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Aerosol Filtration Efficiency of Ventilation Air Cleaners

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INTRODUCTION

The use of air cleaners has steadily moved from one of protecting equipment (such as the heat exchanger in a furnace) to one of protecting people from objectionable indoor aerosol particles (e.g., common dust and allergens). This shift has necessitated the development of new test methods for determining air cleaner filtration efficiency. Under a cooperative agreement with the U.S. Environmental Protection Agency (EPA)[1] and contracts with the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)[2], and the Canadian Electrical Association (CEA)[3], the Research Triangle Institute (RTI) has developed a test method for measuring the fractional aerosol filtration efficiency of air cleaners. The method provides a reliable and accurate means of measuring air cleaner fractional efficiencies over the particle diameter size range of 0.01 to 10 μm.

The need for a fractional efficiency test comes from several sources: (1) the growing concern with indoor air quality (IAQ); (2) the fact that filtration efficiency is often highly particle-size dependent for particles <10 μm in diameter; (3) limitations of the current ASHRAE efficiency test (52.1-1992) which, by design, cannot differentiate between particle sizes[4]; and (4) that respirable particles are generally classified as those <10 μm in diameter.

Implementation of the new method will provide several benefits to the air cleaner community:

- Fractional efficiency data that will allow architects, building managers, and heating, ventilating, and air-conditioning (HVAC) supervisors to specify air cleaners to meet their filtration requirements;
- Manufacturers with a standardized fractional efficiency test of known data quality to replace the many nonstandard methods now in use;
- Architects and IAQ researchers with fractional filtration efficiency data required for use in air cleaning system designs and IAQ models; and
- The consumer with a more realistic assessment of air cleaner performance than is currently given by the single-valued efficiency and arrestance tests.

Furthermore, because the new method provides a more detailed assessment of an air cleaner's performance than the current efficiency and weight arrestance tests of ASHRAE 52.1-1992, use of the new method may lead to the development of improved air cleaners.

TEST DUCT

The test duct, aerosol generation, and aerosol sampling systems are illustrated in Figure 1. Like an ASHRAE duct, the test duct is based on a 24 x 24 in. (610 x 610 mm) duct and accommodates the fractional efficiency tests as well as the dust loading and arrestance tests. Key features of the duct include:

- Positive pressure to minimize room air infiltration;

- Inlet air drawn from indoors to maintain temperature and humidity within the desired range;
- HEPA (high efficiency particulate air)-filtered inlet to remove ambient aerosol;
- HEPA-filtered exhaust to allow indoor discharge;
- Artificially generated, solid-phase, polydisperse potassium chloride (KCl) salt challenge aerosol, generated from an aqueous solution using an air-atomizing nozzle;
- Automated sequential upstream/downstream aerosol sampling;
- A downstream mixing baffle (in addition to the upstream mixing baffle) to ensure well-mixed aerosol conditions at downstream sample probes; and
- 180° bend in the downstream duct to bring upstream and downstream sample locations close to each other, greatly reducing sample line length and facilitating use of a single set of aerosol measurement instrumentation.

AEROSOL GENERATION, SAMPLING, AND MEASUREMENT

The test aerosol was composed of KCl generated from aqueous solution. KCl was selected because of its relatively high water solubility, high deliquescence humidity, known crystalline structure (facilitates complete drying), solid phase, and low toxicity. The aqueous solution was prepared by combining 300 g of KCl with 1 L of distilled water.

A solid-phase aerosol was desired because, due to particle bounce, solid particles tend to penetrate air cleaners at a higher rate than do liquid particles. Thus, using solid-phase aerosol particles provides a more stringent test. At particle sizes above a few micrometers, differences between aerosol penetration measured using solid- and liquid-phase aerosols can be very large for some air-cleaning devices, particularly for low efficiency filters.

To span the size range from 0.01 to 10 µm, three methods of aerosol generation and three methods of aerosol measurements were used (Table 1). This was necessary to optimize measurement accuracy over the entire size range.

From 0.01 to 0.07 µm, the up- and downstream aerosol concentrations were measured with a TSI, Inc., Model 3071 Electrostatic Classifier with a Model 3020 Condensation Nucleus Counter. This instrument measures particle size based on the electrical mobility of the aerosol particles. A Laskin Nozzle using a dilute 0.1% by weight KCl aqueous solution was used to generate the challenge aerosol.

From 0.09 to 3 µm, the aerosol concentrations were measured with a Particle Measuring Systems, Inc. (PMS) LAS-X Laser Aerosol Spectrometer. This instrument measures particle size based on wide-angle light scattering using a laser light source to illuminate the particles. A Collison nebulizer containing a 20% by weight KCl solution was used to generate the test aerosol.

A Climet Instruments Company Model 226 Optical Particle Counter (OPC) with Model 8040 Multichannel Analyzer was used to measure aerosol concentrations over the range of 0.3 to 10 μm diameter. This is a wide-angle light scattering instrument that uses a high intensity white-light illumination source. The aerosol was generated by nebulizing 20% by weight aqueous KCl solution with a two-fluid (air and water) air atomizing nozzle as illustrated in Figure 1.

