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17th DOE NUCLEAR AIR CLEANING CONFERENCE

THE EFFECT OF PARTICLE SIZE VARIATION ON FILTRATION EFFICIENCY MEASURED BY THE HEPA FILTER QUALITY ASSURANCE TEST*

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Abstract

Satisfactory performance of new high efficiency particulate air (HEPA) filters is verified by quality assurance (QA) tests conducted prior to filter installation. Filtration efficiency for this test is defined as the ratio of the downstream aerosol concentration to the concentration upstream of the filter, as measured with a light scattering photometer (penetrometer) sensing light intensity scattered in the near forward direction. Existing QA acceptance criteria is interpreted as requiring the HEPA filter to be at least 99.97 per cent efficient for 0.3 μm diameter, unit density particles. The actual meaning of QA test results is dependent on a number of variables including the average size and size distribution of the challenge aerosol, the efficiency of the filter with respect to particle size, the size distribution of the penetrating aerosol, and the sensitivity of the photometer with respect to particle size and concentration.

A theoretical model has been used to calculate the filtration efficiency that would be indicated by the photometer for challenge aerosols of different size distributions and HEPA filters with different efficiencies as functions of particle size. The model compares the calculated overall efficiency indicated by the photometer with efficiencies calculated with respect to particle number and mass. This calculation assumes three aerosol distributions previously measured at the Filter Test Facilities (FTF) and four different filtration efficiency versus size curves.

The differences in efficiency measured by the QA test procedure and the efficiencies with respect to aerosol mass and number have been calculated for a range of different size particles. The results of these calculations are discussed.

1. Introduction

The measurement of air filter efficiency requires a challenge aerosol and instrumentation to determine aerosol concentration upstream and downstream of the filter. Filtration efficiency may be determined with respect to aerosol mass, particle number or any parameter for which the concentration measurements can be made. In general, filtration efficiency is expressed in terms of the ratio of the downstream concentration to the upstream concentration using the following relationship:

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$$E = 100 \left(1 - \frac{C_D}{C_U} \right) \quad , \text{ where} \quad (1)$$

E is the efficiency in per cent, C_D the downstream concentration and C_U the upstream concentration. This calculation assumes that equivalent concentration measurements have been made at each location.

Quality Assurance (QA) or acceptance tests are conducted on High Efficiency Particulate Air (HEPA) filters to verify that the filters satisfy minimum performance criteria.⁽¹⁾ These tests should be carried out rapidly; should not impact on the useful life of the filter by heavy loading; and should use an aerosol material that does not alter the filter. The aerosol concentration measuring instrument must provide rapid or real time measurements and have sufficient sensitivity to verify acceptable performance. For most applications it is only necessary to verify that the filter efficiency is greater than some minimum value. In the case of HEPA filters, this is generally accepted to be an efficiency of 99.97 per cent when the filter is challenged by a 0.3 μ m diameter test aerosol. The requirement for a rapid measurement for both high (upstream) and low (downstream) aerosol concentrations limits the types of satisfactory instruments. These requirements also make it more difficult to insure that equivalent concentration measurements are obtained at both sampling locations.

There are two common causes of nonequivalent concentration measurements. The large difference in concentration ($\sim 10^4$) encountered across HEPA filters is beyond the linear range of many instruments. In principle, this problem can be handled by careful instrument calibration. However, there is always some doubt about the general application of any calibration. A second cause of nonequivalent concentration measurements is the use of instruments whose response is particle size dependent. Instruments of this type may be used to measure filtration efficiency if the particle size distribution is known at both locations and appropriate corrections are made, or if the challenge aerosol is monodisperse. The existing HEPA filter QA test⁽²⁾ specifies the use of a monodisperse aerosol to insure that the size distribution of the upstream and downstream aerosols are identical and that concentration measurements are equivalent.

The monodisperse aerosol generator used for the FIF QA test is of the LaMer type⁽³⁾ where monodisperse aerosols are produced by evaporation of an organic material followed by controlled condensation of the material. In order to grow to the same size, all particles must have the same temperature and vapor concentration history. These conditions are difficult to obtain at the flow rates and concentrations required to conduct QA tests. Field studies reported elsewhere at this meeting⁽⁴⁾ indicate that the aerosols produced at the QA facilities are not monodisperse, but have geometric standard deviations greater than 1.35. This study has been carried out to investigate the effects of using a polydisperse aerosol with concentration measuring instruments designed for use with monodisperse aerosols.

