CHAPTER 29

AIR CLEANERS FOR PARTICULATE CONTAMINANTS

THIS chapter discusses removal of contaminants from both ventilation and recirculated air used for conditioning building interiors. Complete air cleaning may require removing of airborne particles, microorganisms, and gaseous contaminants, but this chapter only covers removal of airborne particles and briefly discusses bioaerosols. Chapter 47 of the 2019 *ASHRAE Handbook—HVAC Applications* covers the removal of gaseous contaminants.

The total suspended particulate concentration in applications discussed in this chapter seldom exceeds 2 mg/m^3 and is usually less than 0.2 mg/m^3 of air (Chapter 11 of the 2018 *ASHRAE Handbook—Refrigeration*). This is in contrast to flue gas or exhaust gas from processes, where dust concentrations typically range from 200 to 40 000 mg/m^3. Chapter 26 discusses exhaust gas control.

Most air cleaners discussed in this chapter are not used in exhaust gas streams because of the extreme dust concentration, large particle size, high temperature, high humidity, and high airflow rate requirements that may be encountered in process exhaust. However, the air cleaners discussed here are used extensively in supplying makeup air with low particulate concentration to industrial processes.

1. TERMINOLOGY

Definitions

Aerodynamic Diameter. The diameter of a spherical particle with a density of 1000 kg/m^3 and the same settling velocity as the irregular particle of interest.

Arrestance. A measure of the ability of an air-cleaning device with efficiencies less than 20% in the size range of 3.0 to 10.0 μm to remove loading dust from the air passing through the device.

Dust Holding Capacity. The total weight of synthetic loading dust captured by an air-cleaning device over all of the incremental dust loading steps.

Particle Size Removal Efficiency. The fraction or percentage of particles retained by an air cleaner for a given particle-size range.

Particulate Matter (PM). Solid and/or liquid particles of various sizes suspended in ambient air.

Penetration. The fraction or percentage of particles that pass through an air cleaner for a given particle-size range.

Resistance to Airflow. Difference in absolute (static) pressure between two points in a system. This parameter is often called pressure drop.

Acronyms

AFI. Air Filter Institute.
AHRI. Air-Conditioning, Heating, and Refrigeration Institute.
ASME. American Society of Mechanical Engineers.
BI/BO. Bag-in/bag-out.
CEN. Comité Européen de Normalisation.
DEHS. Di-ethyl-hexyl-sebacate.
DHC. Dust-holding capacity.
DOP. Dioctyl phthalate.
EN. European norm (European standard).
EPA. Environmental Protection Agency.
EB. Existing buildings.
ETS. Environmental tobacco smoke.
HEPA. High-efficiency particulate air.
IEST. Institute of Environmental Sciences and Technology.
IPA. Isopropyl alcohol.
ISO. International Organization for Standardization.
LCC. Life-cycle cost.
LEED. Leadership in Energy and Environmental Design.
MERV. Minimum efficiency reporting value.
MIL-STD. U.S. Military standard.
MPPS. Most penetrating particle size.
MSHA. Mine Safety and Health Administration.
NAFA. National Air Filtration Association.
NC. New construction.
NIOSH. National Institute for Occupational Safety and Health.
NIST. National Institute of Standards and Technology.
PAO. Polyalphaolefin.
PM. Particulate matter.
PSE. Particle size removal efficiency.
PSL. Polystyrene latex.
UL. Underwriters Laboratory.
ULPA. Ultra-low particulate air.
VAV. Variable air volume.

2. ATMOSPHERIC AEROSOLS

Atmospheric dust is a complex mixture of smokes, mists, fumes, dry granular particles, bioaerosols, and natural and synthetic fibers. When suspended in a gas such as air, this mixture is called an **aerosol**. A sample of atmospheric aerosol usually contains soot and smoke, silica, clay, decayed animal and vegetable matter, organic materials in the form of lint and plant fibers, and metallic fragments. It may also contain living organisms, such as mold spores, bacteria, and plant pollens, which may cause diseases or allergic responses. (Chapter 11 of the 2017 *ASHRAE Handbook—Fundamentals* contains further information on atmospheric contaminants.) A sample of atmospheric aerosol gathered at any point generally contains materials common to that locality, together with other components that originated at a distance but were transported by air currents or diffusion. These components and their concentrations vary with the geography of the locality (urban or rural), season of the year, weather, direction and strength of the wind, and proximity of dust sources.

