率。故單就濾嘴的過濾效率比較時，垂直方向濾嘴的效率比平行方向高。

關鍵詞：過濾效率、濾嘴

Abstract

Most of the filtration models assume that air streamline is perpendicular to fibers. However, cigarette filters remove aerosol particles apparently by very different filtration mechanisms, because the fiber orientation almost parallels air streamlines. Moreover, most of the earlier studies measured cigarette filter efficiency based on total mass. The experimental data as a function of aerosol size is limited. Therefore, the main objective of this work is to characterize the filtration characteristics of cigarette filter and to experimentally study the difference in principal filtration mechanisms between parallel filter and vertical filter.

Cellulose acetate filter is the most commonly used cigarette filter and was chosen as the test filter. To reduce the variability of cigarette filter when compared to a parallel filter with a vertical filter, a piece of original round filter was molded to form a cube, and the same piece of filter was used for both perpendicular and parallel orientations. In this process, the packing density increased from 0.10 to 0.16. A constant output aerosol nebulizer and an ultrasonic atomizing nozzle were used for generating polydisperse particles smaller than 0.8 μm and larger than 0.8 μm, respectively.

A Po210 radiation source was used to neutralize the challenge aerosols to Boltzmann charge equilibrium. A scanning mobility particle sizer (for < 0.8 μm) and an aerodynamic particle sizer (for > 0.8 μm) were used to measure aerosol number concentrations and size distributions upstream and downstream of the cigarette filters. Pressure drop across the filters was measured using a U-type manometer.

The results showed that parallel and vertical filters behave similarly but the dominating filtration mechanisms may not be exactly the same. The pressure drop across parallel filter was lower than for the perpendicular one, indicating that the airflow is more laminar passing through the parallel filters. On the other hand, aerosol penetration through parallel filter was higher than the vertical filter, very likely for the same reason. When comparison is made based on filter quality, the performance of vertical filter is better than that of parallel filter.

Keywords: filter efficiency, filter

Introduction

Many aerosol scientists have contributed to the development of modern filtration theories. There are a number of excellent reviews that summarize, compare, and correlate derived theoretical or empirical models with experimental data (Yeh and Liu, 1974; Nguyen and Beeckmans, 1975; Ingham, 1981; Brown, 1984, 1989; Liu and Rubow, 1986; Zhang and Liu, 1992; Walsh and Stenhouse, 1997; Barrett, 1998; Romay et al., 1998). As a result of the efforts of air filtration researchers during the past decade, including advances in air filtration modeling and data analysis, filter performance can now be predicted with acceptable accuracy. Nevertheless, most of the previous experimental and/or theoretical studies were on vertical filters, i.e., direction of airflow perpendicular to the fiber orientation. Experimental data on parallel filters are very limited.

Cigarette filter has been designed to reduce the cigarette tar yields. In addition to its aesthetic values, a filter also reduces the cost of the cigarette because it is cheaper than the tobacco. Filter rod making begins when the cellulose acetate filter tow arrives at the rod-making operation in a highly compacted form. For the filter material to be most effective the fibers must have the maximum amount of their surfaces exposed to the smoke stream, therefore, the initial operation in rod making must be the separation of the individual fibers from one another. The main physical characteristics of the cigarette filter rod are defined in terms of length, circumference, firmness or compressibility, weight and pressure drop, or resistance to draw. The packing density (or weight) is an important factor in determining firmness, pressure drop and cost of production. The amount of fiber in the rod determines its density and, in turn, its firmness or resistance to compression. The bonding agent in the rod forms welds between the fibers, which also serve to add rigidity to the fiber mass. Within the usual limits, firmness increases with increasing bonding. Individual fiber denier and cross-section also influence firmness. Cigarette filter is one of the few parallel filters readily available on the market, and was selected as the test filter in this work.

