NMAM

NIOSH Manual of Analytical Methods (NMAM), 5th Edition

Filter Pore Size and Aerosol Sample Collection

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1 Introduction

Aerosol sampling filters are commonly used in industrial hygiene and environmental monitoring to collect airborne particles for analysis. The filter characteristics provided by the manufacturer frequently include the term "pore size" or "equivalent pore diameter," and pore size is also specified in many particle-sampling methods written by government agencies and standards organizations. Unfortunately, the pore size of a filter is often misunderstood, which can lead to the misinterpretation of test results and the selection of filters with much higher flow resistances than are needed for a particular application. The purpose of this article is to discuss how aerosol filters actually work and what the equivalent pore diameter really means, and then to explain how this information should be used when selecting filters and interpreting data. Much of the information and terminology presented here were drawn from Hinds [1999], Brock [1983], Lippmann [2001] and Raynor et al. [2011]. All of these sources provide a more in-depth discussion of filter theory and use and are highly recommended if more information is desired.

2 Physical structures of filters

To understand what the term "pore size" does and does not indicate for filters, we begin by looking at the physical structures of some different types of filters. Most filters used in aerosol sampling fall into one of three categories. Fibrous filters like the glass fiber filter shown in Figure 1A consist of a deep mesh of fibers with random orientations. Porous membrane filters, such as those made from mixed cellulose esters (MCE) or polytetrafluoroethylene (PTFE), have a complex structure with tortuous routes through the filter material as shown in Figures 1B and 1C. A capillary pore filter consists of a thin, smooth polycarbonate (PC) or polyethylene terephthalate (PET) film with circular pores, as shown in Figure 1D. These are also called straight-through pore filters or track-etch membrane filters (because of the manufacturing method), or Nucleopore filters after the original manufacturer.