The aerosol output from each generator was injected into a spray tower (as shown in Figure 1). The tower served two purposes. It allowed the salt droplets to dry by providing an approximate 40 second mean residence time and it allowed larger-sized particles to fall out of the aerosol. After generation, the aerosol passed through a TSI Model 3054 aerosol neutralizer (Kr85 radioactive source) to neutralize any electrostatic charge on the aerosol (electrostatic charging is an unavoidable consequence of most aerosol generation methods). To improve the mixing of the aerosol with the air stream, the aerosol was injected counter to the airflow as illustrated in Figure 1.

SYSTEM QUALIFICATION TESTS

As part of a program with EPA, the new test duct was put through a series of system qualification tests to demonstrate its capability to accurately measure fractional efficiency. The purpose of these tests was to quantify that the test rig and sampling procedures were capable of providing reliable fractional penetration measurements. It is strongly recommended that such tests be included in the new test standard. Similar qualification tests are specified in the Institute of Environmental Sciences Recommended Practice "Testing ULPA Filters"[5] and are an important part of any quantitative test method.

Qualification tests were performed for:

- Airflow uniformity in the test duct,
- Aerosol uniformity in the test duct,
- Downstream detection of aerosol,
- Overloading tests of the OPC,
- 0% penetration test,
- 100% penetration test,
- Aerosol generator response time,
- Duct leak test, and
- Duct temperature and relative humidity.

Table 2 summarizes the results from the system qualification tests. (In the table, "CV" is the coefficient of variation which is equal to the standard deviation of a set of measurements divided by their mean.) Also included are recommended goals for these parameters. In specifying these goals, the objective was to have tight enough control over the critical test parameters to yield accurate and reproducible results and yet not be so tight that the test becomes unrealistically difficult or expensive to perform. The recommended levels are based on a combination of judgment as to what will be required for dependable results and practical experience in trying to achieve optimum test conditions. All of the recommended levels were met or exceeded in the test duct. As data from interlaboratory comparisons become available, these goals may need to be strengthened to improve interlaboratory comparison or relaxed to increase the utility of the method.

Results from the 100% penetration tests are presented in Figure 2. These tests provide a relatively stringent test of the adequacy of the overall duct, sampling, measurement, and aerosol generation system. The test is performed as a normal penetration test except that no air cleaner is used. A perfect system would yield a measured penetration of 1 at all particle sizes. Deviation from 1 can occur due to particle losses in the duct, differences in the degree of aerosol uniformity (i.e., mixing) at the upstream and downstream probes, and differences in particle transport efficiency in the upstream and downstream sample lines. Results show that,at particle sizes below about 2 µm, the losses were less than 2%. Maximum loss of approximately 10% was observed in the 4 to 10 µm range.

TEST PROCEDURES

The penetration was calculated from the average of 10 upstream and 10 downstream samples taken sequentially (i.e., one upstream, one downstream, one upstream, one downstream, . . . until 10 each were obtained). This sequential sampling scheme minimizes the effect of aerosol generator variability. Each sample was 2 min in duration. This was based on having the sample duration long enough to obtain a minimum of 50 particles counted in each sizing channel for each upstream sample (providing a minimum total of 500 particle counts in each channel for the combined 10 upstream samples). For each test, measurements were also made with the aerosol generator off to measure the upstream and downstream background aerosol concentrations.

For each test, we have the following information for each particle size:

- A series of background upstream and downstream measurements performed with the aerosol generator off. These are averaged to obtain U_{bkg} and D_{bkg}.
- A series of upstream and downstream particle counts performed with the aerosol generator on. These are averaged to obtain U_{avg} and D_{avg}.
- A series of 0% filtration efficiency correction factors, F_0.

From these quantities, the filtration efficiency at each particle size was computed as:

$$\text{Filtration Efficiency} = 1 - (1-F_0)(D_{avg} - D_{bkg}) / (U_{avg} - U_{bkg}) .$$

RESULTS

A series of triplicate tests was performed with the test air cleaners (Table 3) to illustrate the characteristic shape of the fractional efficiency curves for the various air cleaners. Under the ASHRAE program, the test air cleaners consisted of a furnace filter, a pleated-paper filter, and a two-stage electrostatic precipitator (ESP). The fractional efficiency measurements were made over the size range of 0.3-10 µm. Under the CEA program, the air cleaners consisted of a furnace filter, a single-stage ESP, a charged-media electronic air cleaner (EAC), and a two-stage ESP. The fractional efficiency measurements on the CEA program covered the size range from approximately 0.01 to

10 µm. On each program, the devices were selected to cover a wide range of filtration efficiencies. Figures 3 and 4 summarize the fractional efficiency results.