Single fiber theory

The single fiber theories are normally used to calculate the total filtration efficiency (Hinds, 1999). Aerosol penetration P_n for a particle with n elementary charges is given by:

$$P_n = \exp\left[\frac{-4\alpha x E_{\Sigma,n}}{\pi d_f}\right]$$

where α is the packing density; d_f is the fiber diameter; x is the filter thickness; and $E_{\Sigma,n}$ is total single fiber filtration efficiency (of a particle with n elementary charges) due to the combined effect of all individual filtration mechanisms.

$$E_{\Sigma,n} = f\left(E_d, E_r, E_i, E_g, E_p, E_{c,n}, E_{im}\right)$$

Where E_d is due to diffusion deposition; E_r is due to interception deposition; E_i is due to impaction deposition; E_g is due to gravitational settling; E_p is due to dielectrophoretic force; $E_{c,n}$ is due to Coulombic force; E_{im} is due to image force. The sum of the first four mechanisms is regarded as the mechanical capture mechanisms, E_m, and the last three as electrostatic capture mechanisms, $E_{e,n}$.

The single fiber efficiency due to diffusional deposition is given by (Lee and Liu, 1982):

$$E_d = 2.6\left(\frac{1-\alpha}{K}\right)^{1/3} Pe^{-2/3}$$

where K is the Kuwabara factor and Pe is the dimensionless Peclet number. The Kuwabara factor is a function of packing density α (also called solidity):

$$K = -\left(\frac{1}{2}\right)\ln\alpha - \frac{3}{4} + \alpha - \left(\frac{1}{4}\right)\alpha^2$$

The Peclet number relates the diffusional transport of particles to the filter to the macroscipic flow, indicated by face velocity V (before entering the filter):

$$Pe = \frac{d_f V}{D}$$

where D is the aerosol diffusion coefficient.

The single fiber filtration efficiency due to interception is presented by (Lee and Liu, 1982; Lee and Ramamurthi, 1993):

$$E_r = \left(\frac{1-\alpha}{K}\right)\left(\frac{R^2}{1+R}\right)$$

where R is the ratio of particle diameter, d_p, to fiber diameter, d_f:

$$R = \frac{d_p}{d_f}$$

The single fiber efficiency for impaction can be presented by (Yeh and Liu, 1974):

$$E_i = \frac{(Stk)J}{2K^2}$$

where Stokes number, Stk, relates the particle's inertial stopping distance to the filter diameter and is defined as:

$$Stk = \frac{\rho_p d_p C_c V}{18\eta d_f}$$

The density of the particle is represented by ρ_p, and C_c is the Cunningham correction factor. η is the viscosity of air and J is:

$$J = \left(29.6 - 28\alpha^{0.62}\right)R^2 - 27.5R^{2.8} \quad \text{for } R<0.4$$

In addition to Yeh and Liu's semi-empirical equation concerning impaction, Nguyen and Beeckmans (1975) also proposed the following equation to estimate the single fiber impaction efficiency:

$$E_i = \frac{Stk^3 \times F^3}{Stk^3 \times F^3 + 0.77\left(1 + \frac{K_3}{(\mathrm{Re}_f)^{1/2}} + \frac{K_4}{\mathrm{Re}_f}\right) \times Stk^2 \times F^2 + 0.}$$

where $F = 1 + K_1 \times \alpha + K_2 \times \alpha^2$

and $K_1 = 4$, $K_2 = 2250$, $K_3 = 4$, and $K_4 = 65$ for real filters.

This equation has the advantage that it will not exceed unity, given that the constants K_1 to K_4 are positive.

Nguyen and Beeckmans' equation actually was a modification of the equation proposed by Landahl and Herrmann (1949):

$$E_i = \frac{Stk^3}{Stk^3 + 0.77 Stk^2 + 0.22}$$

The single fiber filtration efficiency caused by aerosol gravitational settling is given by (Yeh and Liu, 1974):

$$E_g = \frac{\rho_p d_p C_c g}{18 \eta V}$$

which represents the ratio of the particle's gravitational velocity to the face velocity of the flow through the filter.

