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Effect of solid monodisperse particles on the pressure drop of fibrous filters

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Abstract−The increase in pressure drop across glass HEPA filters has been measured as a function of particle mass loading using polystyrene latex particles (PSL). PSL particles in several different sizes were generated as challenge aerosols. For each particle size distribution, the specific resistance (K_2) was calculated by measuring the mass of PSL particles loaded per unit area of filter and the pressure drop across the filters at a given filtration velocity. In all cases, the specific resistance of the filter cake increased as the aerodynamic mean particle diameter decreased at the same mass loading. This correlation equation was modified by using the lognormal conversion method suggested by Raabe [1971] for a polydisperse particle size distribution; then the modified equation was expressed as a function of geometric mean particle diameter and standard deviation which could be obtained by the measuring instruments (PDS 3603; TSI Inc.). The advantage of this approach over other methods is the use of a more convenient prediction of pressure drop, if we know the geometric mean particle diameter and standard deviation, which could be easily measured. The values of porosities, obtained from the pressure drop responses of loading in the filters using the Rundnick and First equation, were compared with other researches.

Key words: Pressure Drop, Collection Efficiency, Specific Resistance (K_2), Porosity

INTRODUCTION

The efficient design of filtration systems continues to be important in the control of air pollution for many applications. In general, the proper design of a filtration system requires the consideration of two parameters, the collection efficiency and particle mass-loading characteristics of the filter. The efficiency and pressure drop of fibrous filters are affected by the size of the filter fibers, their packing density in the filter media, and the velocity of gas flow through the filter. In addition, the filter efficiency and pressure drop also depend on the size of the particles being collected and, to a somewhat lesser extent, particle shape and density.

The particle-loading characteristics describe how the pressure difference, P, increases with the quantity of particles collected on the filter. The need to predict the relationship between mass loading and P is apparent from the number of investigations found in the literature. For example, mass loading of fly ash on baghouse filters from coal-fired power plants has been extensively studied [Dugham and Harrignton, 1971; Airman and Helfritch, 1981]. There has also been significant research done in the nuclear industry on sodium fire aerosols loading high-efficiency particulate air (HEPA) filters [Gunn and Eaton, 1976; McCormack et al., 1978; Jordan et al., 1981; Pratt and Gree, 1987]. An empirical equation from experiments performed using three different materials was developed [Novick et al., 1992]. However, most of this research was conducted on a polydisperse aerosol and specific filtration method. These results clearly show a large difference in mass loadings as a function of aerodynamic particle diameter. The specific nature of most of the studies makes it difficult to generalize the results to different particle sizes or different filters, or even using the same aerosols and filters but varying the conditions of particle collection.

This study characterized the pressure increase and aerosol mass loading for HEPA filter materials as a function of aerodynamic particle diameter and described the specific resistance (K_2) of polydisperse particles using the lognormal conversion method for predicting the pressure drop related to the geometric mean diameter and standard deviation [Raabe, 1971]. In addition, the porosity of the filter cake formed on the filter surface was evaluated and compared with other researches.

EXPERIMENT

1. Description of the Experiments

The experimental set-up (see Fig. 1), consists of an aerosol generator, a filter holder containing the test filters, a dryer, a mass flowmeter and two isokinetic aerosol sampling systems upstream and downstream the filter. The compressed air to the aerosol generator is dried through a refrigeration system. Aerosol particles penetrating the test filter are perfectly captured by a back-up HEPA filter. Temperature (24 °C) and humidity (RH<35%) are controlled by the air conditioner system. Air velocity inside the filter is kept constant by using a flow control system, and pressure drop across the filter is measured with a high accuracy differential pressure transducer. A computer enables date acquisition.

The aerosol is generated with an atomizer operating at 20 psi.