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II. Objectives and Approach

An analytical study was performed to address the potential error introduced in HEPA filter efficiency measurements by the determination of aerosol concentration using a penetrometer, whose response is particle size dependent, under test conditions where the aerosol upstream and downstream from the HEPA filter is polydisperse and has a different size distribution. The analytical study involved:

- a) Calculation of the HEPA filter efficiency defined by the penetrometer for three different assumed aerosol size distributions and four different assumed models of HEPA filter efficiency as a function of size.
- b) Calculation of the HEPA filter efficiency in terms of aerosol mass and particle number for the same aerosols and filter efficiency models noted in (a).

The assumed aerosol size distributions were selected to approximate the aerosols recently measured at the FTF.⁽⁴⁾ HEPA filter efficiency as a function of particle size was based on either of two experimental results or was adjusted from these experimental data to the QA acceptance criteria (99.97 per cent efficient for 0.3 μm diameter particles).

III. Aerosol Concentration Measurement Using a Photometer

The concentration measuring instrument specified for HEPA filter QA tests is the forward light-scattering photometer. This instrument will measure concentration over wide ranges and provides rapid determination of satisfactory filter performance. Figure 1 is a schematic view of a forward light-scattering photometer of the type used in the QA tests. The light from an incandescent lamp is focused in the center of a chamber containing the aerosol sample. The center of the lens is masked to form a conical annulus of light around a central shadow. If there are no particles present in the sample, then the pattern will be repeated beyond the focal point resulting in a shadow on the light-gathering lens system of the light detector. The presence of particles in the focal plane of the lens will result in the scatter of light into the conical shadow beyond the focal plane. This scattered light will be detected by the photomultiplier tube. The signal from the photomultiplier tube is converted to a concentration measurement by calibration of the system.

Dependency of the forward light-scattering photometer on particle size and index of refraction is well known. Sinclair proposed the use of this type of instrument for measuring particle size.⁽⁵⁾ The relative responses of this photometer as a function of particle size for di-ethylhexyl phthalate (DEHP) and di-ethylhexyl sebacate (DEHS) were calculated based on the geometry of a commercially available light-scattering photometer and the wavelength spectrum of the illuminating light which was determined by assuming the lamp is a black body radiator at a temperature of 2850° Kelvin. A Mie computer code was then used to calculate the amount of light scattered to the detector over the wavelength spectrum of the illuminating light. The sensitivity of the photomultiplier tube as a function of wavelength

FIGURE 1
SCHEMATIC VIEW OF FORWARD LIGHT-SCATTERING PHOTOMETER

FIGURE 2
CALCULATED RELATIVE RESPONSE OF FORWARD LIGHT-SCATTERING PHOTOMETER
AS A FUNCTION OF PARTICLE SIZE FOR DI-ETHYLHEXYL PHTHALATE AND
DI-ETHYLHEXYL SEBACATE

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was used to determine the relative response of the photometer. Calculations were made for 100 particle diameter increments of $0.01\text{ }\mu\text{m}$, for particles ranging in size from $0.01\text{ }\mu\text{m}$ up to $1.0\text{ }\mu\text{m}$. The curve shown in Fig. 2 is the smooth connecting curve for these 100 calculated data points. Over the particle size range from 0.01 to $1.0\text{ }\mu\text{m}$ diameter, the relative response varies almost 10 orders of magnitude. The two curves for DEHP and DEHS are close together or coincide over this size range. The plotted points (x) on Fig. 2 are data presented by Sinclair⁽⁵⁾ as measurements of the voltages produced by the photomultiplier when particles of various sizes and refractive indices are passed through the photometer. These data were normalized to fit the curve at $0.84\text{ }\mu\text{m}$ and indicate good agreement between the calculated curve and the experimental data.⁽⁵⁾

Figure 2 illustrates the importance of particle size to the signal produced by the photometer. The curve indicates that it takes about one hundred $0.10\text{ }\mu\text{m}$ diameter particles to produce the same signal as one $0.20\text{ }\mu\text{m}$ diameter particle. The strong dependence of photometer response on particle size indicates that errors may result when concentrations, measured from aerosols having different size distributions, are compared on the basis of the signal obtained using this type of photometer. This effect can be important when measuring the efficiency of a HEPA filter using a polydisperse aerosol, where the size distribution of the test aerosol upstream and downstream from the filter are different.