The single fiber filtration efficiency due to the interaction between a polarized charge fiber and an aerosol particle is given by (Lathrache and Fissan, 1987):

$$E_p = \left(\frac{1-\alpha}{K}\right)^{2/5} \frac{\pi N_d}{1 + 2\pi N_d^{2/3}}$$

where N_d is a dimensionless parameter:

$$N_d = \frac{2}{3} \times \frac{(\varepsilon_p - 1)\sigma^2 d_p^2 C_c}{(\varepsilon_p + 2)\varepsilon_0 (1 + \varepsilon_f)^2 \eta d_f V}$$

and ε_p is the dielectric constant of the aerosol; ε_f is the dielectric constant of the fiber; ε_0 is the dielectric constant in vacuum; and σ is the fiber charge density.

The single fiber filtration efficiency due to the Coulombic force between a charged fiber and an aerosol particle with n elementary charges $E_{c,n}$ is given by (Lathrache and Fissan, 1987):

$$E_{c,n} = \left(\frac{1-\alpha}{K}\right)^{1/8} \frac{\pi N_{c,n}}{1 + 2\pi N_{c,n}^{1/4}}$$

Where $N_{c,n}$ is a dimensionless parameter related to the number of electrons with charge e (1.6×10^{-19} C or $4{,}8 \times 10^{-10}$ electrostatic units).

$$N_{c,n} = \frac{ne\sigma C_c}{3\pi\varepsilon_0 (1 + \varepsilon_f)\eta d_p V}$$

The single fiber filtration efficiency due to image force is given by (Lathrache and Fissan, 1987):

$$E_{im} = \frac{2}{(2 - \ln \mathrm{Re}_f)^{1/2}} (N_m)^{1/2}$$

Where

$$\mathrm{Re}_f = \frac{V d_f}{\nu}$$

and

$$N_m = \frac{(\varepsilon_p - 1) Q_p^2}{12\pi^2 \varepsilon_0 d_p (1 + \varepsilon_f)\eta d_f^2 V}$$

where Q_p is the aerosol charges.

It is assumed that the particle charges are in Boltzmann charge equilibrium, and the interaction terms between the individual mechanisms are not within the scope of the present study. A spreadsheet (Microsoft Excel) was used to calculate and integrate the filtration efficiency by each individual filtration mechanism.

Collection efficiency alone is not enough to distinguish the good filters from bad filters, because pressure drop across the filter is an equally important factor that needs to be taken into account when ranking the quality of filters. The filter quality factor, q_f, is normally used as an indicator of the filter media performance,

$$q_F = \frac{\ln(\frac{1}{P})}{\Delta P}$$

where *P* is the fraction of aerosol penetration and *Δp* is the pressure drop across the filter.

Experimental Materials and Methods

The cellulose acetate tow filter acquired from a local tobacco company was used in this work. The basic properties of this filter are listed in Table 1. This filter rod constitutes 25 mm of length and 7.6 mm of diameter, with packing density of about 0.1 and equivalent fiber size of 18 μm (a denier per filament of 3). The filter was cut into several shorter rods of 5.3 mm length. This rod was manually shaped and compressed to form a cube with the dimension of 5.3 mm, as shown in Figure 1. The compaction increased the packing density from 0.1 to 0.16. In the present study, when aerosols flow into the conventional cigarette filter rod, e.g., flow direction parallels the fiber longitudinal direction, the filter is named parallel filter. By rotating this cube 90 degree, the filter is named vertical filter, as the conventional filter media in which air flows perpendicularly with the fiber orientation.