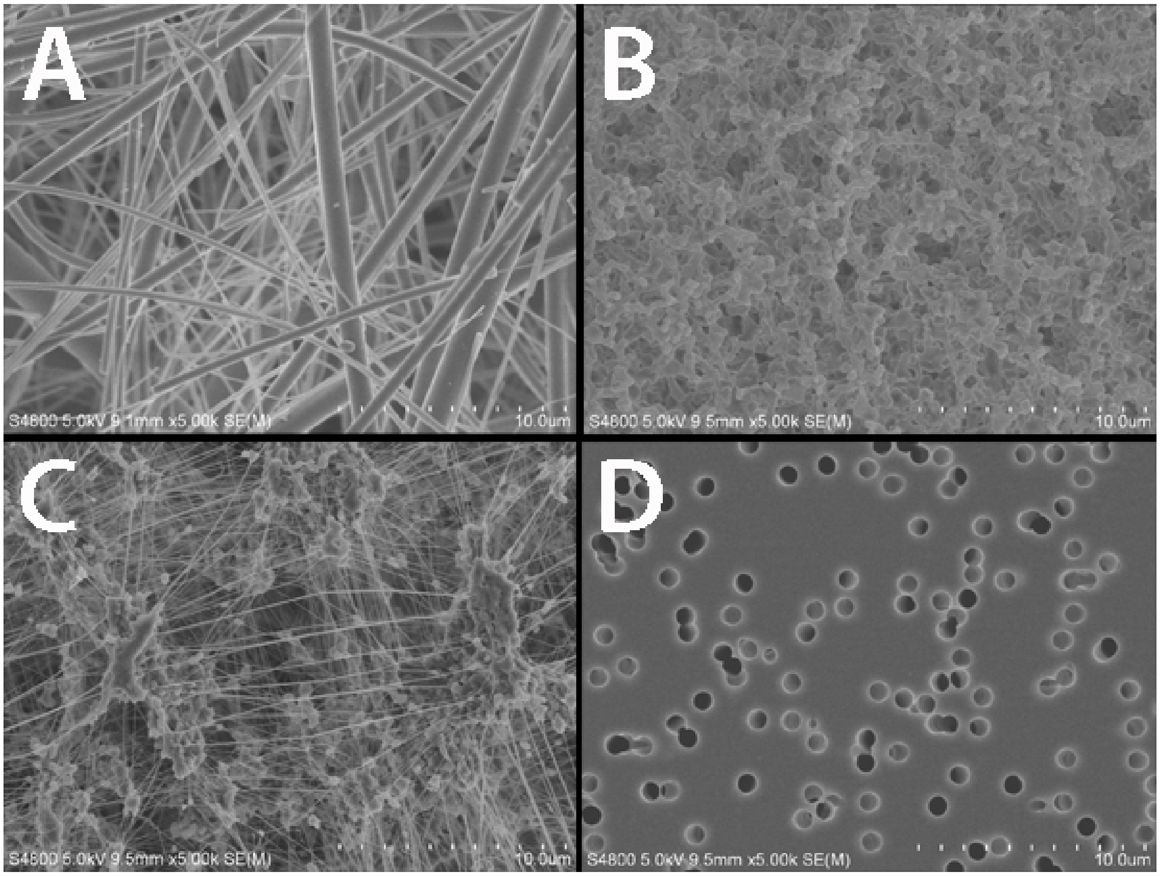

Figure 1: Scanning Electron Micrographs (SEM) of four filter types. The vertical tick marks above "10.0 µm" in the lower right-hand corner of each SEM are 1 µm apart; the entire scale is 10 µm in length.
A: Glass fiber filter with a 1-µm equivalent pore diameter.
B: Mixed-cellulose esters (MCE) filter with 0.8-µm equivalent pore diameter.
C: Polytetrafluoroethylene (PTFE) filter with 3-µm equivalent pore diameter.
D: Polycarbonate capillary pore filter with 1-µm pore size.

3 Determination of equivalent pore diameter

So what is the pore size of a filter? For the capillary pore filter, the pore size is relatively straightforward: the pores are circular and reasonably uniform and run straight through the filter material, so the pore size is the diameter of the pores. This is what many people imagine when they think of the pore size. However, the other types of filters do not have these simple pore structures. The filter material forms intricate paths, and the airstream lines twist and turn as they pass through the filter. Thus, because these filters do not have an obvious, simple dimension that characterizes their pores, an "equivalent pore diameter" is used to describe the filters. This provides a useful way to categorize filters with different sized openings and to ensure consistent performance characteristics. When a manufacturer specifies the pore size of a filter, they are giving the actual pore diameter for capillary pore filters and the equivalent pore diameter for other types of filters.

The equivalent pore diameter is commonly measured by a "bubble-point test" [ASTM 2011]. This test is fairly simple, is non-destructive, and provides a good quality-control check for the filter. A bubble-point test works like this: Imagine that you have an ideal capillary pore filter with smooth holes that are of a uniform diameter, as shown in Figure 2. Now imagine that there is air on one side of this filter and a liquid that wets the filter on the other side. If the air pressure is low, the surface tension of the liquid will stop the air bubble from being pushed through the filter. If you slowly increase the air pressure, at some point it will be high enough to overcome the surface tension, and a visible stream of air bubbles will be produced. This pressure is called the bubble point. The pore diameter can be calculated from the bubble-point pressure with this formula [Brock 1983]:

$$D = \frac{4\gamma \cos\theta}{P} \times 10^6 \qquad \text{(Equation 1)}$$

Where:

D = pore diameter (micrometers)
P = bubble-point air pressure (Pa)
γ = surface tension of the liquid (N/m)
θ = contact angle between the liquid and the filter material

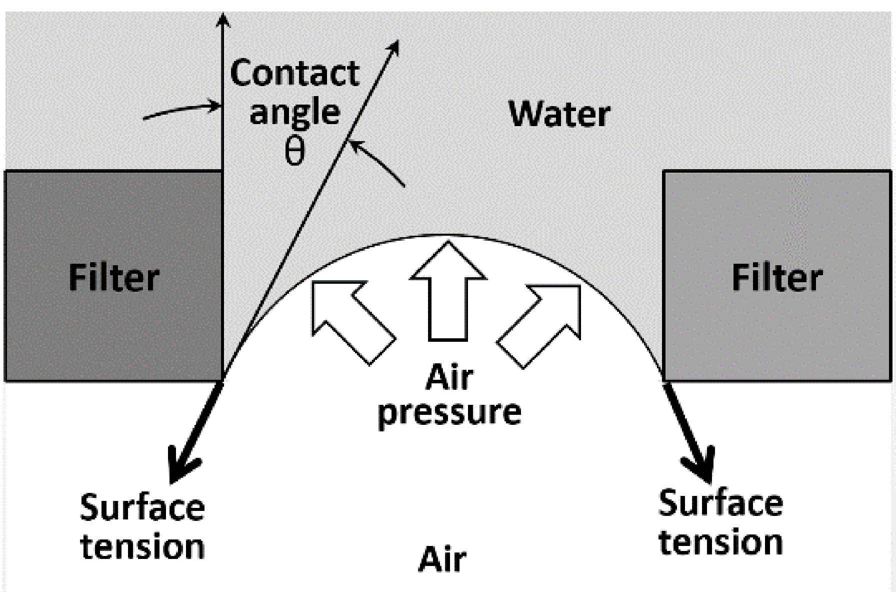

Figure 2: Principle of the bubble-point test.

