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Fractional Aerosol Filtration Efficiency of In-Duct Ventilation Air Cleaners

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Abstract

The filtration efficiency of ventilation air cleaners is highly particle-size dependent over the 0.01 to 3 μm diameter size range. Current standardized test methods, which determine only overall efficiencies for ambient aerosol or other test aerosols, provide data of limited utility. Because particles in this range are respirable and can remain airborne for prolonged time periods, measurement of air cleaner fractional efficiency is required for application to indoor air quality issues. The objectives of this work have been to 1) develop a test apparatus and procedure to quantify the fractional filtration efficiency of air cleaners over the 0.01 to 3 μm diameter size range and 2) quantify the fractional efficiency of several in-duct air cleaners typical of those used in residential and office ventilation systems.

Results show that efficiency is highly dependent on particle size, flow rate, and dust load present on the air cleaner. A minimum in efficiency was often observed in the 0.1 to 0.5 μm diameter size range. The presence of a dust load frequently increased an air cleaner's efficiency; however, some air cleaners showed little change or a decrease in efficiency with dust loading. The common furnace filter had fractional efficiency values of less than 10% over much of the measurement size range.

KEY WORDS:
Air cleaner, Aerosol, Filtration, Efficiency, Fractional

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Introduction

In the past two decades, the number of requests for information and assistance related to indoor air quality (IAQ) received by the U.S. Environmental Protection Agency (EPA) has risen steadily (U.S. EPA, 1991). One area where information has been requested deals with air cleaner efficiency, especially the fractional, or particle-size-dependent, aerosol filtration efficiency. Awareness of the particle-size dependence of health effects and soiling potential has increased the need for these data. Air cleaner filtration efficiency ratings based on current test standards do not provide information sufficient to address IAQ concerns. Therefore, to respond to these requests, the EPA has undertaken a program to measure the fractional filtration efficiency of air cleaners with the purpose of understanding the basic performance of various types of devices. This work has been conducted by the Research Triangle Institute (RTI) under a Cooperative Agreement with EPA.

The objective of this paper is to begin to disseminate results from this on-going test program. The fractional efficiency test used in this project is described, and results of fractional filtration efficiency measurements for clean and dust-loaded air cleaners over the particle diameter size range from 0.01 to 3 μm are presented. The goal of the experiments has been to quantify the fractional aerosol filtration efficiency of in-duct air cleaners typically used in residential and office ventilation systems. This evaluation has covered a wide variety of the available air cleaners including residential furnace filters, a residential electrostatic precipitator, pleated paper-media filters, pocket filters, panel electronic air cleaners, permanently charged panel filters, and washable, self-charging panel electrostatic filters. All the air cleaners tested were designed for in-duct installation (as opposed to the in-room use of portable room air cleaners).

Measuring the fractional efficiency over the 0.01 to 3 μm size range was undertaken because 1) filtration efficiency is often highly particle-size-dependent over this range; 2) the current standard test methods cannot differentiate between particle sizes and cannot be reliably used to predict performance; and 3) particles in this size range are respirable, have relatively low settling velocities (remain airborne for long time periods), and encompass the size range of many indoor aerosol pollutants such as cigarette smoke, cooking fumes, resuspended dusts, and particle-attached radon progeny (Owen et al., 1992).

The investigation was conducted using full-scale air cleaners intended for use in ventilation systems (as opposed to smaller-scale "swatch" tests of filtration media samples). Testing full-scale devices allowed evaluation of "off-the-shelf" air cleaners without modifications that could alter their performance. Because the entire air cleaner was tested, the filtration efficiency measurements include effects of bypass flows that are sometimes present in air cleaner construction.

Current Standardized Test Methods for Ventilation Filters

In the United States, the filtration efficiency rating of in-duct air cleaners (as opposed to room air cleaners) is most often based on ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.) Standard 52–76 (recently revised as Standard 52.1-1992) Atmospheric Dust Spot Efficiency and/or the ASHRAE Weight Arrestance tests (ASHRAE, 1976 and 1992). These tests provide overall values of filtration efficiency for atmospheric aerosol and a coarser test dust (containing dust particles up to 80 μm diameter and cotton lint up to several millimeters in length), respectively. While these tests provide information useful for relative ranking of filter performance, they do not quantify filtration efficiency as a function of particle size.

The atmospheric dust spot efficiency is based on the relative discoloration (measured by light transmission) of filter papers drawn simultaneously from upstream and downstream of the air cleaner challenged with ambient air drawn directly from outdoors. For many types of residential air cleaners (such as furnace filters) the efficiency measured from this test is often <20% and is frequently not reported. The arrestance test, however, almost always yields high values for ventilation air cleaners. This is due to the relatively large particle size of the coarse test dust and the fact that the test is based on the weight percent (as opposed to number percent) captured by the air cleaner which biases the results to the largest, most easily filtered, particle sizes. Furthermore, the values reported for both the atmospheric dust spot efficiency and weight arrestance tests are often average values calculated from initial values and several subsequent measurements made after the air cleaner has been loaded with a prescribed loading dust. For media filters (as opposed to electrostatic precipitators) the dust load often significantly increases both the weight arrestance and dust spot efficiency.