Table 4 shows the upstream and downstream particle counts associated with one of the pleated-paper air cleaner tests covering the 0.3 - 10 µm size range. The upstream counts were similar for the other tests with the downstream counts dependent upon the degree of particle penetration of the air cleaner.

A misunderstanding often encountered in fibrous filter testing is that an air cleaner's filtration efficiency will continuously decrease as the particle size decreases. Actually, this statement holds true only over a certain range of particle sizes and this range is dependent on the filter media. For example, most media-based air filters are least efficient at particle diameters of about 0.2 to 0.3 µm. For both larger and smaller particles, efficiency increases. The increase in efficiency for larger particles results from increased effectiveness of the filtration processes to collect particles due to 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 that 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 increasing filtration efficiency as particle diameter decreases below 0.1 µm. Additionally, particle bounce and reentrainment can reduce an air cleaner's efficiency for the larger particles (i.e., >3 µm diameter). These particles have sufficient kinetic energy to rebound off the air cleaner's collection surface (e.g., a fiber) and bounce their way through the air cleaner.

For ESPs, particles are collected by different mechanisms than for filters. Field charging is responsible for the charging of large particles, and diffusion charging is responsible for the charging of small particles. Both processes are relatively weak in the 0.1-µm size range, resulting in a relative minimum in that range. The falloff in efficiency in the 0.01 to 0.03-µm diameter range is attributed to incomplete charging of these small-diameter particles.

CONCLUSIONS AND RECOMMENDATIONS

Based on the test results, the following principal conclusions are presented:

- The test system provides a reliable means of evaluating the fractional aerosol efficiency of air cleaners over the 0.01-10 µm diameter size range. Specification of appropriate quality control criteria, such as those presented in Table 2 (system qualification tests), are needed to ensure reliable measurements.

- Particle loss in the test duct appears to be ≤10% in the 2 to 10 µm range and ≤1% at smaller sizes. These losses were repeatable and relatively low in comparison to the particle removal efficiency of most air cleaners that will be tested with this method. Thus, air cleaner penetration data can be confidently corrected for these losses using the 100% penetration data.

- The fractional efficiency of air cleaners is highly particle-size dependent.

- The common furnace filter had fractional efficiencies of <20% over the 0.01 to 10 µm size range. The highest efficiency was seen for the 2-stage ESP which had a minimum efficiency of 62% over the entire 0.01 - 10 µm size range.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the significant contributions of ASHRAE, CEA, and EPA to this effort to develop fundamental information on the fractional aerosol efficiency of air cleaners.

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4. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. Standard 52.1-1992 "Gravimetric and Dust-Spot Procedures for Testing Air-Cleaning Devices Used in General Ventilation for Removing Particulate Matter," (1992).

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Table 1

Aerosol Generators and Measurement Instrumentation

Diameter Size Range, µm	**Aerosol Analyzer**	**Aerosol Generator**
0.01 - 0.07	TSI Model 3071 Electrical Mobility Particle Sizer with Condensation Nucleus Counter	Laskin Nozzle with 0.1% by weight KCl in distilled water.
0.09 - 3	Particle Measurement Systems Model LAS-X Laser Aerosol Spectrometer	Collison nebulizer with 20% by weight KCl in distilled water
0.3 - 10	Climet Model 226 Optical Particle Counter with Model 8040 Multichannel Analyzer	Two-fluid spray nozzle

Table 2. System Qualification Measurements and Goals

Parameter	**Level Achieved**	**Recommended Goal**
Airflow Uniformity: Based on traverse measurements made over a 9-pt equal-area grid at each test flow rate.	CV* = 4.1% @ 1,000 cfm** CV = 2.7% @ 2,000 cfm CV = 4.1% @ 3,000 cfm	CV <5%
Aerosol Uniformity: Based on traverse measurements made over a 9-pt equal-area grid at each test flow rate.	CV <7% @ 1,000 cfm CV <10% @ 2,000 cfm CV <10% @ 3,000 cfm	CV <10%
Downstream Mixing: Based on a 9-pt perimeter injection grid and center-of-duct downstream sampling.	CV = 4.6% @ 1,000 cfm CV = 1.0% @ 2,000 cfm CV = 1.7% @ 3,000 cfm	CV <5%
0% Penetration Test: Based on HEPA filter test.	<1%	<1%
100% Penetration Test: Based on five replicate tests at each test flow rate.	90 to 100% for all sizing channels	90 to 110% for all sizing channels
Upper Concentration Limit: Based on limiting the concentration to below the level corresponding to the onset of coincidence error.	10/cm^3 (>0.3 µm)	No pre-determined level.
Aerosol Generator Response Time	10 minutes	No pre-determined level.
Duct Leakage: Ratio of leak rate to test airflow rate.	0.12%	<0.5%
Duct Air Temperature	75 to 85 °F***	50 to 100 °F
Duct Relative Humidity	35 to 55%	<65%
Compressed Air Relative Humidity	<30%	<30%

(*) Coefficient of variation.
(**) 1,000 cfm = 0.47 m^3/s.
(***) $^\circ C = (^\circ F - 32)/1.8$

