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Submicron and Nanoparticulate Matter Removal by HEPA-Rated Media Filters and Packed Beds of Granular Materials

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LIST OF ACRONYMS

BFE	bacteria filter element
EPA	efficient particulate air
ePTFE	expanded polytetrafluoroethylene
HEPA	high-efficiency particulate air
HVAC	heating, ventilating, and air conditioning
ISO	International Organization for Standardization
ISS	International Space Station
MPPS	most penetrating particle size
SEM	scanning electron microscopy
ULPA	ultralow particulate air

NOMENCLATURE

a	superficial surface of a granule per unit volume of bed
C_c	Cunningham slip correction factor
D_{SE}	particle coefficient of diffusion/particle diffusion constant in air
d_f	diameter of the fiber
d_p	diameter of particle/packed bed granule
$d_p G/\eta$	dimensionless group—granule Reynolds number
E_D	diffusion component of overall single fiber efficiency
E_{DR}	combined diffusion and interception component of overall single fiber efficiency
E_G	gravitation capturing efficiency
E_I	inertial impaction component of overall single fiber efficiency
E_R	interception component of overall single fiber efficiency
E_T	overall single fiber efficiency
G	gravity/mass velocity in weight per unit time per unit cross section of bed
H_t	mass transfer zone length
K_n	Knudsen number
k	Boltzmann constant
P	particle percent penetration
Pe	Peclet number
R	ratio of particle to fiber diameter
Re	Reynolds number
St	Stokes number

NOMENCLATURE (Continued)

T	temperature (K)
U	flow velocity
η	gas phase viscosity/dynamic viscosity of carrier gas (kg/m-s)
λ	gas molecular mean free path (m)
$\eta/\rho D_{SE}$	dimensionless group—particle Schmidt number
ρ	gas phase density
ρ_p	density of particle
τ	relaxation time of particle

TECHNICAL MEMORANDUM

SUBMICRON AND NANOPARTICULATE MATTER REMOVAL BY HEPA-RATED MEDIA FILTERS AND PACKED BEDS OF GRANULAR MATERIALS

1. BACKGROUND

Contaminants generated aboard crewed spacecraft consist of both gaseous chemical contaminants and particulate matter. Sources responsible for these contaminants are varied and can include materials used to construct the spacecraft as well as crewmembers' activities. In a crewed spacecraft cabin, suspended particulate matter in the cabin atmosphere can present hazards to crew health and vehicle system performance. The nature of the particulate matter pollutants such as their physical, chemical, and biological properties; the concentration level; and the size spectrum are factors that influence the nature of the hazard which can range from a nuisance to an acute health or equipment impact.

Particulate matter of various types have been isolated aboard crewed spacecraft.[1–3] The size range isolated typically falls above the definition of course particles (>2.5 μm); however, fine particles (<2.5 μm) have also been isolated in smaller quantities. It is also highly likely that equipment and crew activities may also produce submicron particulate matter (<1 μm) and ultrafine particulate matter (<0.1 μm). Material in the latter size range is also classified as nanoparticulate matter, which is formally defined as the size range between 1 and 100 nm (0.1 μm).

Spacecraft cabin atmosphere purification techniques include filtration and physical adsorption processes to remove particulate matter, carbon dioxide, and chemical contaminants from the cabin environment. The efficacy for these separation processes for removing submicron and nanoparticulate matter from the cabin environment are considered by the following discussion.

2. INTRODUCTION TO HIGH-EFFICIENCY PARTICULATE FILTRATION

In the general community, air filtration is intuitively assumed to be similar to the commonly known process of sieving or straining. Here, one intuitively relates to the capture of particles larger than the opening or pore in a filter. Straining mostly occurs at the surface of the filter material. This is more common in liquid filtration where the cake buildup aids in the filtration. Increased buildup leads to higher capture efficiency. At one extreme, a fully blocked or loaded filter is 100% efficient.

High-efficiency air filtration is unlike any other straining-dependent filtration process. The filter media is usually made up of many layers of submicron diameter fibers. In this structure, particles much smaller than the presumed opening in the filter material are readily captured.

2.1 HEPA Filtration Media Overview

High-efficiency filter media is usually made with microfiber glass on wet laid web-forming machines similar to those used for manufacturing paper. It has a homogenous white appearance much like some high rag content 'bond' paper. Hence, it is also common to call filter media filter 'paper.' Fibrous structures needed for the filter media can also be produced by expanded membranes, such as expanded polytetrafluoroethylene (ePTFE). The expansion results in a fibrous structure with uniform submicron dendrites. ePTFE media are more common in higher efficiency ultralow particulate air (ULPA) (>99.99% efficiency) media and where resistance to harsh chemicals such as hydrogen fluoride are required.