Because the standardized tests provide several measures of efficiency (initial dust spot, initial arrestance, average dust spot, and average arrestance), the consumer is often shown only the highest of these values. For many air cleaners, this is the average weight arrestance value (typically >90%). In the retail marketplace, these high average weight arrestance values are often misused to imply high efficiencies for micrometer- and sub-micrometer sized particles where actual efficiencies are often substantially lower (typically <10% for clean media).

Related Work

Recognizing the need for fractional filtration efficiency data, several organizations are now developing standardized test methodologies. ASHRAE has recently completed a research program to develop a standardized fractional filtration efficiency test (Hanley, 1992) and has begun drafting a standard. The Canadian Electrical Association has developed performance specifications for fractional efficiency tests of electronic air cleaners (CEA, 1990). European groups such as EUROVENT (European Committee for Air Handling and Air-Conditioning Equipment Manufacturers) and CEN (European Committee for Standardization) are also considering establishing fractional efficiency standards.

Fractional filtration efficiency tests, though just now becoming standardized, have frequently been used in research programs. Hanley et al. (1990) and Ensor and Hanley (1988) describe tests conducted for the U.S. EPA in which the size-dependent filtration efficiency and ozone generation of electrostatic precipitators were measured. These tests used an artificial test aerosol, particle counters, and electrical mobility aerosol analyzers to evaluate aerosol filtration from 0.01 to 3 μm diameter. Michel and Chevalier (1988) present a method that uses a laser

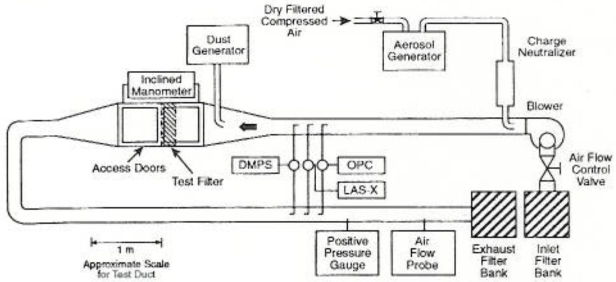

Fig. 1 Schematic diagram of RTI's air cleaner test facility

particle counter to measure the penetration of a polydisperse latex aerosol challenge. Filtration efficiency measurements are made at six particle sizes ranging from 0.3 to 5 μm diameter. The effect of dust load on filtration efficiency is also evaluated. Similar approaches to size-dependent filtration efficiency have been described by Bergman et al. (1985), Lee and Liu (1980), Takada and Kamishima (1986), Umhauer et al. (1990), and others.

Air Cleaner Test Rig

The air cleaners were tested in RTI's filter test facility (Figure 1). The duct accommodates air cleaners with face dimensions up to 610×610 mm (24×24 in.) and operates at flow rates up to 470 *l*/s (1,000 cfm). The test section and attached transitions are constructed of stainless steel. The ducting of the system is 203 mm (8 in.) inside-diameter polyvinyl chloride (PVC). The system is equipped with a High Efficiency Particulate Air (HEPA) filter bank on the blower inlet, allowing the instrument zeros to be verified prior to each test. A second HEPA bank is located on the exhaust to allow indoor discharge. The system operates under positive pressure (i.e., the blower is upstream of the test filter) to minimize infiltration of room aerosol. Aerosol injection is located 10 duct diameters upstream of the sampling probes to provide duct length for aerosol mixing with the airstream. The loading dust is injected at the transition to the air cleaner. Injecting the dust at this location minimizes the potential for dust contamination of the aerosol sampling probes.

The air cleaner test section is composed of two side-door filter holders. The test air cleaner is installed in the upstream unit. The downstream unit serves two purposes. By opening the door on the downstream unit, the downstream face of the test air cleaner can be scanned with an aerosol particle counter. Scanning the air cleaner in this manner has proved very useful in locating areas of high aerosol penetration through an air cleaner (particularly for HEPA and electrostatic precipitators). This information aids in understanding the overall efficiency values measured. For example, scanning may locate leaks between the frame and the medium. The downstream unit is also used to hold a high efficiency backup filter installed during the dust-loading phase of the tests.

Aerosol concentration is measured upstream and downstream of the test section to obtain the challenge and penetrating aerosol concentrations, respectively. The penetration aerosol sample tap is located sufficiently far downstream of the test section to allow the complete mixing of any penetrating aerosol with the entire airstream.

The unconventional 180° bend in the downstream duct serves several important purposes. For typical duct airflows and instrument sampling rates (typically 470 and <0.47 *l*/s [1000 and <1 cfm], respectively), aerosol transport losses due to inertial, diffusional, and gravitational settling (see, e.g., Fissan and Schwientek, 1987) will generally be much greater in the sample lines than in the duct. Therefore, to minimize the combined particle loss in the duct and sample line, it is generally beneficial to use increased duct length to reduce sample line length. Upstream and downstream measurements made without a filter in the test housing were found to be in close agreement with each other, thereby verifying that particle loss in the duct was insignificant over the 0.01 to 3 μm measurement range.