Table 3. Description of the Test Air Cleaners

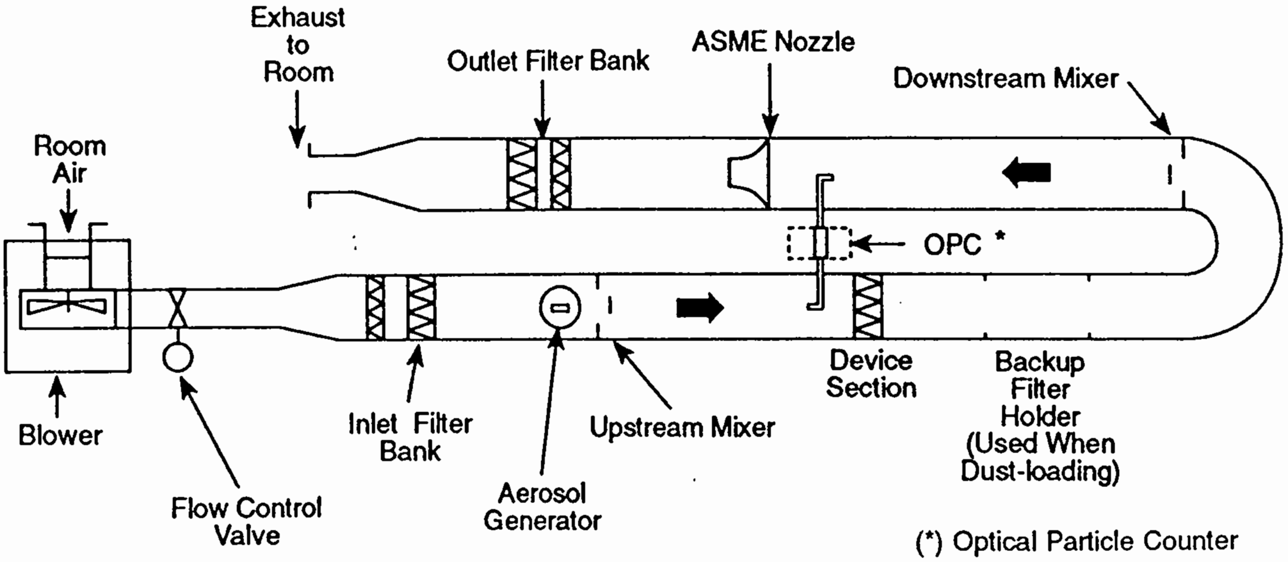
Air Cleaner	Flow Rate, cfm (L/s)	Size Range, μm
Pleated paper 65% dust-spot efficiency 24 x 24 x 6 in. (610 x 610 x 150 mm)	2,000 (940)	0.3 - 10
Two-Stage ESP 16 x 25 x 6 in. (406 x 635 x 150 mm)	1,200 (560)	0.3 - 10
Furnace Filter Spun fiberglass 24 x 24 x 1 in. (610 x 610 x 25 mm)	2,000 (940)	0.3 - 10
Two-Stage ESP 16 x 25 x 6 in. (406 x 635 x 150 mm)	1,000 (470)	0.01 - 10
Single Stage ESP 16 x 25 x 1 in. (406 x 635 x 25 mm)	1,000 (470)	0.01 - 10
Charged-Media Panel Electronic Air Cleaner 16 x 25 x 1 in. (406 x 635 x 25 mm)	1,000 (470)	0.01 - 10
Furnace Filter Spun fiberglass 16 x 25 x 1 in. (406 x 635 x 25 mm)	1,000 (470)	0.01 - 10

Table 4. Upstream and Downstream Particle Counts from One Test of the Pleated-Paper Filter