High-efficiency particulate air (HEPA) filter media is usually made with borosilicate microfibers with diameters from 2 to 500 nm. The fiber lengths and the proportions of the fibers used are usually proprietary. A typical HEPA media is usually under 0.508 mm (0.020 in) thick. Hence, for the fiber diameters used in its manufacture, the media is comprised of several hundred layers of fibers. Thus, even if there are open spaces in a layer, the layers behind it prevent the further transport of particles.

2.2 Capturing Mechanisms in HEPA-Rated Media

The process of capturing particles on the fibers of the filter media is dependent on the properties and conditions of the incoming flow, and of the flow through the internal microstructure of the filter, and the particle's transport (aerosol) properties. In addition, the tortious pathways created by the interconnected interstices between the fibers significantly enhances the residence time of particles inside the media. These characteristics of the filtration process lead to three basic flow-related capturing mechanisms known as the inertial impaction, interception, and diffusion mechanisms. Two additional mechanisms, straining and electrostatic attraction between the particle and fiber, which in some cases affects the performance of lower performing and HVAC filters, only plays a secondary or minor role in HEPA filtration. Electrostatic attraction is not discussed here.

The illustration in figure 1 provides a visual depiction of the particle dynamics and particle/fiber interactions involved in the different capture mechanisms. In this scenario, the particles are assumed to generally follow the flow streamlines as they approach the filter fiber. For small fiber diameters and relatively low velocities, i.e., at low Reynolds numbers ($Re < 1$), which are typical in filter flows, the flow field around the fiber can be considered laminar. However, the flow curvature produced as the streamlines wrap around the fiber imparts a significant amount of flow acceleration that affects the motion of the particles relative to the streamline.