This arrangement also facilitates use of a single set of aerosol instrumentation to perform both the upstream and downstream aerosol concentration measurements. Because filtration efficiency is based on the ratio of the upstream and downstream measurement, using a single set of instrumentation for both measurements increases the accuracy of the filtration efficiency measurement by avoiding errors caused by differences that often exist between two "identical" instruments (due to, for example, flow rate differences, particle sizing differences, and count efficiency differences). This arrangement also has the practical advantage of significantly reducing the overall length of the test rig.

This combination of test rig components and their configuration offers several important benefits.

- Particle losses are reduced by using additional duct length (where losses are generally low) with a 180° bend to reduce sample line length (where losses are generally high).

- Instrument requirements are minimized by using the same instruments to measure both the upstream and downstream aerosol concentrations.
- Inaccuracies associated with dual-instrument use are avoided (i.e., using two instruments – one sampling upstream and one sampling downstream).
- Long duct lengths provide good upstream and downstream aerosol mixing.
- Filtered inlet air and an artificially generated test aerosol avoid inaccuracies due to variable ambient aerosol and allow control of particle concentration to preclude exceeding the concentration limit of the aerosol instrumentation.
- Positive pressure minimizes infiltration of room air.
- In-place scanning of the downstream face of the air cleaner is possible. This capacity allows the detection and quantification of areas of aerosol penetration.
- The filtered inlet air allows in-place confirmation of instrument zeros and quantification of particle shedding from dust-loaded filters.
- Space requirements are reduced by having the downstream leg turn and run back beneath the upstream leg.

Aerosol Instrumentation

To span the particle diameter range from 0.01 to 3 μm, three instruments were used to measure fractional efficiency: a TSI, Inc. Differential Mobility Particle Sizer (DMPS) for particle diameters from 0.01 to 0.09 μm, a PMS Laser Aerosol Spectrometer (LAS-X) for diameters from 0.09 to 0.3 μm, and a Climet 226/8040 Optical Particle Counter (OPC) for diameters from 0.3 to 3 μm. The DMPS measures particle size based on the electrical mobility of the aerosol particles. The LAS-X and OPC are wide-angle light scattering particle counters using a laser and white light source, respectively. While the OPC was capable of measuring particles up to 10 μm in diameter, the 3 μm upper limit of the measurements was due to the relatively low aerosol concentrations at larger diameters present in the test aerosol. Prior to testing, the calibration of the DMPS, LAS-X, and OPC was verified by challenging each instrument with several different monodisperse polystyrene latex aerosols of known particle diameter (Duke Scientific Corp.).

Challenge Aerosol Generation

The test aerosol used in the fractional efficiency tests was solid potassium chloride (KCl) generated by drying a nebulized aqueous solution. KCl was used as the test aerosol because of its relatively high water solubility, high deliquescence humidity, known cubic shape, and low toxicity. A Laskin nozzle and a Collison nebulizer were used to generate the challenge aerosol. Upon generation, the aerosol was passed through a charge neutralizer (TSI Model 3054) to neutralize any electrostatic charge on the aerosol (electrostatic charging is an unavoidable consequence of most aerosol generation methods).

To span the range from 0.01 to 3 μm, the efficiency tests were performed in two steps. The first step covered the range from 0.01 to 0.1 μm (the DMPS measurements). The challenge aerosol was generated from a 0.1 wt% KCl solution (1 g KCl combined with 1 *l* water) in a single-nozzle Laskin Nozzle operating at 276 kPa (40 psi). This produced a sufficiently small-diameter polydisperse aerosol for measurements down to 0.01 μm. The second step covered the size range from 0.09 to 3 μm (the LAS-X and OPC measurements). The challenge aerosol was generated from a 30 wt % KCl solution (30 g KCl/*l* distilled water) nebulized with a single-jet Collison Nebulizer (BGI Model CN–25) operating at 69 kPa (10 psi).

Loading Dust

The loading dust was composed of 93.5% by weight of Standardized Air Cleaner Test Dust Fine and 6.5% by weight finely ground cotton linters. This dust is similar to the loading dust specified in ASHRAE Standard 52–76 except that the ASHRAE dust also includes a carbon black component. The carbon black was omitted from these tests because its presence makes the dust highly conductive and incompatible with the operation of electronic air cleaners. While dusts having high conductivities may be encountered in industrial applications, it appeared unlikely for the residential and office building applications of interest to this study. Use of the other two components of the ASHRAE 52–76 dust (Standardized Air Cleaner Test Dust Fine and cotton linters) was continued because of their familiarity in the air cleaner industry and the immediate need for a loading dust material. The issue of exactly what material(s) should be used for the loading dust to best simulate the effects of dust-loading experienced in actual usage was not addressed.

To inject the dust, preweighed amounts (typically 50 g) of the loading dust were fed into the suction inlet of an air-operated aspirating nozzle. As the dust was fed, the pressure drop of the filter was monitored. The dust injection rate was approximately 2 g/min. Preweighed amounts of dust were fed until the desired pressure drop was achieved. Typically, the filters were loaded to levels of 125 and 250 Pa (0.5 and 1 in. H_2O) pressure drop. This procedure allowed the loading to occur in a practical length of time and without disturbing the fragile dust layer. Loading with atmospheric aerosol would have taken weeks or months, and transporting used filters might have disturbed the dust.