Note that as the pore diameter gets smaller, more air pressure is required for air to bubble through the ideal filter (Figure 3). Thus, you could take your actual filter and see how much air pressure is needed to bubble air through it. You could then calculate the pore size of an ideal filter that requires the same amount of air pressure to form bubbles as does your actual filter using Equation 1. The pore size of an ideal filter with the same bubble point as your actual filter is the "equivalent pore diameter" of your filter.

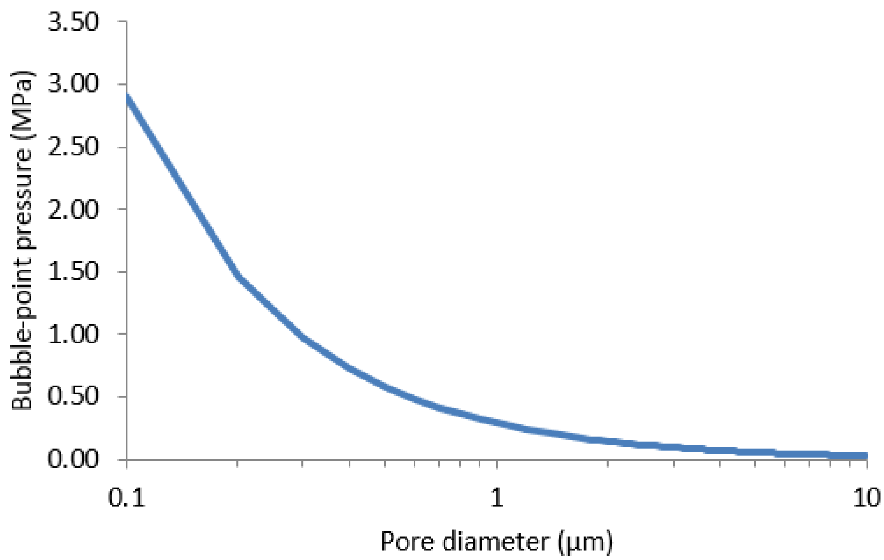

Figure 3: Pore diameter vs. air pressure for ideal filter in bubble-point test. The curve was calculated with use of water (which has a surface tension of 72.8 mN/m) as the liquid. It is assumed that the water completely wets the filter material, and thus the contact angle θ = 0°. Calculated using Equation 1.

Two things should be observed at this point. First, because less air pressure is required to push bubbles through larger openings than through smaller ones, the bubble-point test indicates the size of the largest pores in the filter, not the average pores. For this reason, the bubble-point test is useful for quality control checks of filters, since it will indicate if defects or excessively large pores are present. However, if the filter has a wide range of pore sizes, most of the pores will be smaller than the equivalent pore diameter determined by this test.

Second, the equivalent pore diameter provides a convenient reference point for describing and comparing filters of the same type, but not of different types. For example, the openings in a porous membrane filter with a 5-µm equivalent pore diameter will be somewhat larger than the openings in a porous membrane filter with a 1-µm equivalent pore diameter. However, the pore sizes of different types of filters cannot be meaningfully compared; a capillary filter with a 1-µm pore size bears little resemblance to a porous membrane filter with a 1-µm equivalent pore diameter.

4 How an aerosol filter collects particles

Now that you understand how the equivalent pore diameter is determined, let's discuss how this relates to aerosol sampling. First, we need to review how aerosol sampling filters collect airborne particles. People often assume that a filter works like a sieve—that is, that a filter is like a sheet or mesh with holes of a particular size, and that particles larger than the holes collect on the filter while particles smaller than the holes pass through it. In fact, aerosol filtration is far more complex than this simple model would suggest, and one consequence is that aerosol filters can efficiently collect particles much smaller than would be expected on the basis of the pore size of the filter.