To conduct the aerosol penetration test, aerosol particles with different size distributions were generated by two aerosol generation systems, as shown in Figure 2. A constant output atomizer (model 3076, TSI Inc., St. Paul, MN) and an ultrasonic atomizing nozzle (model 8700-120, Sonotek Inc., Highland, N.Y.) were used to generate polydisperse submicrometer-sized and micrometer-sized aerosol particles, respectively. In order to avoid the particle charge effect, the particles were then passed through a 22.5-mCi Po-210 radioactive source (model P-2001, NRD Inc.) to neutralize the aerosol particles to the Boltzmann charge equilibrium. An aerosol electrometer (model 3068, TSI, Inc.) was used downstream of the test chamber to monitor the aerosol charge neutralization. Two different spectrometers were used to measure the aerosol concentration and size distribution: a scanning mobility particle sizer (SMPS, model 3934U, TSI Inc.) for particles smaller than 0.7 μm, and an aerodynamic particle sizer (APS, model 3320, TSI Inc.) for particles larger than 0.7 μm. Dioctylphthalate (DOP) was chosen as the test agent.

Five filter rods were used for aerosol penetration and air resistance measurements. Seven face velocities ranging from 18 to 300 cm/sec were applied to study flow dependency. Five replicates were conducted for each condition. All flows were controlled and monitored by mass flow controllers (Hastings Instruments, Hampton, VA), and calibrated using an electronic bubble meter (Gilibrator, Gilian Instrument Corp., Wayne, NJ).

Results and Discussions

The pressure drop across the vertical filters appeared to be significantly higher than that across parallel filters, as shown in Figure 3. Airflow through parallel filters is more like flow through numerous pipes and tends to be laminar for Reynolds number less than 2000. The exponent of the power fit curve of parallel filter (1.04) is only slightly higher than 1, indicating that airflow must be quite laminar when passing the channels formed by the parallel fibers. On the other hand, for airflow through vertical filters, eddies forming downstream of the fiber gradually become more numerous and vigorous, as the Reynolds number increases above 1. The exponent of power fit curve of vertical filter is 1.13, notably higher than 1.04 of parallel filter. The pressure drop patterns of both the vertical and parallel filters agree reasonably well with the semi-empirical model developed by Brown (1984). The mismatch is probably due to the inhomogeniety of the filter rod. The fact that the size distribution of fiber diameter apparently is not very monodisperse, might also contribute to the mismatch.

The aerosol penetration curves of vertical and parallel filters looked similar, as shown in Figure 4. The most penetrating size (MPS) also referred to as collection minimum, decreases with increasing face velocity. The MPS is about 0.5 μm when face velocity is set at 18 cm/sec, and the MPS may become less than 0.1 μm if the face velocity goes beyond 300 cm/sec. It is also worthwhile to note that the whole penetration curve moves toward smaller aerosol size, and for particles smaller than MPS, the aerosol penetration increases with increasing face velocity, apparently due to shorter retention time for aerosol deposition by diffusion. For particles larger than MPS, the aerosol penetration decreases with increasing face velocity because of higher inertial force. From Figure 4, it is difficult to make a distinction as to which type of filter has better collection efficiency or lower aerosol penetration. Yet, Figure 5 clearly shows that aerosol penetration through parallel filters is higher than that through vertical filter, very likely for the same reason that parallel filter create lower air resistance, but at the cost of higher aerosol penetration. The differences in aerosol penetration appeared to shrink as the face velocity increased, probably because the airflow also became more turbulent and caused more aerosol deposition.

When the experimental data were compared with the models, the equation of Landahl and Herrmann agreed best among the modeled curves (shown in Figure 6), in particular on the right hand side of the MPS, although the model was proposed the earliest. It was apparently over-modified by Nguyen and Beeckmans because now the aerosol penetration and the most penetrating size are lower and/or smaller than the experiments. The equation by Yeh and Liu appeared to perform reasonably well on the size range smaller than the MPS. Yet, the same reasons that might cause the deviation in pressure drop between the experiment and theory may also apply for aerosol penetration, i.e., inhomogeniety of filter media and polydispersity of fiber diameter.