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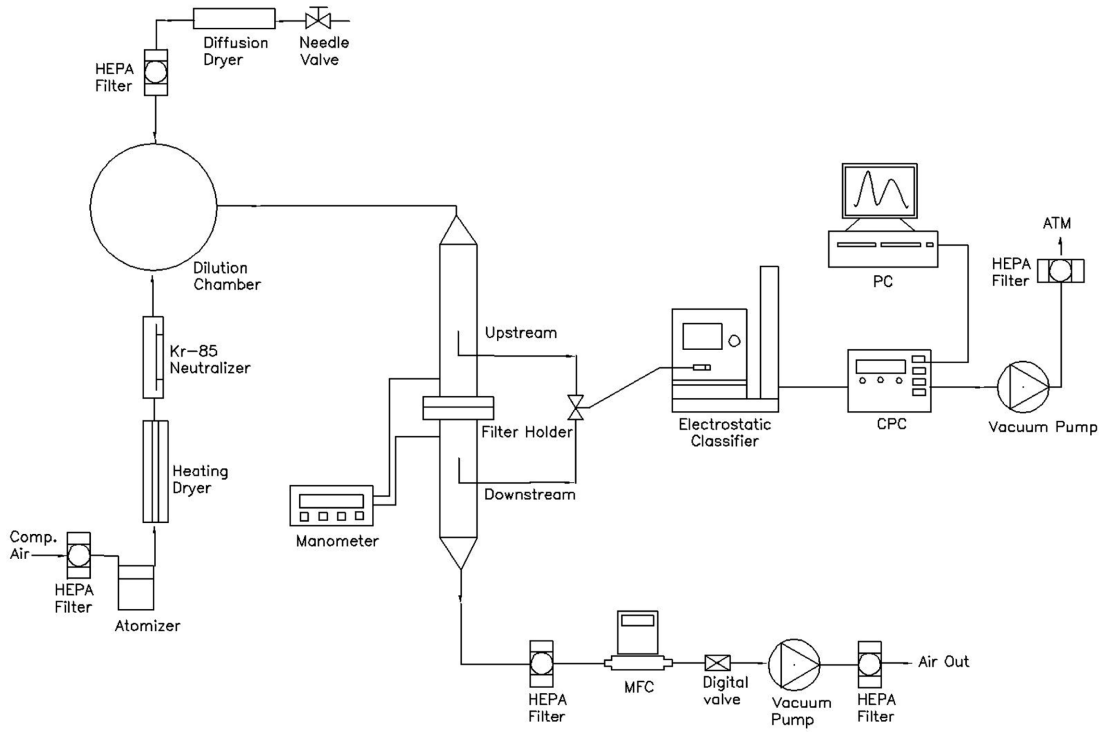


Fig. 1. Schematic diagram of experimental set-up.

Monodisperse PSL particles were generated with a geometric standard deviation less than about 1.16. Particle-laden air was passed through a heating dryer, mixed with clean air in a dilution chamber and introduced to the filter at a flow rate 10.41 L/min. The particle-laden air drawn by using vacuum was passed through the filter.

An isokinetic sampling tube was used for measuring the representative particle concentrations upstream and downstream from the filter. Short sampling tubes of equal length and diameter were used in the experiments to minimize loss and bias at the desired flow rate. For each particle size the particle concentrations, upstream and downstream from the filter, were measured by a Particle Size Distribution Analyzer (PSD 3603; TSI Inc.) and SMPS (Model 3022 CPC with Long DMA; TSI Inc.).

2. Test Aerosols

The aerosols used to evaluate the pressure drop of the fibrous filters were made of commercial monodisperse polystyrene latex (Duke Scientific Corp.) with a density of 1.05 g/cm^3. Table 1 shows the test aerosols used in this study. The test aerosols from these diluted suspensions were generated by a commercial atomizer (Model 9302, TSI Inc.). Polydisperse particles were generated after these monodisperse aerosol suspensions were mixed in a container. Fig. 2 shows the size distribution of the polydisperse aerosols generated by mixing D1, D2, D3, D4, and D5 monodisperse aerosol suspensions, giving a similar log-normal size distribution. A scanning election micrograph of the loaded filter in Fig. 3 shows the deposited particles during clogging.

Table 1. Characteristics of monodisperse polystyrene latex particles used in this experiment

Particle	Model	Diameter, d_p^* (μm)	Type	CV (%)
D1	5030A	0.304	Polystyrene latex	2.2
D2	5050A	0.505	Polystyrene latex	1.9
D3	5072A	0.722	Polystyrene latex	1.8
D4	5110A	1.1	Polystyrene latex	1.0
D5	5200A	2.0	Polystyrene latex	<4.0

*: Particle diameter as specified by manufacturer (GSD<1.16)