When an airstream containing airborne particles passes through a filter, the particles are collected by five mechanisms (Figure 4):

1) *Interception:* Interception occurs when a particle moving with the airstream contacts the filter material. Intercepted particles include those that are bigger than the filter pores (sieving), and also particles that are smaller than the pores but are carried close enough to touch the surface of the filter as they follow the airstream. The closer the diameter of the particle is to the diameter of the opening in the filter, the more likely interception is to occur. Interception can be very important in the collection of fibers and other irregularly shaped aerosol particles because an elongated particle is more likely to come in contact with the filter, especially if it is sideways to the flow or if it is tumbling [Issacs et al. 2005].

2) *Impaction:* Impaction occurs when the airstream changes direction abruptly and the inertia of a particle causes it to continue in its original direction and collide with the filter material. Impaction is analogous to an insect hitting the windshield of a car driving on a highway: the air molecules can quickly change direction and move up and over the car, but the inertia of the insect causes it to change direction more slowly and impact the windshield. The likelihood that a particle will deposit by impaction increases proportionally with the density, velocity and diameter^2 of the particle. Impaction usually is most important for larger particles (around 1 µm and larger) because of their greater inertia.

3) *Diffusion*: Brownian motion causes small aerosol particles to move randomly and disperse within an airstream. If the particles collide with the filter material, they can deposit on it. Diffusion is most important for particles of around 0.1 µm and smaller.

4) *Electrostatic attraction:* Aerosol sampling filters may carry an electrostatic charge, which can attract charged airborne particles. Charged filter materials can also attract neutral particles by inducing a dipole within the particle, and charged particles can be attracted to

neutral filter materials by image forces (forces created when a charged particle induces an opposite charge in the filter material). This mechanism is especially important for electret-treated filters (filters treated to have permanent electrostatic charges).

5) *Sedimentation:* Sedimentation (or settling) occurs when particles fall onto filter materials because of gravitational forces. Sedimentation is generally significant only for very large particles, very slow flow velocities, or if the air is flowing downward into the filter. Because of this, few particles are collected by sedimentation during most workplace aerosol sampling.

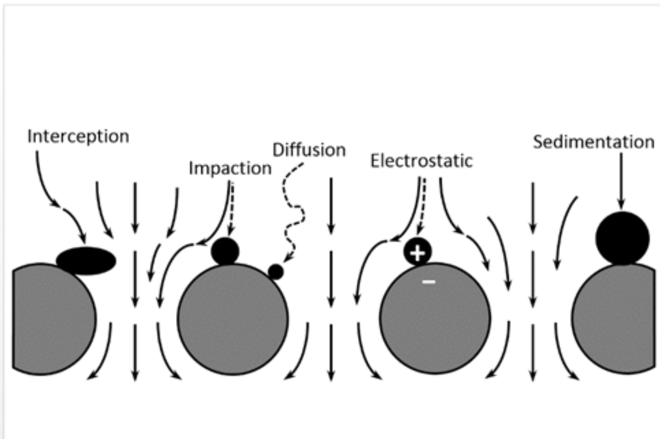

Figure 4: Aerosol particle collection mechanisms. Different types of filters have different structures but they all collect particles using the mechanisms shown here. The relative importance of the various collection mechanisms depends upon the size, shape, density and electrostatic charge of the aerosol particles and the velocity of the air flow through the filter.

An example of the collection efficiencies due to each mechanism for different aerosol particle sizes is shown in Figure 5. The effectiveness and relative importance of these mechanisms depend upon many factors. For example, a higher flow velocity favors impaction by increasing the momentum of the particles, whereas a lower velocity allows more time for particles to diffuse to the filter surface. A highly charged filter and/or aerosol will encourage electrostatic deposition. Fibers and particles with irregular shapes or branching structures are more likely to be intercepted. The filter collection efficiency remains high for nanoparticles from 10 nm down to at least 2 nm; it is thought that the collection efficiency for nanoparticles smaller than 2 nm may decrease due to thermal rebound, but this is still being investigated [Givehchi and Tan 2014; Wang and Tronville 2014].