Figure 7 shows the filter quality of the tested vertical filters. Filter quality apparently increased with decreasing face velocity for almost the whole size range except 1 to 2 μm, the transition region from diffusion to inertial impaction. This also indicated that large unit of filter should be utilized in order to decrease the face velocity and therefore higher filter quality, given that space and initial installation fee are not of concern. The modeled filter quality by Landahl and Hermmann again had the closest match with the experimental data, although their model was derived earlier than others.

The pressure drop across the vertical filter is almost twice that of the parallel filter as shown in Figure 3. Yet the turbulence and energy dissipation downstream of the fibers apparently significantly enhance the collection efficiency, and the consequential filter quality factors were almost identical, as shown in Figure 8. However, for filters operated under lower face velocity (< 60 cm/sec), the vertical filters performed slightly better than the parallel filters when examined closely over the whole size range. But for small particles (less than the MPS), the parallel filter should be used when high face velocity (> 120 cm/sec) needs to be employed, as shown in the lower plot of Figure 8.

Conclusions and Recommendations

Air resistance triggered by vertical filters is about two times higher than that by parallel filters because of the turbulence occurring downstream of the fibers of vertical filters. However, this extra energy to overcome the pressure drop across the vertical filters did not simply dissipate. In fact, the vertical filter almost totally regained the dissipated energy and converted it to higher collection efficiency. Therefore, the filter qualities of vertical and parallel filters are about the same despite the huge difference in air resistance.

In general, vertical filters perform better than parallel filter over all size range, but for particles smaller than the most penetrating size and under high face velocity, the parallel filter might perform better, from the perspective of filter quality.

Acknowledgement

The authors would like to thank the National Science Council (Grant No. NSC90-2320-B-002-191) for the financial supports.

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Table 1. Properties of tested filter

Fiber material	Cellulose acetate
Density of cellulose acetate (g/cm^3)	1.3
Original packing density	0.10
Packing density after compression	0.16
Fiber size (denier)	3.0
Equivalent fiber diameter (μm)	18

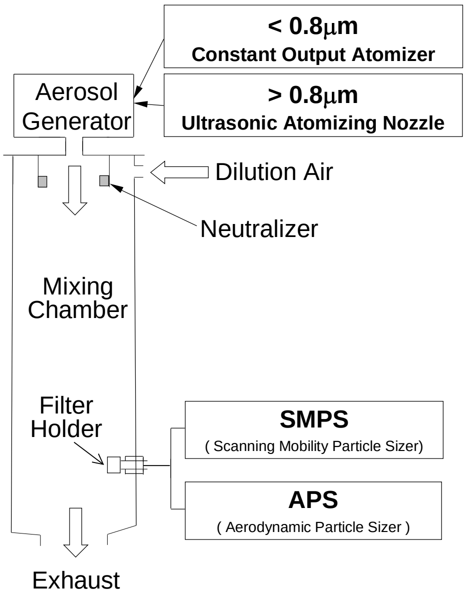


FIGURE 2. Schematic diagram of experimental system set up.

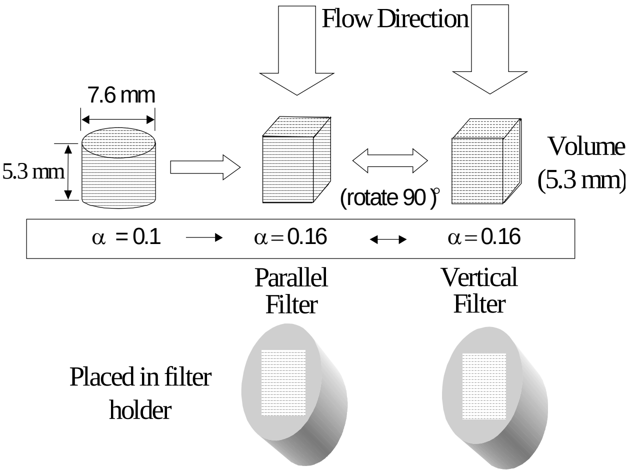


FIGURE 1. Formation of parallel and vertical cellulose acetate filter cubes.