IV. Procedure

The differences between filtration efficiency with respect to aerosol mass, aerosol particle number, and light-scattering photometer readings have been investigated by computer calculations. The calculations have been limited to the narrow range of filter test conditions encountered during QA tests of HEPA filters. A flow diagram indicating the steps used in this calculation is given in Fig. 3. The first step involved the numerical creation of an aerosol based on selected parameters for a log normal size distribution of particle volume. The size distribution was then sub-divided into 1700 intervals and the mass and number of particles in each interval was calculated using the log normal distribution function to determine mass and

$$N_i = \frac{6 M_i}{\rho \pi D_i^3} \quad (2)$$

to determine number. In equation (2): N_i is the number of particles in the i^{th} size interval; M_i is the mass associated with particles in the i^{th} size interval; ρ is the density of the particles; and D_i is the average particle diameter in the i^{th} interval. Photometer response for particles in the i^{th} interval was estimated by multiplying the relative photometer response (Fig. 2) for D_i times N_i . The relative photometer response was determined by interpolation between the 100 individual calculations for particles between 0.1 and $1.0\text{ }\mu\text{m}$ in size. A best fit curve was taken from the data of Sinclair⁽¹⁾ to determine relative photometer response for particles larger than $1.0\text{ }\mu\text{m}$.

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FIGURE 3
FLOW DIAGRAM FOR COMPUTER MODEL OF EFFICIENCY MEASUREMENTS

Aerosol mass and number concentrations, and photometer response was calculated for each size interval, and also summed over all size intervals, for the upstream aerosol. These same data were determined for the aerosol penetrating the HEPA filter (downstream aerosol) based on the number of particles in each size interval times a HEPA filter efficiency factor obtained from a filter efficiency curve (discussed below) for the average particle size in each size interval. These upstream and downstream data are then used to calculate overall filter efficiency based on aerosol mass, particle number, and photometer readings.

While Mie theory and physical measurement of the photometer optics provide a sound basis for defining relative photometer response, filter efficiency as a function of particle size varies between filters so some representative values had to be used. Four different filtration efficiency curves were considered. The first, shown in Fig. 4, is a second order exponential fit to data from an experimental measurement of DEHP penetration by Schuster and Osetek⁽⁶⁾ in the particle size region of 0.1 to 0.3 μm . The high efficiency of HEPA filters have resulted in very little information on the penetration of micron size particles. The efficiency curve for particles larger than 0.35 μm was based on a smooth transition from the curve fitting the data to a penetration of essentially zero (3×10^{-10}) at 3.0 μm .

The QA test specifies the satisfactory performance of HEPA filters as an efficiency of at least 99.97 per cent for particles of 0.3 μm diameter. An important aspect of the QA test is the sensitivity to detection of a filter that just satisfies or just fails this minimal performance criteria. The evaluation of the QA test performed on a border line filter required the use of a hypothetical filtration efficiency curve. The shape of the curve shown in Fig. 4

FIGURE 4

HEPA FILTER PENETRATION FOR DEHP PARTICLES (SCHUSTER AND OSETEK)(5)

was used to create the hypothetical curve. This efficiency curve was selected because the QA test is based on the assumption of a particle size that is most difficult to filter with a subsequent, easiest to measure lower efficiency. This type of efficiency curve (Figs. 4, 5, and 6) is consistent with the concept of several filtration mechanisms (diffusion, impaction, and interception). The hypothetical efficiency curve was created by displacing the particle size axes in Fig. 4 to set the maximum penetration at a particle size of $0.3 \mu\text{m}$. The amplitude of the curve in Fig. 4 was increased by multiplication by a constant factor to provide a penetration of 0.0003 for the maximum penetrating particle size of $0.3 \mu\text{m}$. The resulting curve is shown in Fig. 5. This curve has been created to match the single specified test condition in the QA test. Efficiency measurements that have been carried out to date(6,7) indicate the hypothetical low efficiency curve is not representative of high efficiency filters with respect to magnitude of penetration or particle size of maximum penetration. The shape of the curve is similar to most experimental filtration efficiency curves.

A filter efficiency curve from Dupoux and Briand(7) was also used, as this curve (Fig. 6) extends over a wider range of particle sizes. The maximum penetration observed by Dupoux and Briand (7) is about an order of magnitude higher than was observed by Schuster and Osetek.(6) For the reasons previously noted, the data of Fig. 6 was also adjusted (particle sizes increased by $0.15 \mu\text{m}$ and penetration multiplied by 2.6) to provide a maximum penetration of 0.0003 at a particle size of $0.3 \mu\text{m}$ for one set of efficiency calculations.