3. Filter Materials

The glass HEPA filters used in this experiment were provided by the filter manufacturer (Pall Life Sciences Corp.). The filters represent a range of filter characteristics found in open, high efficiency media. Some structural and performance characteristics are shown in Table 2. It can be seen that these media are of exception-

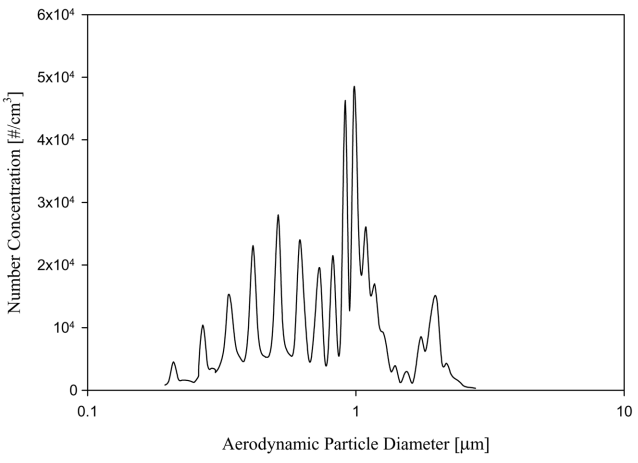


Fig. 2. Particle size distribution of polydisperse aerosols.

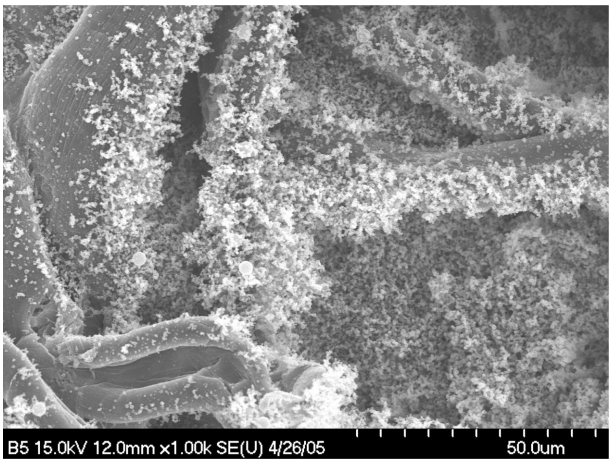


Fig. 3. SEM image of collected particles in the fibrous filter.

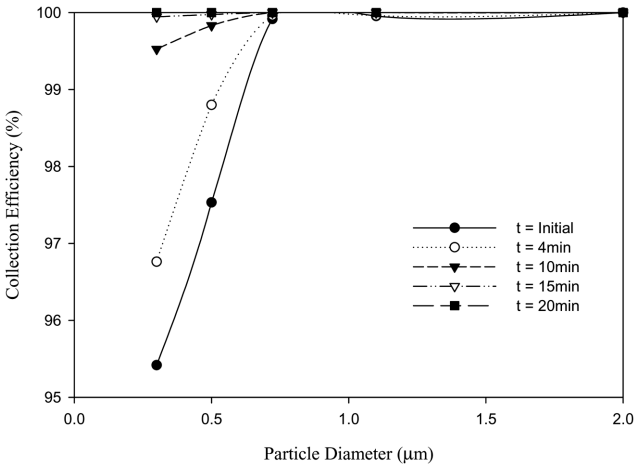


Fig. 4. Particle fractional collection efficiency of cellulose paper filter with time.

ally low variability.

RESULTS AND DISCUSSION

1. Filter Efficiency During Clogging

Collection efficiency of fibrous filter media was calculated as follows [Park and Park, 2005].

$$E = \left[1 - \left(\frac{C_{downstream}}{C_{upstream}}\right)\right] \times 100,\ \% \quad (1)$$

where E is the collection efficiency, $C_{upstream}$ and $C_{downstream}$ the aerosol concentrations before and after passing through the media, respectively. In this study, the number concentration of aerosol particles was measured.

Because the efficiency of glass HEPA filters is above 99.95% in all ranges of particle size, a fibrous paper filter was used to evaluate the fractional collection efficiency in the case of small particles.

The evolution of filter efficiency is shown graphically in Fig. 4. The fractional efficiency of particles larger than 0.722 μm is approximately 99.99%. As mass was loaded on the filter, the fractional efficiency was also increased, especially for smaller sizes. When the loading time reached 10 minutes, the total efficiency was almost 99.5%. The reason for increasing efficiency as loading time is elapsed is that deposited particles on the fiber form dendrites. These dendrites spread out on the surface of the fibers with random arrangements [Tomas et al., 1999]. Because of this complex geometry, we consider that the collected particles form dendritic deposits which can be approximately as newly formed fibers.