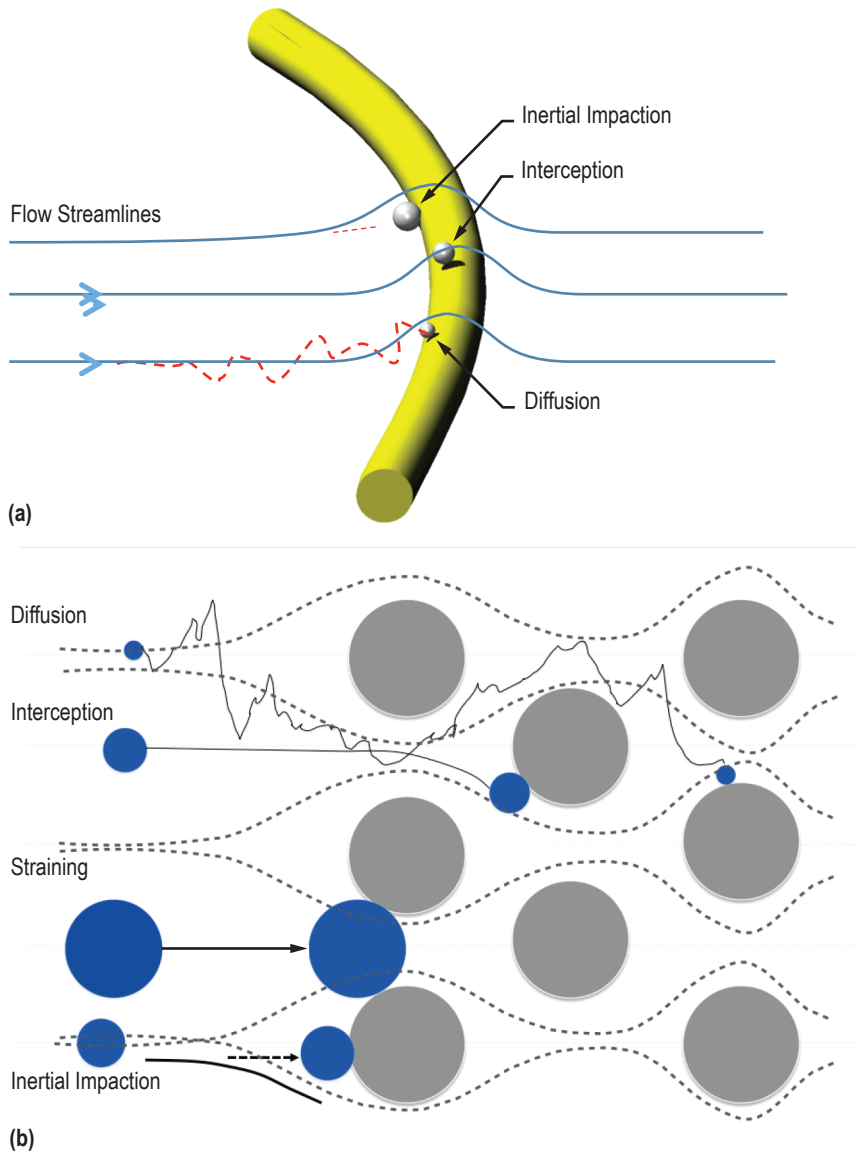

Figure 1. Particle-capturing mechanisms on (a) a single fiber and (b) fiber network. (© R. Vijayakumar. *Used with permission*.)

The fate of different diameter particles along the isolated streamlines are illustrated in figure 1. Inertial impaction is the dominant capturing mechanism for the large diameter particle, as shown by the particle following the top streamline in figure 1(a). The increased inertia causes the particle to deviate from the streamline path when it encounters sufficient flow curvature. If sufficiently massive, the particle directly impacts onto the fiber surface and adheres to it. Adhesion forces (Van der Waals, electrostatics, and capillary) between small particles (<10 μm) and the fiber surfaces ensures collected particles stay on the fibers. The interception mechanism is illustrated in the middle streamline as the particle comes within one radius of the surface of the fiber. In this case, the particle has sufficient contact time with the fiber surface to also get trapped. Lastly, very small diameter particles, as shown in the bottom streamline, are more susceptible to Brownian motion and are intermittently and incrementally knocked off the streamline path by molecular collisions. Due to the randomness of the diffusional collisions, the particle has a chance to approach the fiber surface and also get trapped.

Figure 1(b) shows the mechanisms involved in the straining capturing mode, found more typically in surface filtration. It is recognized that this mechanism only plays a role for very large particles that are typically collected on the front face of the filter media. For reference, a scanning electron microscopy (SEM) micrograph of a filter media coupon cut from an International Space Station (ISS) bacteria filter element (BFE) returned to the ground for analysis after in-flight service is shown in figure 2. This micrograph reveals the intricate fibrous structure of the HEPA media. The micrograph shows the particles captured on the surface of the media during its approximately 2 years of operation aboard the ISS. Any micron and submicron particles that were captured are embedded in the interior of the media and not easily visible in the micrograph.

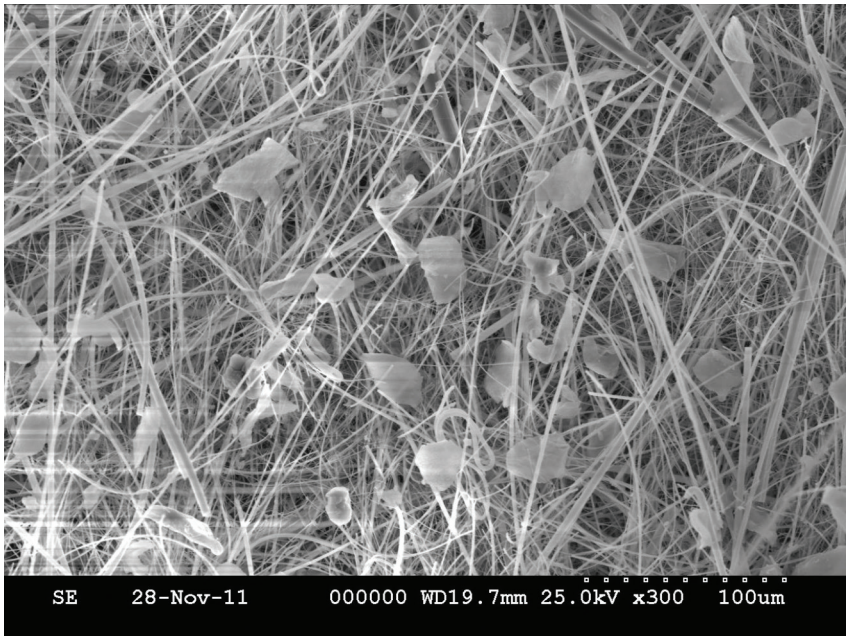

Figure 2. A SEM micrograph of ISS BFE media.