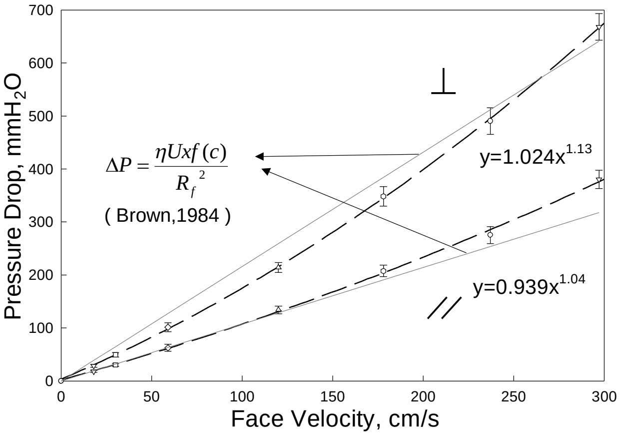


FIGURE 3. Pressure drops across vertical and parallel filters as a function of face velocity.

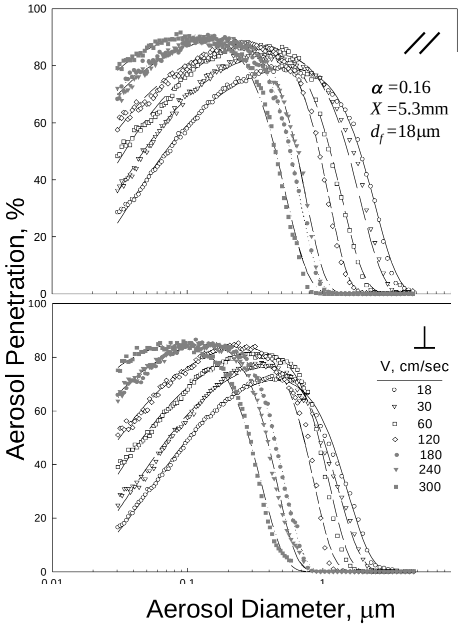


FIGURE 4. Aerosol penetration through vertical and parallel filters under differen showing as a function of aerosol size.

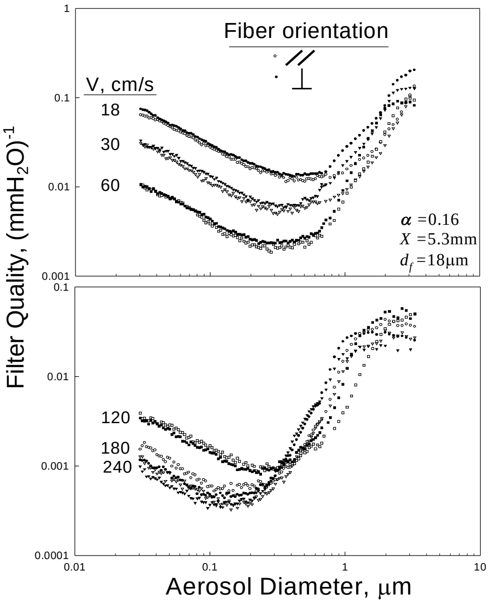


FIGURE 6. Comparison of filter quality factor of vertical and parallel filters.