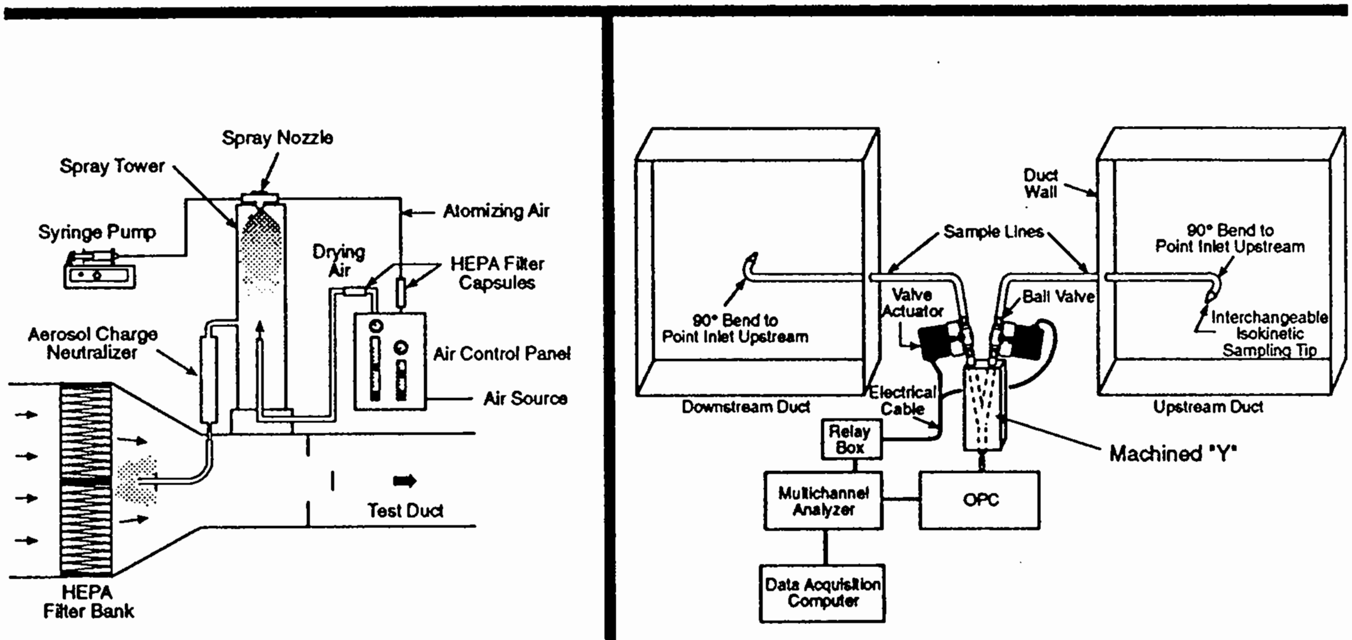
Particle Counts per Indicated OPC Channel (2-Minute Samples @ 0.25 cfm*)

OPC Channel Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Min. Diam. (um)	0.3	0.4	0.5	0.6	0.8	1	1.5	2	3	4	5.5	6	7	8	9
Max. Diam. (um)	0.4	0.5	0.6	0.8	1	1.5	2	3	4	5.5	6	7	8	9	10
Geo. Mean Diam (um)	0.35	0.45	0.55	0.69	0.89	1.2	1.7	2.4	3.5	4.5	5.7	6.5	7.5	8.5	9.5
Upstream-Bkg	5	0	0	1	0	1	0	1	0	0	0	0	0	0	0
Upstream-Bkg	37	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Upstream-Bkg	6	3	1	0	2	2	4	5	3	7	3	2	1	1	0
Upstream-Bkg	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Upstream-Bkg	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Upstream	20860	20630	15350	18990	9893	16490	20470	7695	2757	1507	249	339	197	91	39
Upstream	21530	21300	15770	19620	10070	16860	21070	8050	2791	1602	244	361	192	108	58
Upstream	20340	20350	15060	18660	9839	15980	19970	7718	2695	1380	225	281	171	106	58
Upstream	20640	20410	14980	18710	9976	16020	20250	7794	2635	1511	220	360	188	122	65
Upstream	21100	20780	15580	19490	9972	16280	20930	7903	2761	1541	247	315	179	99	59
Upstream	21220	20850	15570	19280	10090	16550	20870	8124	2701	1488	240	342	189	93	62
Upstream	20690	20660	15360	18790	9846	16330	20370	7608	2739	1459	193	342	170	129	51
Upstream	20520	20310	14970	18680	9643	15920	20390	7683	2626	1504	249	327	167	100	52
Upstream	20990	20660	15530	19070	10060	16530	20580	7953	2803	1569	230	327	172	138	69
Upstream	20260	20320	14910	18690	9725	16000	20180	7632	2691	1487	240	340	157	104	50
Upstream-Bkg	142	2	0	0	0	1	0	0	0	0	0	0	0	0	0
Upstream-Bkg	168	0	0	0	0	0	2	1	0	0	0	1	1	1	0
Upstream-Bkg	157	4	1	0	1	0	2	1	0	0	0	0	0	0	0
Upstream-Bkg	142	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Upstream-Bkg	142	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Downstream-Bkg	12	1	1	0	0	0	0	0	0	0	0	0	0	0	0
Downstream-Bkg	37	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Downstream-Bkg	35	13	20	13	4	2	14	7	4	7	2	0	0	0	0
Downstream-Bkg	23	0	0	0	0	0	1	1	1	1	0	0	0	0	0
Downstream-Bkg	16	1	3	6	6	8	15	1	2	0	0	0	1	0	0
Downstream	17060	15830	10940	11670	4938	6056	3353	259	32	22	3	2	1	0	0
Downstream	17030	16010	10920	11640	5027	6036	3424	257	23	12	5	3	2	0	0
Downstream	17280	15840	10920	11990	5004	6021	3363	262	27	14	4	3	1	0	0
Downstream	17180	16120	10930	11580	4952	6047	3370	235	25	3	1	1	1	0	0
Downstream	17400	15980	10890	11640	5028	6124	3464	271	27	18	6	1	2	0	0
Downstream	17280	15800	10860	11590	4881	6004	3342	249	19	14	3	1	0	0	0
Downstream	16530	15270	10540	11280	4960	5851	3168	237	26	6	1	2	1	0	2
Downstream	16950	15500	10680	11330	4866	6024	3358	247	24	1	0	0	1	1	0
Downstream	17370	15790	10970	11700	5033	6007	3347	270	29	13	5	1	1	1	0
Downstream	17680	16370	11170	11930	5154	6239	3529	253	26	8	0	1	3	1	0
Downstream-Bkg	142	0	0	1	1	0	0	0	0	0	0	0	0	0	0
Downstream-Bkg	182	23	18	10	6	2	5	5	1	1	0	1	0	0	0
Downstream-Bkg	148	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Downstream-Bkg	133	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Downstream-Bkg	158	1	0	0	1	0	1	0	0	0	0	0	0	0	0
Meas. Penetration	0.82	0.77	0.71	0.61	0.50	0.37	0.16	0.03	0.01	0.01	0.01	0.00	0.01	0.00	0.00
P100 Correction Value	0.99	0.98	0.99	0.99	0.99	0.99	1.00	0.99	0.98	0.96	0.94	0.96	1.02	1.08	1.14
Corrected Penetration	0.84	0.78	0.72	0.62	0.51	0.37	0.16	0.03	0.01	0.01	0.01	0.00	0.01	0.00	0.00