2.3 Filter Performance

2.3.1 Filter Efficiency

The efficiency of the filter media takes into account the various competing particle-capturing mechanisms discussed above. One approach to establishing a basic foundation for filter efficiency is through the Single Fiber Theory. This considers an idealized analysis which assumes uniform fiber size and flow conditions around the fibers, and therefore its utility is in showing the dependence of different particle and flow properties on filter efficiency. According to the theory, the overall single fiber efficiency (E_T) is found from the product of the compliment of all the individual single fiber efficiencies due to inertial impaction (E_I), diffusion (E_D), interception (E_R), diffusion and interception combined (E_{DR}), and gravity (E_G) as shown in equation (1):

$$E_T = 1-\left(1-E_I\right)\left(1-E_D\right)\left(1-E_R\right)\left(1-E_{DR}\right)\left(1-E_G\right) \ . \tag{1}$$

Equation (1) can be approximated by

$$E_T \approx E_I + E_D + E_R + E_{DR} + E_G \ , \tag{2}$$

assuming that one capturing mechanism dominates over the others in order to minimize competing effects of more than one mechanism on the same particle. This is generally the case, as a particle of a specified size will mostly be dominated by just one of the capturing mechanisms. The approximation in equation (2) simplifies the analysis of overall single fiber efficiency as an additive effect of the individual efficiencies of the different capturing modes.

The Stokes and Peclet numbers are the two key physics-based flow parameters, along with several empirically derived constants and coefficients that influence filtration efficiency and performance. Usually only one of these flow parameters tends to have a dominant effect on a specific capturing mechanism. The influence of Stokes drag on a particle near a fiber is characterized by the particle's Stokes number (St):

$$St = \frac{U\tau}{d_f} \ , \tag{3}$$

where U is the flow velocity, τ is the so called relaxation time of the particle, and d_f is the diameter of the fiber. The relaxation time is found from the classical analysis of laminar flow over a sphere and expressed as

$$\tau = \frac{\rho_p d_p^2 C_c}{18\eta} \ , \tag{4}$$

where ρ_p and d_p are the density and diameter of the particle, respectively, C_c is the Cunningham slip correction factor (discussed later in relation to packed beds), and η is the viscosity of the air

medium. The slip factor accounts for gaseous slip at the surface of the particle, which reduces the drag, essentially causing the particle to behave as if it were a larger, more inertial particle. The slip effect becomes a factor with very small particles and at low operating pressures. Under these pressure conditions, enhanced filter efficiency has been reported due to the slip effect.[4] The relaxation time relates to the time it takes for the particle to adjust to new flow conditions, similar to the time it takes a particle to reach settling velocity in a still fluid medium. When $St \gg 1$, the particle is unaffected by flow curvature and continues in a straight line, as is experienced in inertial impaction. At a very low Stokes number ($St \ll 1$), particles follow the flow perfectly, although diffusional forces start to come into effect with very small particles. The second parameter is the Peclet number (Pe), which accounts for the relative importance of diffusional effects:

$$Pe = \frac{Ud_f}{D_{SE}} \ , \tag{5}$$

where D_{SE} is the particle coefficient of diffusion (also discussed in relation to packed beds). Diffusion effects dominate when the Peclet number is very small.

The trend for each of the component single fiber efficiencies can be expressed in terms of the flow parameters given in equations (3) and (5). Impaction single fiber efficiency is directly proportional to the Stokes number, i.e., $E_I \sim St$. This relation shows that the efficiency increases with particle diameter and is dominant at the largest particle diameters. In the diffusional regime, the effect is on small particles where Brownian motion, imparted by the thermal energy of the molecules on the particle, causes a net velocity perturbation on the particle. The single fiber efficiency due to diffusion is inversely proportional to the Peclet number to the –2/3 power, i.e., $E_D \sim Pe^{-2/3}$.[5] Therefore, the efficiency is significantly enhanced at very small particle diameters below the most penetrating particle size (MPPS), typically 120 nm for HEPA and ULPA media filters. Current data from the University of Minnesota indicate that this theory of filtration holds true for particulate matter down to 5 nm in diameter.[6–8] Single fiber efficiency by particle interception is dependent on the ratio of particle to fiber diameter, $R = d_p / d_f$, as $E_R \sim R^2$. In the range of the MPPS, diffusion and interception effects mutually interact and produce a combined fiber efficiency as $E_{DR} \sim Pe^{-1/2}$. Lastly, gravitation capturing efficiency (E_G) is dependent on the ratio of the particle settling velocity to the mean ventilation or cabin velocity, and typically varies as the square of the particle diameter. This last mechanism is not expected to play a role in reduced or microgravity environments.