The dust was injected counter to the airflow at the transition (see Figure 1). Through a series of qualitative tests, it was determined by visual inspection of the filter face that injection at this point resulted in a uniform dust load across the face of the air cleaner. An advantage of injection at this point versus a point farther upstream was that the upstream aerosol sample probes were not at risk of dust contamination.

Test Procedures

The tests involve two basic phases. One phase is the fractional filtration efficiency test. For these tests, artificial aerosols are generated that cover particle diameters from 0.01 to 3 μm. The airflow rates for these tests were set to 50, 100, or 200% of the pleated filters' rated flow of 235 *l*/s (500 cfm).

The other phase of the tests is loading the filter with a relatively coarse dust. The purpose of the dust-loading phase is to build a dust cake on the air cleaner similar to that which forms during normal operation. Because it would take weeks (perhaps months) to load a filter with ambient aerosol, a test dust is injected into the duct to accelerate loading. The presence of a dust load on an air cleaner can significantly alter its filtration efficiency. Thus, after loading the filter, the efficiency test is repeated.

RTI refers to this process of measuring the filtration efficiency of air cleaners as the "Load and Probe" method. It is similar in concept to the ASHRAE test. "Load" refers to the use of a loading dust to simulate dust accumulated in the air cleaner from long-term usage (months). "Probe" refers to the use of an artificially generated challenge aerosol (0.01 to 3 μm diameter) for the fractional efficiency tests. The "Probe" test uses an aerosol mass concentration several orders of magnitude less than the "Load" test and has a negligible effect, under these conditions, on air cleaner performance. The "Probe" concentration can be controlled to below the concentration limit of the aerosol instrumentation.

The tests began by setting the airflow rate to the desired level, then verifying that the aerosol measuring devices read at or near zero. The test proceeds with measuring the clean filter pressure drop and initial fractional filtration efficiency. The loading dust was then injected into the upstream air stream until the air cleaner's pressure drop reached 125 Pa (0.5 in. H_2O). The fractional efficiency measurement was then repeated. A second dust-loading was then performed to bring the air cleaner's pressure drop to 250 Pa (1 in. H_2O). (This pressure drop is often specified as the maximum for ventilation air filters.) The fractional efficiency measurement was repeated.

Sampling and Data Analysis

Each test began with a series of three upstream and three downstream background measurements with the aerosol generator off. While the upstream values were always at or near zero, the downstream background concentrations were often elevated after the air cleaners were dust-loaded due to shedding of the loading dust off the filter; this was particularly true of the lower efficiency air cleaners.

After the background measurements were obtained, the aerosol generator was turned on, allowed to operate for 10 minutes to stabilize, and then the upstream and downstream aerosol concentration measurements began. A three upstream – six downstream – three upstream sampling sequence was used to reduce the effect of drift in the challenge aerosol concentration. When completed, the aerosol generator was turned off, and followed by three additional upstream-downstream measurements of the background particle concentrations.

For each particle size, the air cleaner's filtration efficiency was then computed as:

$$\mathit{Filtration\ Eff} = 1 - \frac{\mathit{AvgDownstreamConcentration} - \mathit{AvgDownstreamBackground}}{\mathit{AvgUpstreamConcentration} - \mathit{AvgUpstreamBackground}}$$

In this equation, background values are subtracted from the upstream and downstream counts to remove the effect of shedding from the computed efficiency. (This also corrects for any noise counts generated from within the OPC itself and particle

Table 1 Description of air cleaners

Description	Test results shown in Figure(s)	Experimental Conditions
Pleated Paper-Media Filter 305×610×152mm (12×24×6″) 95% ASHRAE Dust Spot Average Efficiency	2	1.3 m/s Face Velocity Clean Filters
Pleated Paper-Media Filter 305×610×152mm (12×24×6″) 85% ASHRAE Dust Spot Average Efficiency	2 and 3	Face Velocities: 0.65, 1.3, and 2.25 m/s
Pleated Paper-Media Filter 305×610×152mm (12×24×6″) 65% ASHRAE Dust Spot Average Efficiency	2	1.3 m/s Face Velocity Clean Filters
Pleated Paper-Media Filter 305×610×51mm (12×24×2″) 40% ASHRAE Dust Spot Average Efficiency	2	1.3 m/s Face Velocity Clean Filters
Residential Electronic Air Cleaner 406×660×178mm (16×25×7″) Two stage electrostatic precipitator Consisted of 28 ionizing wires and 114 collection plates The unit operated at 1.12 mA at 6.8 kV	4	Face Velocities: 0.45, 0.90, and 1.80 m/s
Pleated Panel Filter 508×508×25mm (20×20×1″) 25–30% ASHRAE Dust Spot Average Efficiency	5	1.87 m/s Face Velocity Clean: 68 Pa Naturally and Artificially Loaded @ 125 Pa
Pocket Filter 610×610×560mm (24×24×22″) 95% ASHRAE Dust Spot Average Efficiency 8 pockets, nonwoven fiber media	6	1.3 m/s Face Velocity Clean and Dust-Loaded Filters @ 50, 125, and 250 Pa
Pleated Paper-Media Filter 610×610×150mm (24×24×6″) 65% ASHRAE Dust Spot Average Efficiency	7	1.3 m/s Face Velocity Clean and Dust-Loaded Filters @ 40, 125, and 250 Pa
Furnace Filter 610×610×25mm (24×24×1″) Spun fiberglass in a cardboard frame	8	1.3 m/s Face Velocity Clean and Dust-Loaded Filters @ 10, 125, and 250 Pa
Panel Electronic Filter 610×610×25mm (24×24×1″) Consists of high voltage screens sandwiched between dielectric fiber media	9	1.3 m/s Face Velocity Clean and Dust-Loaded Filters @ 50, 125, and 250 Pa
Self-Charging Panel Filter 610×610×25mm (24×24×1″) Contains static prone materials intended to develop a static charge as air flows through the media thereby increasing filtration efficiency	10	1.3 m/s Face Velocity Clean and Dust-Loaded Filters @ 35, 125, and 250 Pa
Permanently-Charged Panel Filter 610×610×25mm (24×24×1″) The media consists of permanently charged electret fibers	11	1.3 m/s Face Velocity Clean and Dust-Loaded Filters @ 50 and 250 Pa