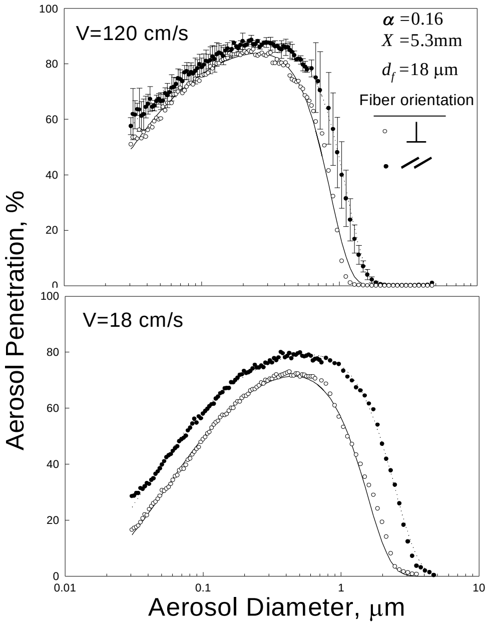
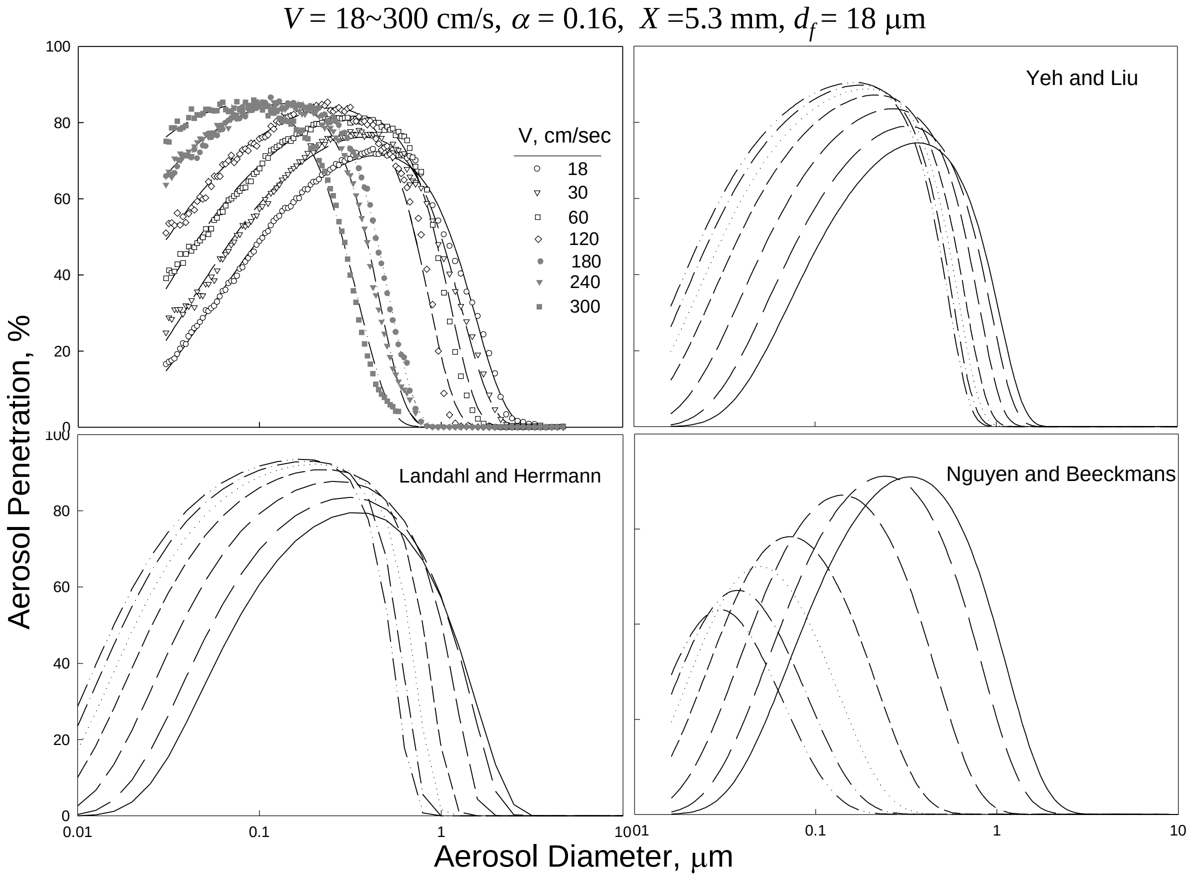


FIGURE 5. Comparison of aerosol penetration curve of vertical and parallel filters.