In addition, the overall filter efficiency has to also include factors for the filter thickness, fiber diameter, and solidity factor of the filter medium. These factors are built into some of the coefficients that define the individual single fiber efficiencies above. For a more indepth analysis of the application of single fiber efficiency to filter efficiency, the reader is referred to reference 5.

The overall (total) filter efficiency of a HEPA filter has been empirically obtained as a function of particle diameter and represented in figure 3. Superimposed are plots showing the trends found from single fiber theory, and showing the relative importance of the different particle capture mechanisms in contributing to the shape of the efficiency curve. The diffusion regime is dominant in the range of the smallest particle diameters, submicron and below. A very high proportion of the particles in this size range, up to 100% at the very smallest particle sizes, get captured by the fibers

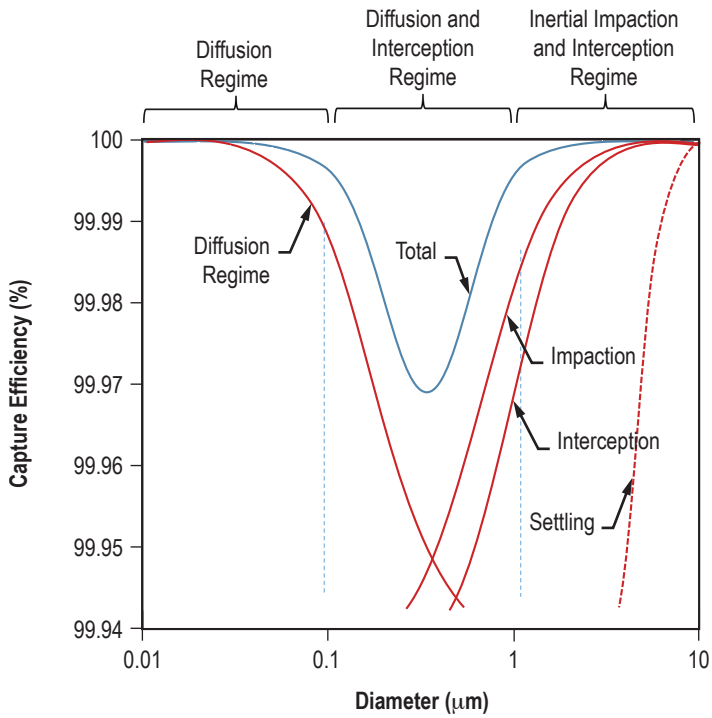

Figure 3. Filter efficiency as a function of particle diameter.

throughout the media. In the upper particle size range, the supermicron range, inertial impaction, and interception are the key capture mechanisms. This regime is also characterized by a very high percentage of particle capture, particularly at the largest particle sizes. In the intersecting regime between these two particle size ranges, the effects of the particle diffusion are shown to taper off while the effects of inertial impaction and interception start to dominate. This is made clear by the plotted efficiency curves of the individual mechanisms showing the trends derived from single fiber efficiency theory. The net effect is a small reduction in filter efficiency that is characterized by a well-defined 'valley' and minimum point. The concept of the MPPS is applicable in this range and is typically taken to be the near minimum efficiency point. The MPPS for typical HEPA filters varies from 200 to 300 nm, depending on flow rate. The key implication to emphasize is that HEPA filters are nearly 100% efficient at capturing the spectrum of particles down to the very smallest airborne particles.

Small changes in flow velocities through the media result in large changes in particle penetration through the filter. Particle penetration (P) is defined simply as the number of particles crossing the filter divided by the number of particles incident on the filter and is related to overall efficiency (E_T) as $P = 1 - E_T$.[9] As a rule of thumb, reducing the velocity by half not only reduces the pressure drop by half but also decreases particle penetration through the filter media by nearly an order of magnitude. This is illustrated in figure 4 where decreasing the velocity by three-fourths reduces the particle penetration over three orders of magnitude with a corresponding efficiency increase from 99.998% to 99.99998%. In other words, a simple HEPA-rated filter will perform as an ULPA-rated or better filter by simply lowering the flow velocity through the media.