(*) 0.25 cfm = 0.00012 m^3/s.



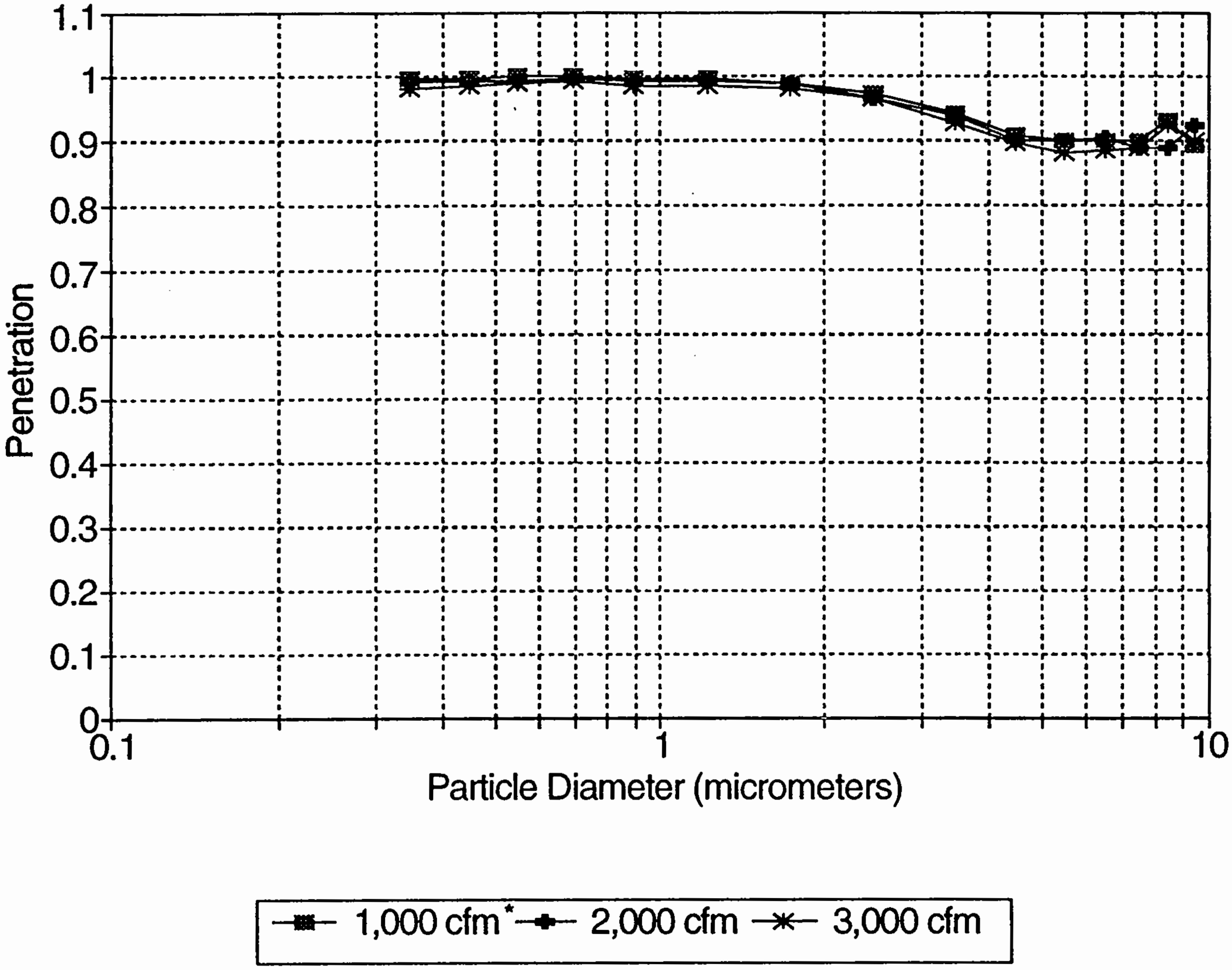
Overview of Test Duct Configuration (Top View)



Aerosol Generation System (Side View)

Aerosol Sampling System (Side View)

Figure 1. Schematic diagram of air cleaner test duct, aerosol generator, and sampling system.