counts arising from shedding from the test rig ducting.) In some applications, it may be appropriate to compute efficiency without subtracting off the shedding background counts. Note, however, that 1) shedding may be highly dependent upon the nature of the loading dust (e.g., particle size and stickiness) and, 2) the influence of shedding on the computed efficiency depends upon the aerosol concentration level used in the test. Therefore, if shedding is not to be subtracted from the observed downstream counts, one should ensure that the nature of the loading dust and the level of the challenge aerosol are consistent with the actual use conditions.

Results

Table 1 describes the air cleaners and the relevant test conditions. As an additional descriptor of the air cleaners, their ASHRAE 52–76 Average Efficiency (an overall measure of efficiency for ambient aerosol) is listed when available. These values often differ from the measured fractional efficiencies reported here because of the different particle size ranges and levels of dust-loading associated with the measurements.

Note that the fractional efficiency of apparently similar filters can vary widely. For example different brands of filters with the same type of construction (e.g., 25.4 mm (1 in.) pleated media) or filters with similar ASHRAE Efficiency Ratings may yield different fractional efficiency curves. Therefore, while the test results illustrate the general shape of the fractional filtration efficiency curve and the effect of flow rate and dust load, the results should not be applied arbitrarily to other air cleaners.

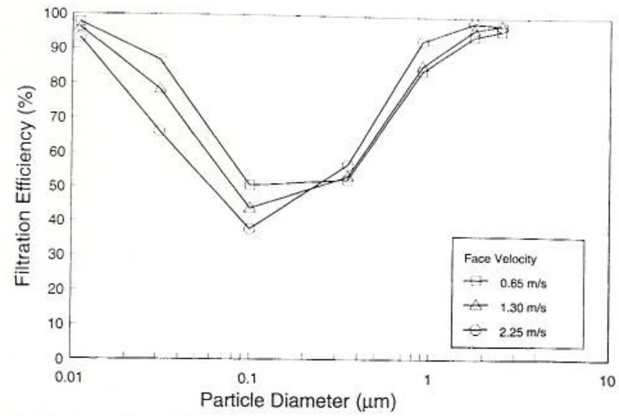

Fig. 3 The effect of face velocity on the fractional filtration efficiency of an 85% ASHRAE pleated paper filter

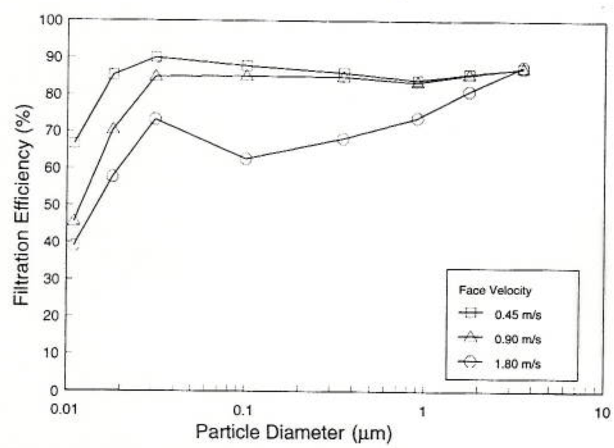

Fig. 4 The effect of face velocity on the fractional filtration efficiency of an electrostatic precipitator type electronic air cleaner

Fractional Efficiency of Clean Air Cleaners

Figure 2 compares the fractional efficiency of four clean (i.e., no dust load present on the air cleaner) filters having ASHRAE Average Efficiencies ranging from 40 to 95%. Figures 3 and 4 show the effect of flow rate on the performance of a clean media filter and an electronic air cleaner, respectively.