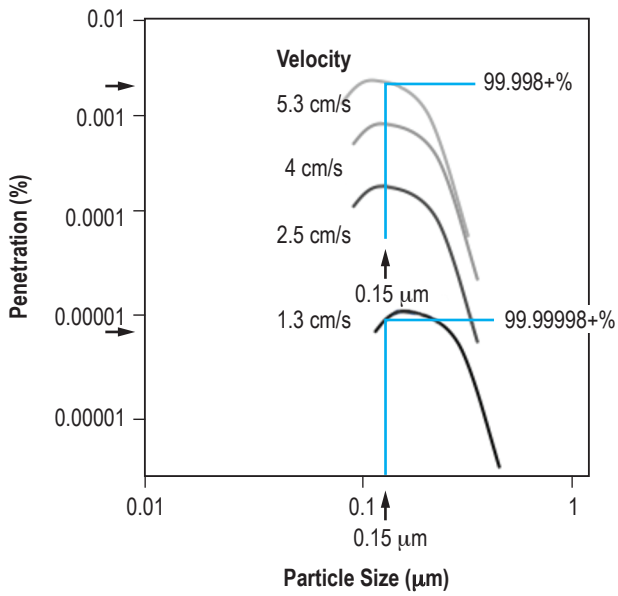

Figure 4. Filter efficiency dependence on velocity; lower velocity increases efficiency. (© R. Vijayakumar. *Used with permission*.)

2.3.2 Hydrodynamic Performance

The fibrous network structure, unlike that of granular filters, is a fairly open, highly porous structure even when densely packed as in high-efficiency media. This characteristic structure translates into relatively low pressure drops across the media. Typical pressure drops across clean HEPA media is usually on the order of 249 Pa (a column inch of water) or less. Typical HEPA filters operate at ~2.55 m^3/0.0929 m^2 (90 ft^3/min/ft^2) or ~27.43 m/min (90 ft/min) velocity. This velocity corresponds to the air flow into the filter cartridge. However, the velocity of the air flow directly impinging on the surface of the media in the filter cartridge—in a well-designed HEPA filter—is usually under 1.5 m/min (5 ft/min) and often half that. At these low velocities, the resistance to air flow is in the D'Arcy regime for flow through porous beds and varies linearly with air flow rate. The nominal media velocity is determined as the total flow over the face of the filter divided by the area of media in the filter. The performance of a filter depends on the media velocity.

The relationship between pressure drop and media velocity of a sample filter media is shown in figure 5. Two very distinct characteristic flow regimes are apparent in the performance curve. First, in the low velocity regime, the resistance to air flow varies linearly with velocity. This performance trend is advantageous since it results in smaller growth in resistance with velocity. A second advantage is that lower velocities afford greater residence times for particles to be collected due to Brownian motion while at the same time reducing the collection due to inertia. Thus, lower velocities increase collection efficiencies of small particles. The opposite effects result when higher velocities are used. As seen in figure 5, the higher flow regime is characterized by a nonlinear and much larger rate of pressure drop increase with media velocity, while particle capturing is dominated less by diffusional capturing and to a greater extent by inertial impaction of larger particles.

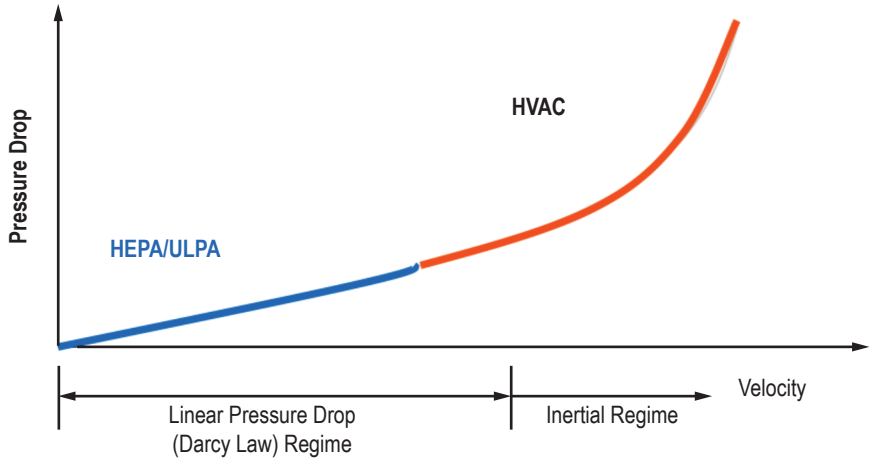

Figure 5. Influence of flow velocity on filter pressure drop.
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2.4 HEPA Filter Classification and Standards

HEPA filters are usually tested twice, and often a third time. First they are tested to determine efficiency followed by testing for leaks or integrity to ensure that there are no local areas of the filter that exceeds acceptable limits even if the overall efficiency is as claimed. In addition, in regulated industries, the filters are tested for integrity in their installed configuration.