V = 18~300 cm/s, α = 0.16, X =5.3 mm, d_f = 18 μm

FIGURE 7. Experimental and modeled penetration curves of vertical filter.

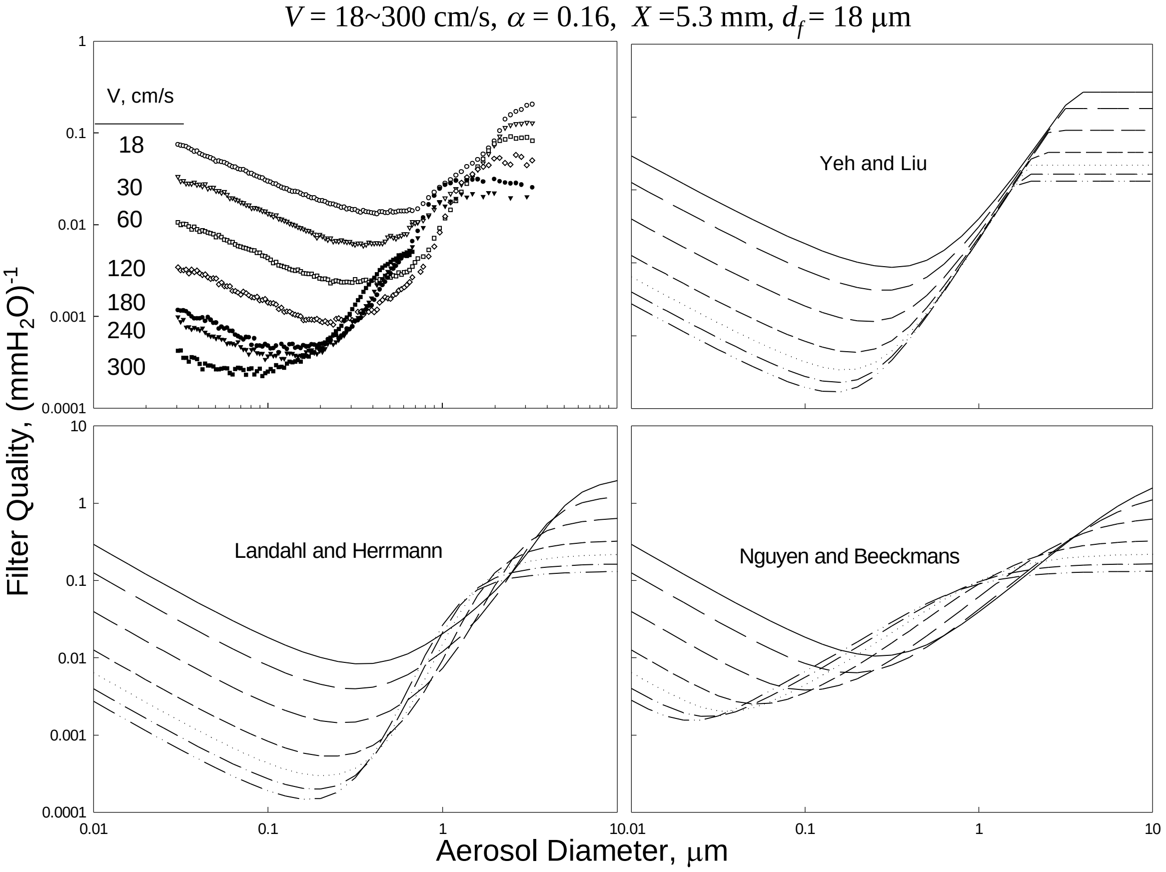


FIGURE 8. Experimental and modeled filter quality factors of vertical filter.

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計畫類別：■個別型計畫　　□整合型計畫
計畫編號：NSC 90－2320－B－002－191
執行期間：90 年 08 月 01 日至 91 年 07 月 31 日

計畫主持人：陳志傑
共同主持人：
計畫參與人員：林宛筠 張光男

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中 華 民 國 91 年 10 月 29 日