2. Evolution of Specific Resistance (K_2) of Monodisperse Particles

When there is significant particle mass loading on a HEPA filter, it is generally accepted that the total pressure decrease across the filter can be written as the sum of the pressure decrease across the clean filter plus the pressure decrease across the filter cake due to particle loading:

$$\Delta P = \Delta P_0 + \Delta P_p \quad (2)$$

This simple model is appropriate for HEPA filters because their high collection efficiency causes a particle cake to rapidly form on the front surface of the filter. From Darcy's law, ΔP_0 can be written in terms of the gas media velocity times a constant that depends upon the physical characteristics of the filter media, such as the fiber diameter, filter packing density and thickness, and ΔP_p can be expressed in terms of the face velocity and mass loading times, a constant that depends on the physical characteristics of the filter cake such as particle diameter and cake porosity. Eq. (2) then becomes

$$\Delta P = K_1 V + K_2 V_0 M/A \quad (3)$$

where V is gas velocity, M collected mass on the filter, A the filtra-

Table 2. Characteristics of the HEPA filters

Filtration parameters	Filter paper identification			
	Filter A	Filter B	Filter C	Filter D
Filter media	Borosilicate glass without binder	Borosilicate glass without binder	Borosilicate glass without binder	Glass fiber with acrylic binder**
Pore size (μm)	1	1	1	1
Thickness (μm)	330	660	254	1270
Typical air flow rate (L/min/cm^2 at 1 psi)	8	24	40	26
Typical aerosol retention*	99.98%	99.98%	99.98%	99.97%

*Following ASTM D 2986-95A 0.3 μm (DOP) at 32 L/min/100 cm^2 filter media.
**Binder is 5% of total material.

tion area, and V_0 face velocity defined as Q/A.

According to the Berman et al. [1979] theory, the specific resistance (K_2) no longer depends on the particle cake porosity but does depend on the inverse of only the first power of the particle diameter. However, as with the cake model, some of these parameters are also difficult to determine or quantify a priori. For these reasons, it is more practical to define K_2 in terms that are more easily measurable:

$$K_2 = (\Delta P - \Delta P_0)\frac{A}{MV_0} \quad (4)$$

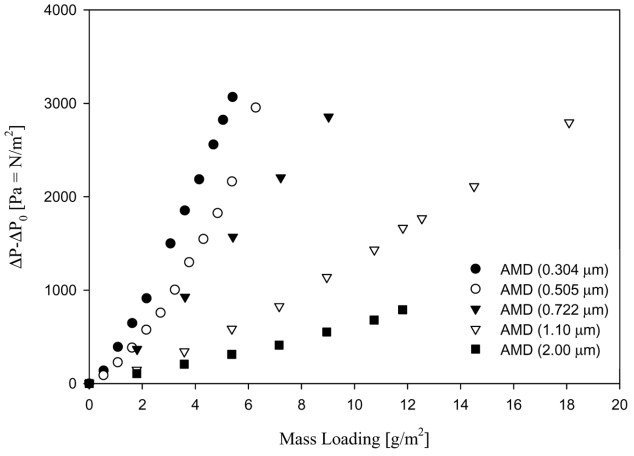
This methodology allows K_2 to be experimentally correlated with parameters that are known or easily estimated so that accurate predictions can be made for the pressure decrease as a function of mass loading.

The results of the pressure drop vs mass loading measurements with glass HEPA filters are given in Figs. 5 and 6 for some of the different monodisperse particle diameters of PSL. As expected, the mass loading at a given pressure drop is greater as the diameter of the challenge aerosol is increased.