Filter testing is governed by United States or International Organization for Standardization (ISO) standards. In all standards, the filter efficiency is determined at the rated flow and at or near the MPPS. Since particles in the MPPS diameter range are the most penetrating or 'leaky' particles, efficiencies equal to or greater than the rated efficiency can be expected for all particle sizes. Leak testing is usually conducted with particles larger than MPPS simply to avoid false results. That is, at larger sizes, the filter is more efficient than the rated value and hence any leak is more readily detected. Since both these tests are nondestructive, 100% of HEPA filters are tested and individually certified. In fact, most test standards require this individual certification to be classified as a HEPA filter.

In most standards, the filters are classified according to their efficiency. Whereas some indicate the performance value in the classification in some fashion (ISO 29463), others use a letter designation (U.S. Institute of Environmental Sciences and Technology). Although the standards start with the same theoretical basis of testing at MPPS, no two are alike; they specify different aerosols and detectors. For example, in the United States, a photometer is still the main particle detector used for HEPA filter testing while particle counters are the common devices used in Europe. Further, both the ISO and European standards have introduced a new filter classification—efficient particulate air (EPA) filters—with efficiencies of 99.95% and lower.

3. PARTICULATE REMOVAL BY PACKED BEDS

Packed beds of granular or pelletized porous adsorbent media are typically used for the removal of gaseous and molecular contaminants. Beds of substantial depths may also provide an assist to media filters for removing particulate matter <0.1 μm. However, using absorbent beds for particle removal usually reduces the effectiveness and life of the bed for gaseous and molecular contaminants due to loading of the pores in the adsorbent media with particulate matter. The media in a packed bed can function similarly to a depth filter and remove fine and ultrafine particulate matter via impaction, interception, and diffusion mechanisms. Studies on particulate matter removal by packed beds have found that, similarly to HEPA media filters, the 0.3-μm size is the MPPS.[10] These studies, however, found that packed bed efficiencies for removing 0.3-μm-size particles, the HEPA media filtration MPPS, are an order of magnitude lower than for particulate matter <0.1 μm and >1 μm in size.[11] Therefore, while deep packed beds have been shown experimentally to remove ultrafine and course particulate matter, they are not suitable by themselves for providing HEPA-rated performance for the most penetrating particle size of 0.3 μm. The efficiencies afforded by shallow packed beds are negligible and, in practice, such beds are unsuitable for providing particulate filtration and must be combined with media filtration to effectively remove particulates and volatile components from a gas stream.

Experimental studies have found that granular adsorbent media such as activated carbon removes 0.3-μm-diameter particulate matter and gaseous contaminants by a similar mechanism over a wide range of diffusion coefficient magnitude.[12] The removal occurs primarily in the interstitial space between packed bed granules and, for porous granules, to a very small degree in the granules' macropores. Besides the particulate matter size, the primary factors influencing the removal are the carrier gas velocity and the diffusion constant of the aerosol. An effective bed penetration depth represented as the height of a bed mass transfer zone can be estimated by equation (6) which is a modification of the Mecklenburg approach used for estimating adsorbent bed breakthrough:[12]

$$H_t = \left(\frac{1}{a}\right)\left(\frac{d_p G}{\eta}\right)^{0.41}\left(\frac{\eta}{\rho D_{SE}}\right)^{0.67}, \tag{6}$$

where H_t is the mass transfer zone length, a is the superficial surface of a granule per unit volume of bed, d_p is the diameter of a packed bed granule, G is the mass velocity in weight per unit time per unit cross section of bed, η is the gas phase viscosity, ρ is the gas phase density, and D_{SE} is the particle diffusion constant in air. The dimensionless group, $d_p G/\eta$, is the granule Reynolds number while the dimensionless group, $\eta/\rho D_{SE}$, is the particle Schmidt number. Units of measure used in equation (6) should be consistent for determining the Reynolds and Schmidt numbers and SI units of kilograms, meters, and seconds are recommended.

The particle diffusion constant, D_{SE}, is defined by equation (7) which is the Stokes-Einstein equation modified for the slip regime:[13]

$$D_{SE} = {kTC_c}/{3\pi\eta d_p}\ , \tag{7}$$

where k is the Boltzmann constant (1.31×10^{-23} J/K), T is temperature in Kelvin, C_c is the Cunningham slip correction factor, η is the dynamic viscosity of the carrier gas in kg/m-s, and d_p is the particulate diameter in meters. The Knudsen number (K_n) relates the gas molecular mean free path (λ) in meters to the particle size (d_p) in meters as shown by equation (8):[14]