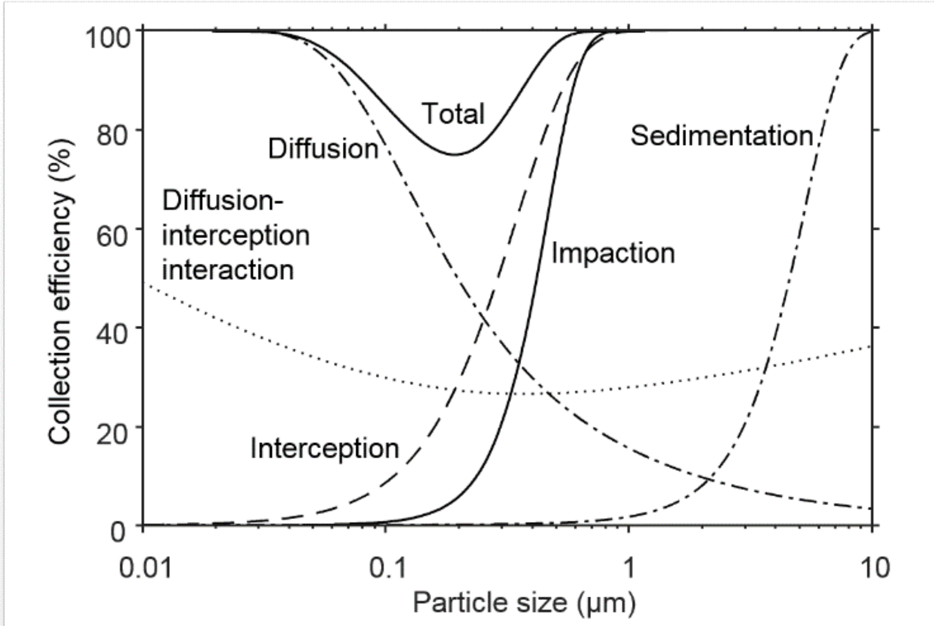

Figure 5: Theoretical collection efficiencies of aerosol particle collection mechanisms for a fibrous filter 1 mm thick with 2 µm fibers and an air velocity of 10 cm/sec. Diffusion-interception interaction is the particle collection due to an enhancement of interception by particle diffusion. The filter surface is assumed to be horizontal with air flowing downward into it, which enhances sedimentation. Total shows the collection efficiency of the filter due to all mechanisms combined. Electrostatic collection is not included because it is very difficult to model. These calculations were based on "single-fiber efficiency" for filters, which is explained in more detail in Hinds [1999]. Figure is adapted from Hinds [1999].

5 Aerosol filter efficiency and pore size

Now, with these collection mechanisms in mind, think about the structures of the different filter types shown in Figure 1. The fibrous and porous membrane filters do not have simple, well-defined pores like a sieve or a simple mesh. Instead, these filters have pathways with a broad range of sizes and a variety of irregular shapes. Thus, particles entering these filters are forced to follow a meandering path, which greatly increases the likelihood that the particles will be intercepted, impact on the filter, or diffuse onto it. For this reason, the probability that a particle will be collected by one of these filters is much higher than one might think based simply on the stated pore size (which is the equivalent pore diameter of the filters). The capillary pore filters provide a more direct pathway through the filter, but even in this case interception, impaction, and diffusion act to collect particles smaller than the sizes of the pores because of the deposition mechanisms discussed in the previous section and shown in Figure 4.

The effect of the structures of these filters and the aerosol particle collection mechanisms that we have discussed can be seen in Figure 6. This plot shows how well particles of different sizes are collected by porous membrane filters, which have tortuous flow paths with equivalent pore diameters of 0.3 and 3 µm, and capillary pore filters with pore diameters of 1 and 3 µm. Note that for all particle sizes, the collection efficiency was ≥99.7% for the 0.3-µm porous membrane filter and ≥98.4% for the 3-µm porous membrane filter, even though the test particles were much smaller than the equivalent pore diameters of the filters. The collection efficiencies of the capillary pore filters were substantially lower, but these filters were also able to collect particles much smaller than their pore sizes. This can also be seen in Figure 7, which shows submicron NaCl aerosol particles collected using a 3-µm porous membrane filter. These results clearly illustrate that the equivalent pore diameter of a filter does not indicate the size of the airborne particles that the filter will collect and that the structure of the filter has a much greater effect on the collection characteristics.