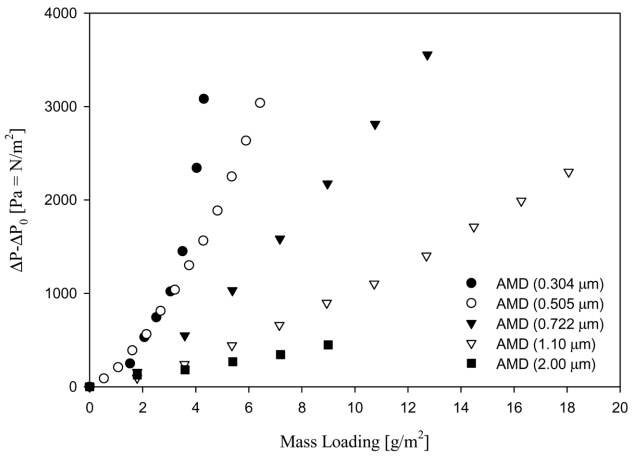
The pressure drop of four filters as a function of mass loading of monodisperse PSL particles is plotted in Figs. 5 and 6. The specific resistance, K_2, can be obtained by calculating the slope of each curve in Figs. 5 and 6. The curve slope is equal to K_2 times the gas velocity, V_0, at the face of the filter media. We made use of a linear fit assuming that the pressure drop was a linear function of collective mass loading, even though some of curves were not exactly fitted onto a straight line. This correlation is very useful because we can simplify the prediction equation of pressure drop as a function of particle diameter alone at a given face velocity and mass loading.

K_2, which was obtained from Figs. 5 and 6, was plotted against the inverse of the aerodynamic particle diameter as shown in Fig. 7. The data of filter D are scattered wider than those of filter A, B and C, because filter D has a different filter media with acrylic binder and also has a thicker structure than the others. These are likely due to the difference deposition patterns of aerosol particles between the fibers and particles. For the case of initial deposition, the particles might be deposited in the depth of the filter which caused more variation of data in filter D than those of others.

For simplification, the K_2 data was fitted as a linear function of $1/d_p$ assuming no particle density dependence, leading to Eq. (5). Novick et al. [1992] also stated that the pressure drop was a func-

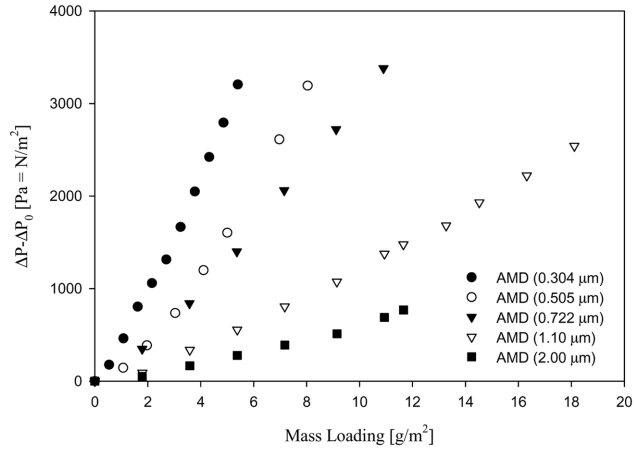


(a) Filter A

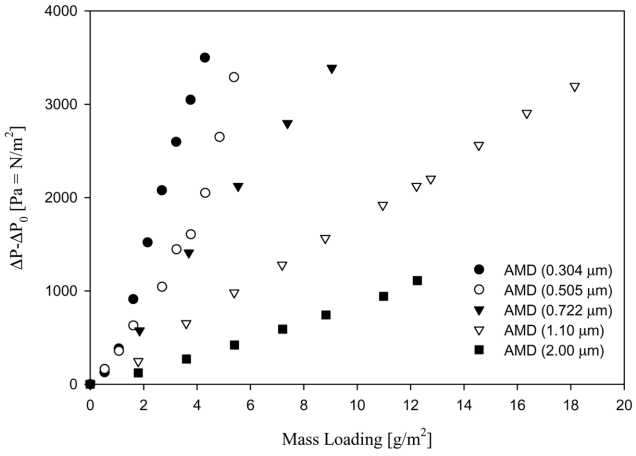


(b) Filter B

Fig. 5. Net pressure drop as a function of mass loading for different monodisperse particles size distributions of PSL on Filter A and B.



(c) Filter C



(d) Filter D

Fig. 6. Net pressure drop as a function of mass loading for different monodisperse particles size distributions of PSL on Filter C and D.