A misunderstanding often encountered in fibrous filter testing is that the smaller the particle size the greater will be its penetration. This statement holds true only over a certain range of particle sizes, and this range is dependent on properties of the filter media. For example, HEPA filters are generally least efficient at particle diameters of about 0.2 to 0.3 μm. For larger *and smaller* particles, efficiency increases. The increase in efficiency for larger particles results from increased effectiveness of the filtration processes to collect particles by the physical mechanisms of inertial impaction and interception, as well as straightforward sieving of particles when the particle diameter is greater than the "pore size" of the filter. The increase in efficiency for smaller particles is caused by diffusion. Particle diffusion is the consequence of the Brownian motion small particles undergo due to bombardment by air molecules. Particle diffusion increases rapidly with decreasing particle size. Thus, smaller particles diffuse to the filter fibers and are collected more rapidly than larger ones, resulting in filtration efficiency increasing as particle diameter decreases below 0.1 μm. The concept of a "most penetrating particle size" is well documented in the literature for flat-sheet filter media (e.g., Lee and Liu, 1980).

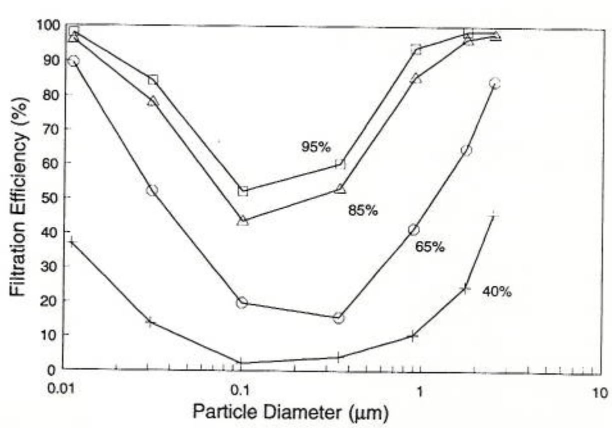

Fig. 2 Fractional filtration efficiency of four ASHRAE-rated filters at 1.3 m/s face velocity

The relative changes in the efficiency curves as flow rate changed for the media filter (Figure 3) reflect the effects of diffusion and impaction. For the smallest particles (less than about 0.1 μm diameter), efficiency is seen to decrease with increasing flow rate. This is consistent with the diffusion process being the dominant mechanism at small sizes, since