Aerosol sizes range from 0.01 μm and smaller for freshly formed combustion particles and radon progeny; to 0.1 μm for aged cooking and cigarette smokes; and 0.1 to 10 μm for airborne dust, microor-

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The preparation of this chapter is assigned to TC 2.4, Particulate Air Contaminants and Particulate Contaminant Removal Equipment.

ganisms, and allergens; and up to 100 μm and larger for airborne soil, pollens, and allergens.

Concentrations of atmospheric aerosols generally peak at submicrometre sizes and decrease rapidly as the particulate size increases above 1 μm. For a given size, the concentration can vary by several orders of magnitude over time and by location, particularly near an aerosol source, such as human activities, equipment, furnishings, and pets (McCrone et al. 1967). This wide range of particulate size and concentration makes it impossible to design one cleaner for all applications.

3. AEROSOL CHARACTERISTICS

The characteristics of aerosols that most affect air filter performance include particle size and shape, mass, concentration, and electrical properties. The most important of these is particle size. Figure 3 in Chapter 11 of the 2017 *ASHRAE Handbook—Fundamentals* gives data on the sizes and characteristics of a wide range of airborne particles that may be encountered.

Particle size in this discussion refers to aerodynamic particle size. Particles less than 0.1 μm in diameter are generally referred to as **ultrafine-mode** or **nanoparticles**, those between 0.1 and 2.5 μm are termed **fine mode**, and those larger than 2.5 μm as **coarse mode**. Whereas ultrafine- and fine-mode particles may be formed together, fine- and coarse-mode particles typically originate by separate mechanisms, are transformed separately, have different chemical compositions, and require different control strategies. Vehicle exhaust is a major source of ultrafine particles. Ultrafines are minimally affected by gravitational settling and can remain suspended for days at a time. Fine-mode particles generally originate from condensation or are directly emitted as combustion products. Many microorganisms (bacteria and fungi) either are in this size range or produce components this size. These particles are less likely to be removed by gravitational settling and are just as likely to deposit on vertical surfaces as on horizontal surfaces. Coarse-mode particles are typically produced by mechanical actions such as erosion and friction. Coarse particles are more easily removed by gravitational settling, and thus have a shorter airborne lifetime.

For industrial hygiene purposes, particles ≤ 5 μm in diameter are considered **respirable particles (RSPs)** because a large percentage of this size range has been shown to reach the alveolar region of the lungs. A cutoff of 5.0 μm includes 80 to 90% of the particles that can reach the functional pulmonary region of the lungs (James et al. 1991; Phalen et al. 1991). Willeke and Baron (1993) described a detailed aerosol sampling technique for RSPs, including the use of impactors. See also the discussion in the section on Sizes of Airborne Particles in Chapter 11 of the 2017 *ASHRAE Handbook—Fundamentals*.

In the United States, **particulate matter (PM)** levels in outdoor air are regulated by the Environmental Protection Agency (EPA). Outdoor PM is a complex mixture of small particles and liquid droplets; their effects on health are related to size. Smaller particles have more impact because they penetrate deeper into the respiratory system. Currently, there are two regulated size ranges:

- **PM_{10}** (i.e., all particles that have aerodynamic diameters less than or equal to 10 μm according to the EPA); typical sources include road dust and industrial emissions
- **$PM_{2.5}$** (i.e., all PM with aerodynamic diameter less than or equal to 2.5 μm); the main sources are industrial emissions and combustion exhaust from automobiles, power plants, and heating systems

PM_1, which is not regulated, consists of fine and ultrafine particles of less than 1 μm aerodynamic diameter.

The U.S. Clean Air Act requires the EPA to impose both primary standards designed to protect public health, and secondary standards intended to protect against adverse environmental effects. The limits presently in place (Federal Register 2013) are shown in Table 1. There is no filtration requirement for areas of noncompliance.