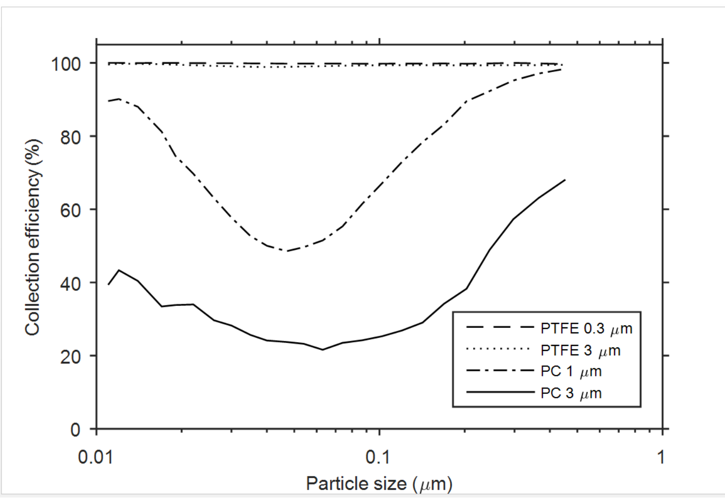

Figure 6: Aerosol particle diameter vs. collection efficiency for polytetrafluoroethylene (PTFE) porous membrane filters with 0.3-µm and 3-µm equivalent pore diameters, and polycarbonate (PC) capillary pore filters with 1-µm and 3-µm pore sizes. The differences in performance are not due to the different materials used for the filters, but rather because the porous membrane filters have tortuous paths which greatly increase the likelihood of particle deposition, while the capillary pore filters have pores that are straighter and smoother. The collection efficiency is the percentage of the particles in the airstream that are collected by the filter. The face velocity (average flow velocity of air into the filter) was 3.5 cm/s for the 0.3-µm PTFE filter and 16 cm/s for the others. The aerosol particles were NaCl. Figure is adapted from Burton et al. [2007].

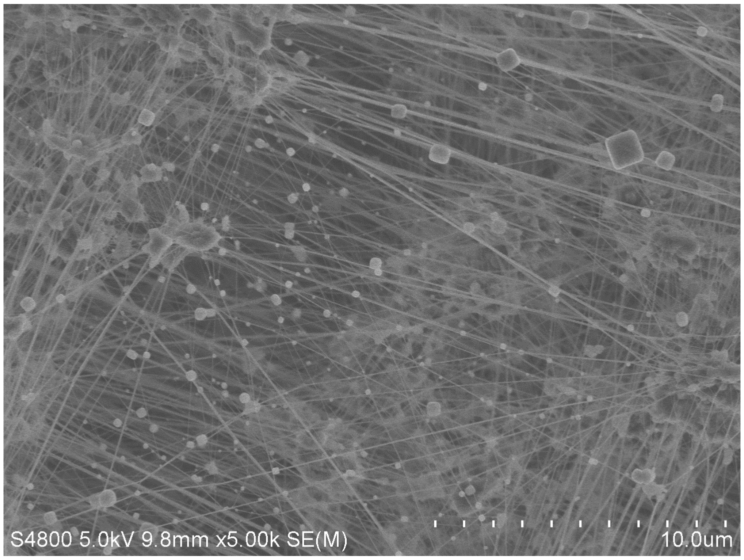

Figure 7: NaCl aerosol particles collected using a PTFE porous membrane filter with a 3-µm equivalent pore diameter at a face velocity of 8.3 cm/s. As can be seen, particles much smaller than 3 µm were captured by the filter.

It is also of interest to note that the collection efficiencies of the capillary pore filters decreased as particle size decreased down to 0.047 and 0.063 µm, and then increased as the particle sizes decreased further. This phenomenon is seen with other types of filters as well. As seen in Figure 5, this occurs because impaction decreases as the particle size decreases, which causes the overall collection efficiency curve to dip downward. However, as particles become even smaller, diffusion becomes a more important collection mechanism, and the collection efficiency increases. The particle size for which the collection efficiency is lowest is called the "most penetrating particle size", or MPPS. The MPPS for a given filter will vary depending upon the air flow rate, the electrostatic charges of the particles and the filter, the amount of particles that are deposited on the filter, and other factors [Lee and Liu 1980; Martin and Moyer 2000].

6 Significance of pore size

So why is it important to understand pore size? First, an investigator may assume incorrectly that an aerosol sample collected by a filter includes only particles larger than the stated pore size of the filter, when in fact the filter collected smaller particles as well. This can lead to a misinterpretation of test results and a misunderstanding of the actual size characteristics of the aerosol being sampled. An investigator also might wrongly try to use a filter with a particular stated pore size as a pre-filter to remove larger particles before collecting a sample; in this case, many smaller aerosol particles would be removed as well, and the true exposure to small particles could be badly underestimated.