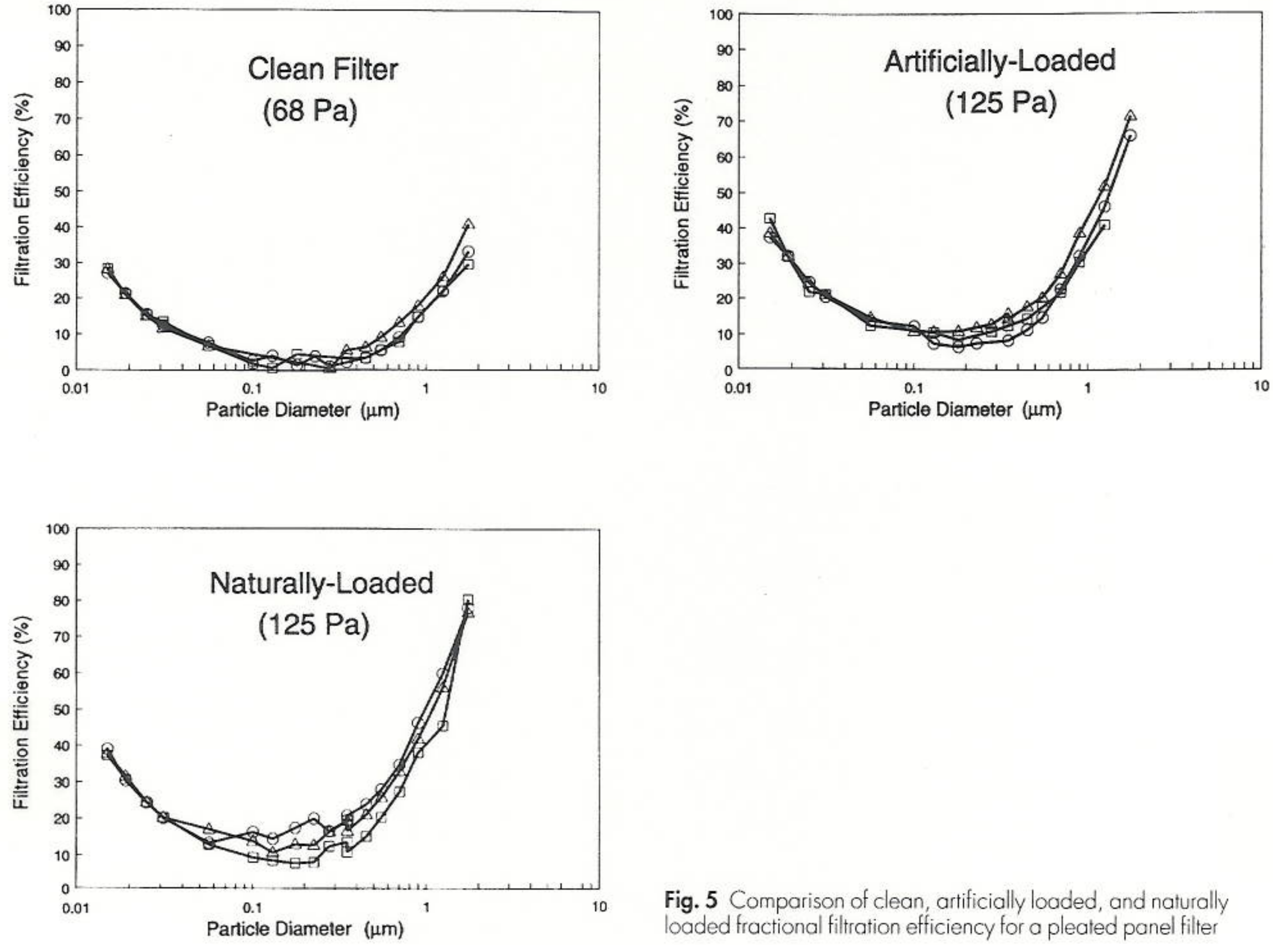

Fig. 5 Comparison of clean, artificially loaded, and naturally loaded fractional filtration efficiency for a pleated panel filter

at higher flow rates, the particles have less time to diffuse. For the larger particle sizes (greater than about 1 µm), efficiency increases with increasing flow rate. This is consistent with the impaction process being dominant at these sizes. As flow rate increases, the inertia of the particles increases and their impaction efficiency with the filter fibers increases.

For the electronic air cleaner (Figure 4), the particles are collected by different mechanisms than for the fibrous media filters. Field charging is responsible for the charging of large particles, and diffusion charging is responsible for the charging of small particles. The charged particles are driven to the collection plates by an electric field. At the two lower face velocities, the filtration efficiency of the electronic air cleaner was approximately 85% for the 0.3–3 µm diameter range. At the higher face velocity, a relative minimum was seen at approximately 0.1 µm diameter. For all face velocities, a decrease in efficiency was observed for particle diameters <0.3 µm that we attribute to charging limitations for small particles (Hanley et al. 1990).

Effect of Dust Load

To provide an initial assessment of the validity of using the test dust to artificially load the air cleaners, a pleated panel filter was retrieved from actual service (used for filtration of recirculating in-

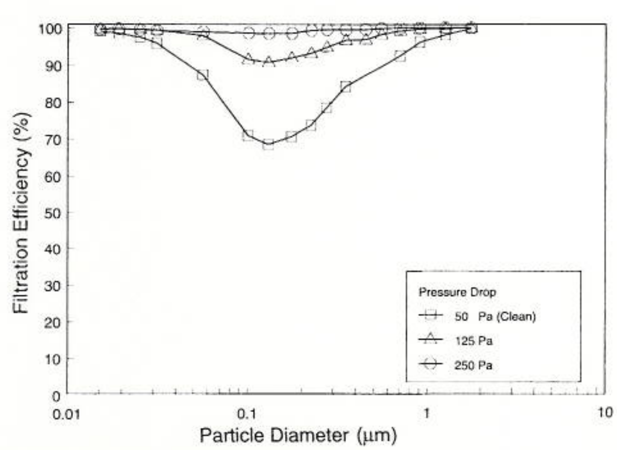

Fig. 6 The effect of dust load on the fractional filtration efficiency of a pocket filter of non-woven fiber media at 1.3 m/s

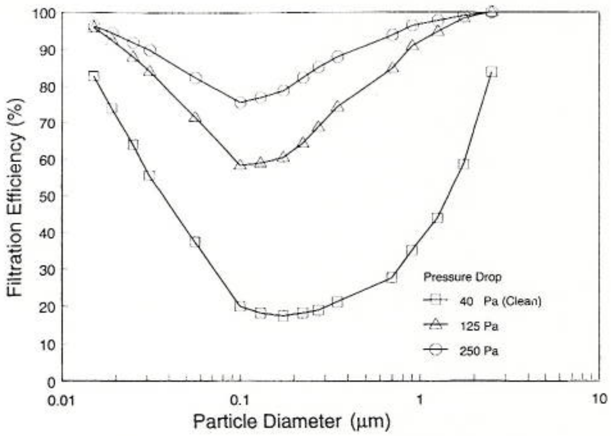

Fig. 7 The effect of dust load on the fractional filtration efficiency of a pleated paper filter at 1.3 m/s

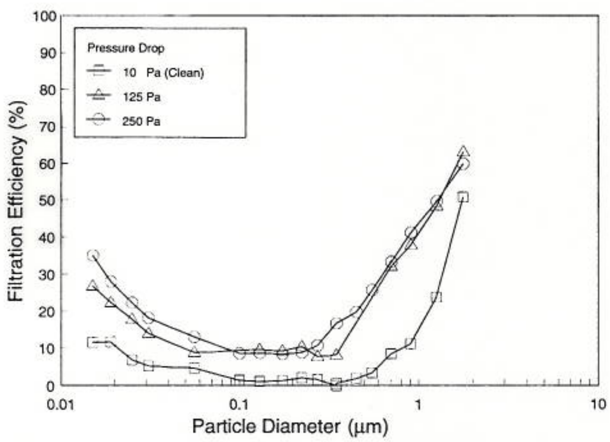

Fig. 8 The effect of dust load on the fractional filtration efficiency of a furnace filter at 1.3 m/s

door air in an office area) for comparison with an identical filter (same brand and size) that was artificially dust-loaded to the same pressure drop. Figure 5 shows the results for triplicate tests of the artificially dust-loaded filter (first tested clean and then with the dust load) and the naturally loaded filter retrieved from actual service.