$$K_n = {2\lambda}/{d_p}\ . \tag{8}$$

Continuum flow exists when K_n is <<1 while molecular free flow exists when K_n is >>1, while the slip regime exists for $0.4 < K_n < 20$. The Knudsen number is a parameter used to calculate the Cunningham slip correlation factor according to equation (9) for solid particles:[15]

$$C_c = 1 + K_n\left[1.142 + 0.558e^{-0.999/K_n}\right]\ . \tag{9}$$

Research has observed 75% to 90% removal of 0.004-µm particles by a 1.9-cm-deep activated carbon bed containing 6×16 mesh (<3.327 mm and >0.991 mm) carbon granules.[15] Deep packed beds may be expected to approach HEPA-like removal efficiency for ultrafine and nanoparticulate contaminants. This approach to high removal efficiency was observed during a test of a 38-cm-deep activated carbon bed challenged with 200.5 mg/m^3 of 0.6-µm particles. The beginning efficiency of 88.4% rose to 97% after 135 minutes.[13] This reported performance equates to ~2.3% to ~2.5% per centimeter of bed depth if a linear dependence on depth is assumed. In reality, this relationship may be nonlinear. A 2-cm-deep bed, therefore, would at best provide ~4.6% to ~5.1% removal efficiency for 0.6-µm particles based on these experimental results. To provide reasonable effectiveness, the bed would need to be >40 cm deep, or more specifically, several times deeper than a comparably performing HEPA media filter to even approach the performance provided by a HEPA-rated media filter.

Although most adsorbent beds used aboard crewed spacecraft for atmosphere revitalization purposes typically are >30 cm deep, the adsorbent beds used in payloads are typically <5 cm deep, and high flow rate applications in a cabin ventilation system are typically <10 cm deep. Based on the results reported in the literature, shallow activated carbon beds used in payload and spacecraft cabin ventilation system applications may be capable of providing some degree of removal efficiency for ultrafine particles (≤100 nm). However, the expected performance for removing larger submicron (fine) particles is poor, particularly in the MPPS range. Therefore, granular adsorbent beds alone are not suitable for providing highly effective removal performance for particles in the fine and ultrafine size ranges. For applications where both particulate removal and gaseous contaminant removal must be provided, both high-efficiency media filtration and adsorbent bed components are necessary.

By this evidence, filtration media effectiveness for removing ultrafine and nanoparticulate materials can be enhanced to a small degree when used in combination with a packed bed of granular media located downstream of the filtration media. The opposite is also true in that the fine particulate removal effectiveness of a shallow adsorbent bed can be significantly enhanced by including a media filtration component upstream of the adsorbent bed.

Many gas purification components associated with containing experimental payload and system process vents typically include both adsorbent and media filtration components; therefore, in combination, they can provide an effective particulate removal function when used in an appropriate configuration consisting of a media filtration component upstream of a packed adsorbent bed component.

4. CONCLUSION

The phenomena associated with particulate matter removal by HEPA media filters and packed beds of granular material have been reviewed relative to their efficacy for removing fine (<2.5 μm) and ultrafine (<0.01 μm) sized particulate matter. The ultrafine particulate range constitutes the range defined as nanoparticulates. Generation sources may be diverse and the means to remove nanoparticulates via conventional methods is a valuable capability aboard crewed spacecraft. Both HEPA media filters and packed beds of granular material, such as activated carbon, which are both commonly employed for cabin atmosphere purification purposes, are found to have efficacy for removing nanoparticulate contaminants from the cabin atmosphere. When used alone, HEPA-rated media provides superior performance for removing virtually 100% of particulates. However, using these methods in an appropriately combined configuration for removing particulates and gaseous contaminants, consisting of a media filtration component upstream of a packed adsorbent bed component, provides the most effective performance for a broad range of particle sizes including nanoparticulates.

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14. ABSTRACT
Contaminants generated aboard crewed spacecraft by diverse sources consist of both gaseous chemical contaminants and particulate matter. Both HEPA media filters and packed beds of granular material, such as activated carbon, which are both commonly employed for cabin atmosphere purification purposes have efficacy for removing nanoparticulate contaminants from the cabin atmosphere. The phenomena associated with particulate matter removal by HEPA media filters and packed beds of granular material are reviewed relative to their efficacy for removing fine (<2.5 μm) and ultrafine (<0.01 μm) sized particulate matter. Considerations are discussed for using these methods in an appropriate configuration to provide the most effective performance for a broad range of particle sizes including nanoparticulates.

15. SUBJECT TERMS
particulate matter, filtration, nanoparticulates, HEPA filter, packed bed, particle capturing mechanisms

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