(*) 1,000 cfm = 0.47 m^3/s.

Figure 2. Average results for the 100% penetration tests.

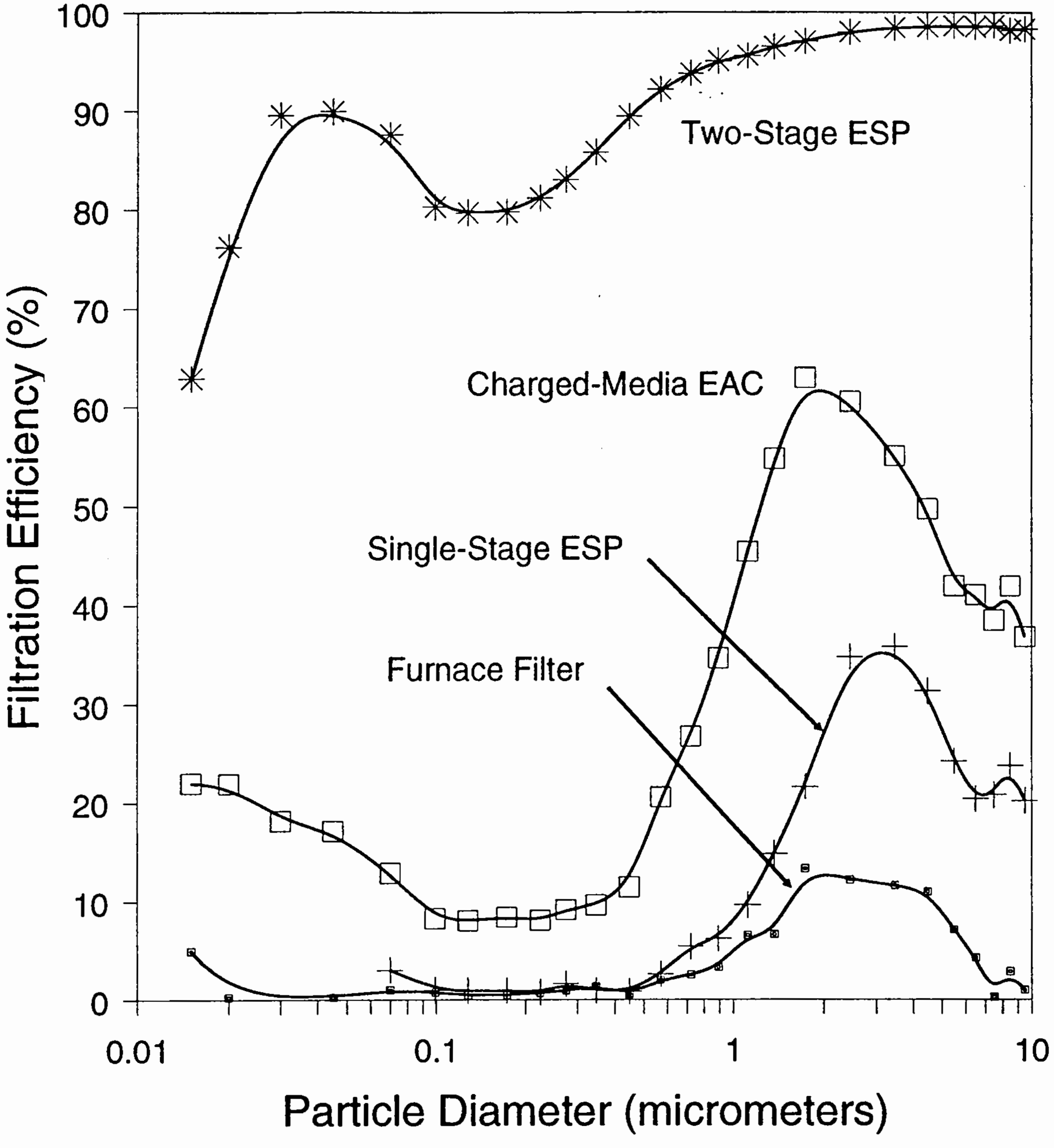


Figure 3. Fractional efficiency of several air cleaners over the 0.01 - 10 μm diameter size range.