Second, it may be mistakenly thought that two filters with the same stated pore size have the same particle collection characteristics. In fact this is not at all true for filters of different types, as seen in Figure 6: the collection efficiency of a porous membrane filter with a given equivalent pore diameter can be much higher than a capillary pore filter with the same stated pore size.

Third, a filter with a smaller pore size usually has a higher resistance to flow (and therefore a higher pressure drop across the filter) than does a filter of the same type with a larger pore size [Breuer 2012]. Thus, an aerosol sampling pump has to create a stronger vacuum to pull air at the same flow rate through a filter with a smaller pore size. If a filter with a very small pore size is selected on the erroneous belief that the small pore size is needed to collect all of the airborne particles, then the pump may not be able to reach the desired flow rate or may not be able to maintain the desired flow rate as the filter becomes loaded with particles and the flow resistance increases. This may cause the collected sample to be smaller than expected. If the sampling pump is battery powered, its running time may be greatly reduced, and the pump may even shut down prematurely.

7 Filter selection

Given all of this, what is the best way to select an aerosol filter for a particular application? The first step is to consider the purpose of the sampling and how the samples will be processed. For example, polycarbonate capillary pore filters are often used when samples are to be examined using scanning electron microscopy (SEM). Fibers are typically collected using mixed cellulose ester filters, which can be rendered transparent for counting by phase-contrast microscopy. Alkaline dusts are collected using PTFE filters, which allow for analysis by titration. For gravimetric analysis, filters that are not hygroscopic and that have stable weights, such as PVC, are needed. The characteristics of the aerosol particles to be collected also influence the choice of filter. Bioaerosols, for example, may lose viability due to damage or desiccation when collected onto filters. Liquid aerosol droplets behave in much the same manner as solid particles while airborne, but once they are collected the liquids can coat the fibers and coalesce into larger droplets, which can reduce the collection efficiency of a filter [Charvet et al. 2010; Contal et al. 2004]. In addition, oils can mask the charged regions of electret-treated filters, which can greatly reduce the collection of particles by electrostatic mechanisms [Barrett and Rousseau 1998].

The next step is to see if a recommended test method has been published for the aerosol particles of interest. Organizations such as the National Institute for Occupational Safety and Health (NIOSH), the Occupational Safety and Health Administration (OSHA), the Environmental Protection Agency (EPA), the American Conference of Governmental Industrial Hygienists (ACGIH), and ASTM International (formerly known as the American

Society for Testing and Materials) publish test methods for a variety of aerosols that include the characteristics of the filters to be used. For example, in the NIOSH Manual of Analytical Methods, Method 0600 for respirable particle sampling specifies the use of a size-selective cyclone and a "5.0-µm pore size, polyvinyl chloride filter or equivalent hydrophobic membrane filter supported by a cassette filter holder (preferably conductive.)" The NIOSH Manual of Analytical Methods also has several chapters discussing different aspects of aerosol sampling, including general considerations and factors affecting aerosol sampling, sampling bioaerosols, sampling airborne fibers, sampler wall losses, and avoiding bypass leakage in filter cassettes [NIOSH 2003; NIOSH 2014].

If a test method is not available, the collection characteristics of different types of filters can be found in reference texts such as those by Lippmann [2001] and Raynor et al. [2011]. A search of the scientific literature also can produce the results from the testing of various filters to collect different kinds of airborne particles. For example, information on the flow resistance of many types of filters and sampling tubes can be found in Breuer [2012], and Soo et al. [2016] recently tested 29 commercially available aerosol filters and reported their flow resistances and collection efficiencies. Filter manufacturers often provide data on the collection characteristics of their filters and on recommended filters for various applications. Finally, it is important to note that filter collection performance can vary with the flow rate and aerosol particle characteristics as well as the filter type and manufacturer. Thus, care should be taken when applying results from one sampling situation to a different set of conditions.

8 Conclusion

The equivalent pore diameter provides a helpful way to categorize filters and to test for consistency in filter characteristics. However, it should not be construed as an indication of the sizes of aerosol particles that will be collected by the filters. A better understanding of the meaning of the term pore size, the structures of the different types of filters, and the mechanisms by which aerosol particles are collected will help in selecting a filter for a particular application and to correctly interpret the results of aerosol sampling.

Acknowledgements

The author thanks Giles Barton of GE Healthcare and Leonid Turkevich, Nancy Burton, Stephen Martin and Seleen Collins of NIOSH for their advice and assistance. The filter images were taken by Diane Schwegler-Berry of NIOSH.

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