Filtration efficiency curves cannot be uniquely defined as they vary between filters and possibly by the method used to measure efficiency. However, for the purposes of this study, it is sufficient

FIGURE 5
HEPA FILTER PENETRATION CURVE FROM SCHUSTER AND OSETEK TRANSPOSED TO
MAXIMUM PENETRATION OF 0.0003 AT 0.3 μm

that the efficiency curve has a particle size variation that is characteristic. Figures 4, 5, and 6 all are similar to most experimental efficiency measurements with some difference in magnitude and location of the peak. The monotonic response of the photometer shown in Fig. 2 indicates that location of the peak anywhere between 0.05 to 0.50 μm will have little effect on the calculations. The two experimental efficiency curves give overall efficiencies very similar to the results of experimental measurements of HEPA filters.

In all four cases, the filter efficiency calculation was checked by use of a computer generated challenge aerosol having (1) the same volume median diameter as the aerosol of interest, but a geometric standard deviation of 1.05 (approximately monodisperse) and (2) a count median diameter (cmd) that matches the size of maximum penetration for the efficiency curve also with a geometric standard deviation of 1.05. In all of these cases, all three efficiencies (mass, number, and photometer) were identical and matched the filtration efficiency curve values for the median diameters. The calculations for monodisperse aerosols confirmed the performance of the calculation procedure.

The efficiency curves used in this model may not be representative of the efficiency curves of filters having performance that is marginal or performance that would fail the QA test. The curves were obtained with filters that were significantly better than the acceptance criteria. It is possible that filters having efficiencies below 99.97 per cent will not have sharp peaks in their efficiency curves. However, at the present time there is no information on the performance characteristics of filters that do not meet the acceptance criteria. This indicates the need for a better definition of

FIGURE 6

FILTER PENETRATION AS A FUNCTION OF PARTICLE SIZE (DUPOUX AND BRIAND)

filter efficiency as a function of particle size based on both experimental and theoretical work. If the efficiency curves vary significantly between acceptable and non-acceptable filters, then the type of efficiency measurement that is being made may also vary significantly. The results of this study should be representative for normal operating or acceptable filters.

V. Results

Filtration Efficiency Curve Varied for Three Experimentally Measured Aerosols

The efficiencies calculated for the three aerosols observed at the FTF are given in Table I. The reference column indicates if the filter efficiency model is based on the work of Schuster(6) or Dupoux.(7) The size at minimum efficiency column indicates if the filter efficiency model has been adjusted to produce minimum efficiency at 0.3 μm diameter, or if it is based on the experimental data which indicates the size of maximum penetration is 0.196 μm (6) or 0.146 μm .(7)

Except for one test, the difference between the per cent efficiency based on particle mass, particle number or photometer reading for the three aerosol sizes analyzed are all less than 0.01 per cent. This magnitude of difference would have a negligible effect on overall efficiencies specified to .01 per cent.

Table 1. Filtration Efficiencies

Aerosol Characteristic			Filter Efficiency Curve			Calculated Overall Removal Efficiencies (%)			
Material	CMD ¹ (μm)	GSD ²	Minimum Efficiency (%)	Size at Minimum Efficiency (μm)	Efficiency for 0.3 μm Diam. Particles	Reference	Particle Mass	Particle Number	Photometer Reading
DEHP	0.18	1.38	99.9982	0.146	99.9996	6	99.999	99.999	99.999
DEHP	0.18	1.38	99.9887	0.146	99.9943	7	99.992	99.990	99.995
DEHP	0.18	1.38	99.970	0.300	99.970	6	99.984	99.991	99.983
DEHP	0.18	1.38	99.970	0.300	99.970	7	99.980	99.987	99.977
DEHP	0.19	1.45	99.9982	0.196	99.9996	6	99.999	99.999	100.00
DEHP	0.19	1.45	99.9887	0.146	99.9943	7	99.994	99.991	99.996
DEHP	0.19	1.45	99.970	0.300	99.970	6	99.985	99.990	99.988
DEHP	0.19	1.45	99.970	0.300	99.970	7	99.979	99.985	99.981
DEHS	0.17	1.34	99.9982	0.196	99.9996	6	99.999	99.999	99.998
DEHS	0.17	1.34	99.9887	0.146	99.9943	7	99.991	99.990	99.990
DEHS	0.17	1.34	99.970	0.300	99.970	6	99.985	99.992	99.988
DEHS	0.17	1.34	99.970	0.300	99.970	7	99.981	99.988	99.982

¹Count Median Diameter

²Geometric Standard Deviation

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These results also indicate that the QA test conducted with these aerosols does not provide a consistent or accurate measurement of the criterion specified for the QA test. The QA test is supposed to measure the filtration efficiency for $0.3\text{ }\mu\text{m}$ diameter particles. In general (75 per cent of the measurements) the photometer measured efficiency is greater than the actual filtration efficiency for $0.3\text{ }\mu\text{m}$ diameter particles.