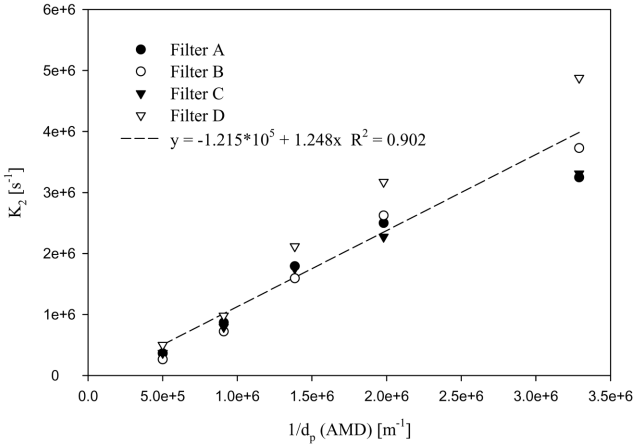


Fig. 7. The average specific resistance of the PSL filter cake plotted as a function of the inverse of the aerodynamic particle diameter on HEPA filters.

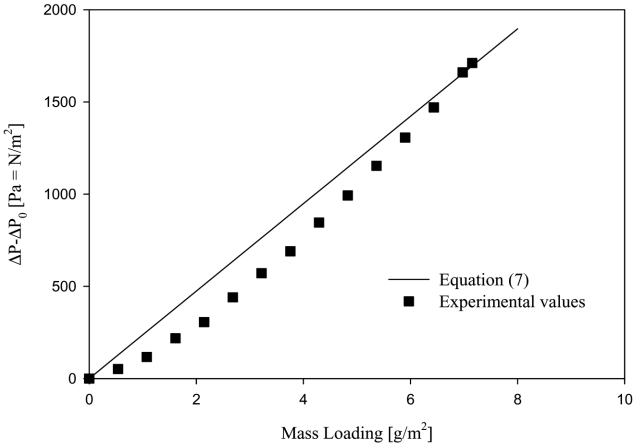


Fig. 8. Comparison of pressure drop with calculated (Eq. (7)) and experimental results with Filter B.

tion of particle diameter instead of the square of the diameter, and Bergman et al. [1979] noted that the pressure drop across a filter could be developed to be a function of $1/d_p$ in the case that particles are imbedded in filter fibers.

Using the better correlated fit to the data from Fig. 7 and substituting the correlation into Eq. (4) yields an expression that can be used to predict a final pressure decrease across HEPA filters given the filtration area (m^2), clean filter pressure decrease (Pa), gas velocity of the filter media (m/s), the aerodynamic particle diameter (m), and the total mass of particulate material (kg).

$$\Delta P(\Delta P-\Delta P_0)=\left(\left(\frac{1.248}{AMD(d_p)}\right)-1.22\times 10^5\right)\frac{V_0 M}{A} \quad (5)$$

Eq. (5) can also be used to predict the maximum amount of mass that can be collected on an existing filtration system given an estimate of the aerodynamic particle diameter. This correlation is valid for dry and solid particles at relatively low humidity. Finally, the prediction made, based on Eq. (5), should be considered to have some error, because we use the method of linear fit assuming that the pressure drop is a linear function of collective mass loading in Figs. 5 and 6.

3. Evolution of Specific Resistance (K_2) of Polydisperse Particles

The real power and utility (and perhaps the popularity) of the lognormal distribution comes from the fact that any type of average diameters can be easily calculated for any known lognormal distribution, that is, a distribution for which one average diameter and geometric standard deviation (GSD) are known. This is useful because it is frequently necessary to measure one characteristic of the size distribution such as number distribution when what is really needed is some other characteristic such as the mass distribution or the diameter or the diameter of average mass.

If a detailed size distribution is available, it is possible to calculate the other weighted distributions, their means, medians, and moment average. This procedure is tedious and may be inaccurate if there is insufficient detail. If and only if the distribution is lognormal, these quantities can be calculated directly by using the lognormal conversion equations derived by Raabe [1971]. The lognormal conversion equation is written as

$$d_p=d_g\exp(p\ln^2\sigma_g) \quad (6)$$

where p is a parameter which serves to define the various possible diameter. In case of arithmetic mean particle diameter, p is 0.5.