Figures 6 through 11 show the clean and dust-loaded (to two levels of pressure drop) fractional filtration efficiency for the various air cleaners. Generally, dust-loading resulted in increased filtration efficiency along with an increase in pressure drop. However, the magnitude of the efficiency change varied between the different filter types. For the charged-fiber filter, the efficiency dropped after dust-loading. The unusual shape of the efficiency curve for the charged-fiber filter below 0.1 μm will be examined more closely in future tests and is pres-

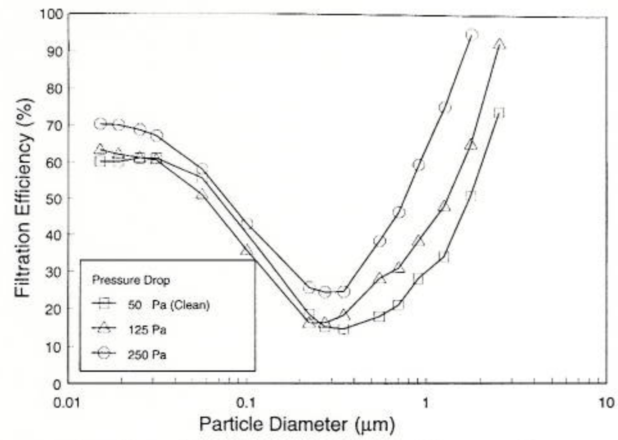

Fig. 9 The effect of dust load on the fractional filtration efficiency of a panel electronic air cleaner at 1.3 m/s

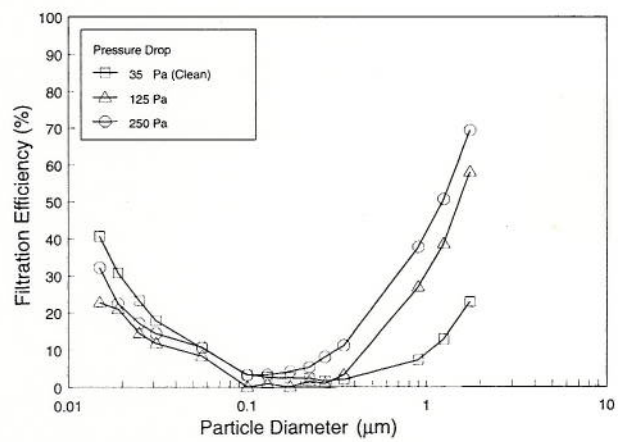

Fig. 10 The effect of dust load on the fractional filtration efficiency of a self-charging panel filter at 1.3 m/s

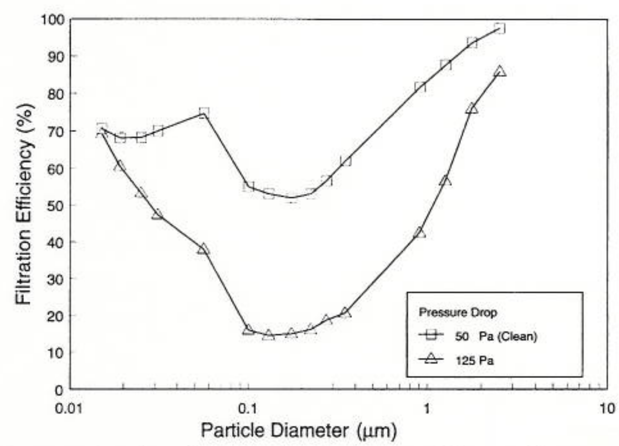

Fig. 11 The effect of dust load on the fractional filtration efficiency of a permanently charged fiber filter at 1.3 m/s

ently attributed to enhanced collection due to the electrostatic charge on the fibers. The naturally loaded and the artificially loaded filter efficiency curves are quite similar with slightly less capture for low particle diameters and slightly higher efficiency at larger sizes. Based on this one comparison, the use of artificial dust-loading appears satisfactory. Further tests of naturally loaded filters are planned to continue the assessment of loading dust.

Conclusions

The test results led to the following conclusions and recommendations:

1. The fractional filtration efficiency of air cleaners is often strongly dependent upon particle size, flow rate, and dust-loading.
2. Naturally loaded and artificially loaded filters show similar efficiency curves.
3. A minimum in filtration efficiency was often observed in the 0.1 to 0.5 μm diameter size range.
4. The furnace filter had a clean fractional filtration efficiency of less than approximately 10% for particle diameters between 0.02 and 1 μm. The efficiency improved somewhat with dust-loading, but remained below 20% over the 0.03 to 0.3 μm diameter range.
5. The air cleaners generally showed increased filtration efficiency with dust-loading. A notable exception was the charged-fiber filter which showed a decrease in efficiency after dust-loading.
6. The charged-fiber filter appears to have had a significantly increased initial filtration efficiency due to the electrostatic charge on the fibers. Dust-loading, however, appears to have inhibited this electrostatic effect, and the filtration efficiency was seen to be substantially lower than for the clean condition.
7. The self-charging panel filter had a relatively low filtration efficiency, similar to that for the furnace filter.

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