Effect of Aerosol Parameter Variation on Efficiency Measurement

The correlation between efficiency measurement method and characteristics of the particle size distribution was investigated by calculating the filtration efficiency with respect to particle number, and photometer measurements for aerosols having volume median diameters up to $5\text{ }\mu\text{m}$ and geometric standard deviations up to 2.5.

These calculations were carried out for all four filter efficiency models. The models based on actual experimental efficiency measurements (Figs. 4 and 6) indicated no photometer response to the downstream aerosol when the challenge aerosol has a volume median diameter of greater than $1.0\text{ }\mu\text{m}$. Measurements made under these conditions would provide little information on filter performance. The lower efficiency curves derived by adjustment of the two experimental efficiency curves to 99.97 per cent efficiency for $0.3\text{ }\mu\text{m}$ particles illustrate the effect particle size distribution can have on efficiency measurements. These results are shown in Figs. 7 and 8. The photometer measured efficiencies are lower than the number efficiencies (Photometer Eff - Number Eff < 0) when the challenge aerosol has a small median diameter ($D < 0.5\text{ }\mu\text{m}$). This diameter increases as the geometric standard deviation increases. The photometer measured efficiency is greater than the number efficiency when the median diameter is greater than about $1\text{ }\mu\text{m}$ with the difference increasing as geometric standard deviation increases. The range between 0.5 and $1.0\text{ }\mu\text{m}$ is interesting as in place filter tests use aerosols in this size range. There appears to be some possibility for significant differences in this range. However, the reason for these differences is not apparent.

VI. Discussion

The calculated efficiencies in Table I indicate the photometer will provide a reasonable and often conservative measure of "true" filter performance for the FTF test aerosols. However, the measured efficiencies do not provide a good correlation with the criteria (efficiency at $0.3\text{ }\mu\text{m}$) specified by the QA test. This is probably the result of the very sharp peak in the filtration efficiency curves (i.e., Fig. 5). Any polydispersity in the test aerosol or any difference in the mean diameter of a monodisperse aerosol from the diameter specified for the test ($0.3\text{ }\mu\text{m}$) can result in significant differences between the measured filtration efficiency and the actual efficiency for monodisperse $0.3\text{ }\mu\text{m}$ particles. Significant in this case means differences that could result in errors in acceptance or rejection of filters.

The results shown in Figs. 7 and 8 indicate that the photometer measured efficiencies will be lower than the actual number efficiencies when the particles are small, where the relative response of the

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FIGURE 7

DIFFERENCE BETWEEN EFFICIENCY CALCULATED FOR THE PHOTOMETER READING AND CALCULATED NUMBER EFFICIENCY FOR SCHUSTER AND OSETEK EFFICIENCY CURVE ADJUSTED TO 99.97 PER CENT EFFICIENCY AT 0.3 μm , GEOMETRIC STANDARD DEVIATION EQUAL = 1.5, 2.0, and 2.5.

photometer is low. The use of a test aerosol having larger particles will result in an overestimate of the number efficiency. There is, of course, less difference between efficiency with respect to mass and the photometer measured efficiency, since the larger particles make the most significant contribution to the airborne mass and the relative photometer response is much higher for the larger particles.

The most significant difference between the test as it is often conducted with a polydisperse aerosol having a median diameter of less than 0.3 μm , is that the test does not measure the performance specified by the test. The filters that leave the filter test facilities carry a stamp saying they will remove at least 99.97 per cent of the 0.3 μm particles. However, these results indicate that slight variations in the challenge aerosol result in almost no information about filter performance with respect to 0.3 μm diameter particles. These calculations also indicate that specification of filter performance with respect to a single particle size provides extremely limited information. The results provided by the QA test are usually a conservative or an underestimate of filter performance with respect to the challenge that will be encountered in the field. The test results with the polydisperse aerosol are actually more representative of filter performance than the efficiency measured for 0.3 μm diameter particles.

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FIGURE 8
DIFFERENCE BETWEEN EFFICIENCY MEASURED BY PHOTOMETER AND NUMBER EFFICIENCY FOR DUPOUX AND BRIAND EFFICIENCY CURVE ADJUSTED TO 99.97 PER CENT EFFICIENCY AT 0.3 μ m, GEOMETRIC STANDARD DEVIATION = 1.5, 2.0, and 2.5.

The differences calculated and discussed between the various efficiencies are quite small, but it is important to remember that a penetration of .0025 is acceptable while a penetration of .0035 means the filter is rejected.

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