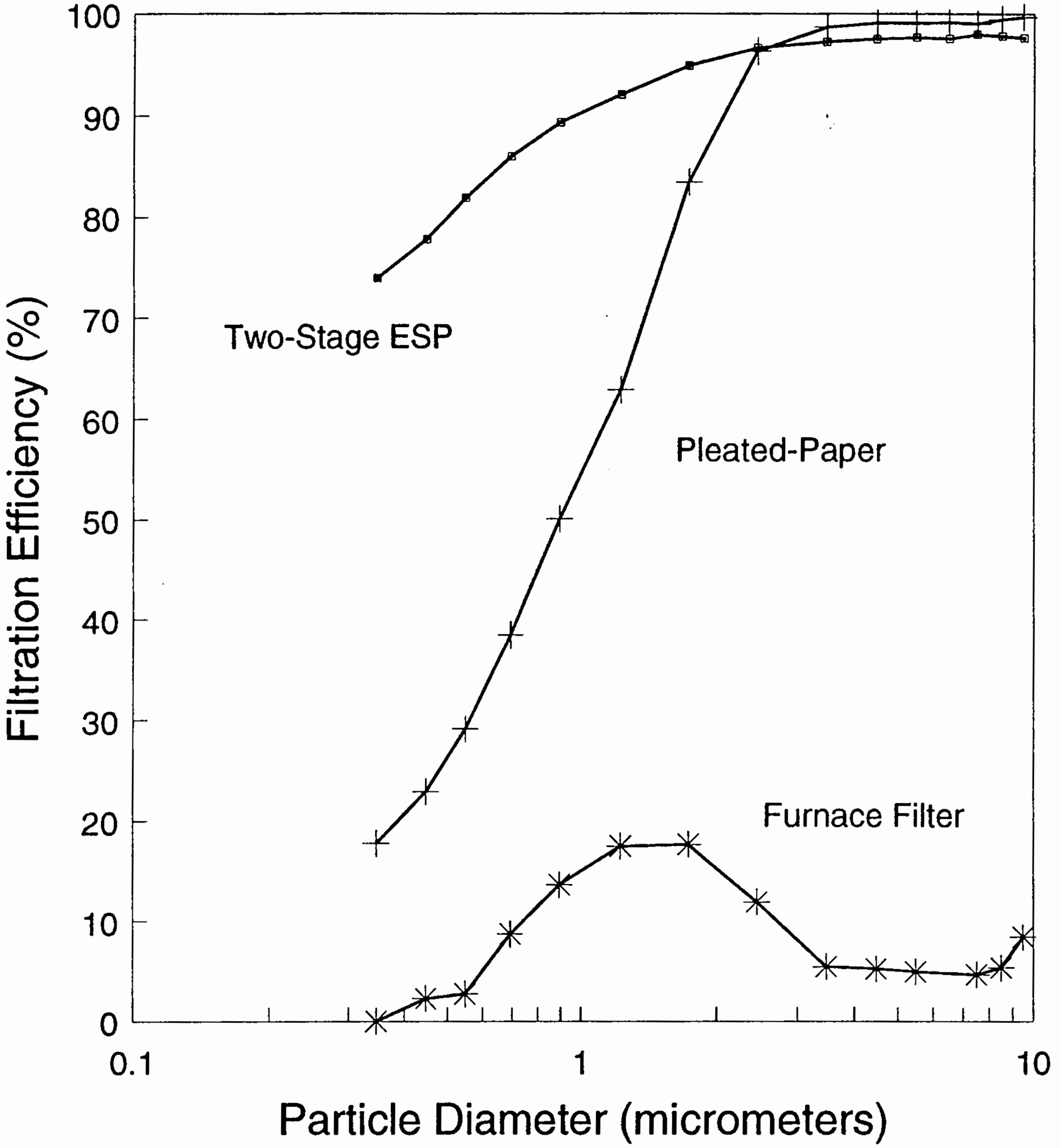


Figure 4. Fractional efficiency of several air cleaners over the 0.3 - 10 μm diameter size range.

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16. ABSTRACT

The paper discusses a test method for measuring the fractional aerosol filtration efficiency of air cleaners. The method provides a reliable and accurate way to measure air cleaner fractional efficiencies over the particle diameter size range of 0.01 to 10 micrometers. (NOTE: The use of air cleaners has moved steadily from one of protecting equipment (e.g., the heat exchanger in a furnace) to one of protecting people from objectional indoor aerosol particles; e.g., common dust an allergens. This shift has necessitated the development of new test methods for determining air cleaner filtration efficiency.) The need for a fractional efficiency test comes from several sources: (1) the growing concern with indoor air quality (IAQ); (2) that filtration efficiency is often highly particle-size dependent for particles < 10 micrometers in diameter; (3) limitations of the current American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) efficiency test which, by design, cannot differentiate between particles sizes; and (4) that respirable particles are generally classified as those < 10 micrometers in diameter.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Measurement	Pollution Control	13B
Aerosols		Stationary Sources	07D
Filtration		Particulate	
Ventilation			13A
Air Cleaners			13I
Particles			14G

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