The specific resistance, K_2, is proportional to the inverse of aerodynamic mean particle diameter. We modified the previously obtained Eq. (5), using the lognormal conversion equations suggested by Raabe [1971]. Eq. (5) can be converted to Eq. (7) including geometric mean particle diameter and geometric standard deviation.

$$\Delta P_p(\Delta P-\Delta P_0)=\left(\left(\frac{1.248}{GMD(d_g)}\right)\times\exp(-0.5\ln^2\sigma_g)-1.22\times 10^5\right)\frac{V_0 M}{A} \quad (7)$$

Eq. (7) can predict the pressure drop as polydisperse particles are loaded on the glass HEPA filter. The experimental results and the calculated values, obtained modified Eq. (7), of pressure drop are compared in Fig. 8 for the polydisperse aerosols and good agreement is observed between experimental and calculated.

4. Calculation of Filter Cake Porosity

The evolution of pressure drop as a function of collected mass shows a linear increasing (during surface filtration). We are able to calculate the porosity of the filter cake by a permeability method. When a filter is clogged, additional particles will act as a packed bed of spheres of porosity ε in accordance with Rudnick First equation [Rudnick and First, 1978]:

$$\Delta P=\frac{18\mu}{\rho_p C_c d_p^2}\left[\frac{3+2(1-\varepsilon)^{5/3}}{3-4.5(1-\varepsilon)^{1/3}+4.5(1-\varepsilon)^{5/3}-3(1-\varepsilon)^2}\right]\frac{MV_0}{A} \quad (8)$$

where V_0 is filter face velocity (cm/s), ε is porosity (dimensionless), μ is gas viscosity (N s/m^2), C_c is Cunningham correction factor (dimensionless), M is collected mass in the filter (g), and A is filter surface area (m^2).

$$C_c=1+Kn\left[A+Q\exp\left(-\frac{b}{Kn}\right)\right] \quad (9)$$

Kn is defined as ratio of mean free path to particle radius (A=1.252, Q=0.399, and b=1.100) [Jennings, 1988].

The values for porosity calculated from Eq. (8) were obtained from the pressure drop responses of loading the glass HEPA filter

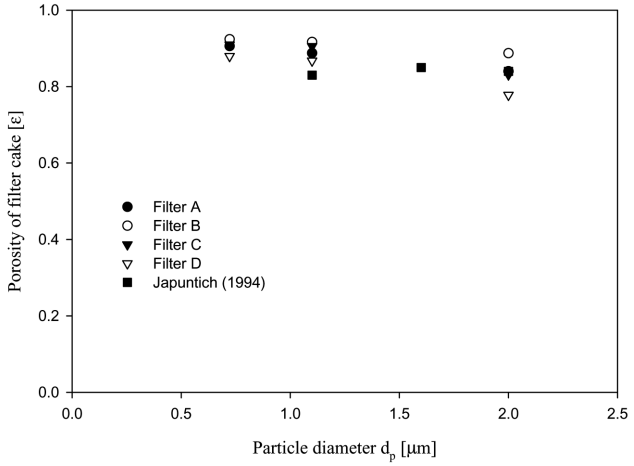


Fig. 9. Evolution of porosity of filter cake as a function of particle diameter.

with particles of 0.722, 1.1 and 2.0 μm challenge aerodynamic mean diameter (GSD<1.16). The porosities of all filter media give similar values for each particle size regardless of the thickness of each filter and represent a good agreement with those of previous research [Japuntich et al., 1994] in Fig. 9. This shows that the porosity on the filter cake is slightly dependent on filter media, and may be a strong function of particle diameter.

SUMMARY AND CONCLUSIONS

As particles were loaded on the filter, the fractional efficiency increased, especially at smaller sizes. This is because deposited particles on the fibers form dendrites which spread out on the surface of the fibers with random arrangements [Tomas et al., 1999].

The evolution of pressure drop of glass HEPA filters with different thicknesses was experimentally described and related to the way that the entire range of particles are collected on the fibers for different clogging degrees. The early stage where filtration occurs inside the filter bed is followed by the second step where it mainly occurs on the front edge of the filter. This study presents a new empirical equation to give a quantitative prediction of pressure drop as a function of aerodynamic particle diameter during filter clogging in the HEPA filters. In addition, a modified equation using lognormal conversion method was presented to predict the pressure drop increase during filter clogging for the condition of polydisperse aerosols.

The porosity of all filter media has a similar value for each particle size. This shows that the porosity of the filter cake is not dependent on the filter media, so we can assume it is a function of particle diameter. The values of porosity of the filter cakes of the different solid particle diameters were between 0.79 and 0.92, and the results compared well with other researches.

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