Table 1 U.S. EPA Standards for Particulate Matter in Outdoor Air

Type of Standard	Time Period Applicable	PM_{10}, μg/m^3	$PM_{2.5}$, μg/m^3
Primary	24 h	150	35
	1 yr	—	12
Secondary	24 h	150	35
	1 yr	—	15

Source: EPA (2015).

Bioaerosols are a diverse class of particles of biological origin. They include bacteria, fungal spores, fungal fragments, pollen grains, subpollen particles, viruses, pet- and pest-associated allergens, and plant debris (Fröhlich-Nowoisky et al. 2016). They are of particular concern in indoor air because of their association with allergies and asthma and their ability to cause disease. Chapters 10 and 11 of the 2017 *ASHRAE Handbook—Fundamentals* contain more detailed descriptions of these contaminants.

Bioaerosols range in size from 0.01 to 100 μm. Single bacterial cells are approximately 1 μm or less in aerodynamic diameter; however, they are often transported as larger bacterial cell agglomerates (~2 to 5 μm) or attached to other biological and abiotic particles. Unicellular fungal spores are generally 2 to 5 μm in aerodynamic diameter and multicellular fungal spores are larger than 10 μm (Després et al. 2012, Qian et al. 2012). Fungal fragments are typically less than 1 μm in size (Mensah-Attipoe et al. 2016). Pollen grains range in size from 10 to 100 μm (Després et al. 2012), whereas subpollen particles span ~0.01 μm to several micrometers in size (Taylor et al. 2004). Individual viruses can be as small as 0.02 to 0.03 μm, but are typically carried on larger particles (Verreault et al. 2008). Pet- and pest-associated allergens are approximately 1 to over 20 μm (O'Meara and Tovey 2000).

4. AIR-CLEANING APPLICATIONS

Different air-cleaning applications require different degrees of air cleaning effectiveness. In industrial ventilation, only removing the larger dust particles from the airstream may be necessary for cleanliness of the structure, protection of mechanical equipment, and employee health. In other applications, surface discoloration must be prevented. Unfortunately, the smaller components of atmospheric aerosol are the worst offenders in smudging and discoloring building interiors. Electronic air cleaners or medium- to high-efficiency filters are required to remove smaller particles, especially the respirable fraction, which often must be controlled for comfort and health reasons. In cleanrooms or when radioactive or other dangerous particles are present, high- or ultrahigh-efficiency filters should be selected. For more information on cleanrooms, see Chapter 19 of the 2019 *ASHRAE Handbook—HVAC Applications*.

Major factors influencing filter design and selection include (1) degree of air cleanliness required, (2) specific particle size range or aerosols that require filtration, (3) aerosol concentration, (4) resistance to airflow through the filter, (5) design face velocity to achieve published performance, (6) change-out cycle requirements, (7) energy consumption requirements, (8) special disposal mandates, and (9) resistance to certain conditions (physical, chemical, or biological).

5. MECHANISMS OF PARTICLE COLLECTION

In particle collection, air cleaners made of fibrous media rely on the following five main principles or mechanisms (Figure 1):

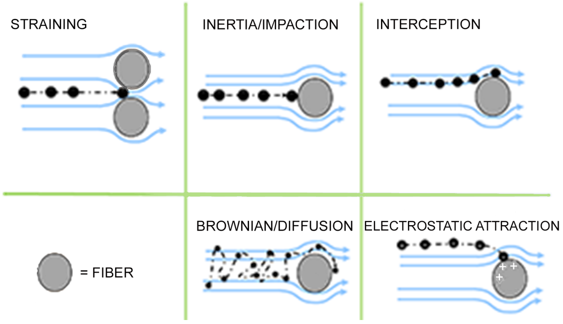

Fig. 1 Collection Mechanisms for Filter Fiber

Straining. The coarsest kind of filtration strains particles through an opening smaller than the particle being removed. It is most often observed as the collection of large particles and lint on the filter surface. The mechanism is not adequate to achieve the filtration of submicrometre aerosols through fibrous matrices, which occurs through other physical mechanisms, as follows.

Inertial Impingement. When particles are large or dense enough that they cannot follow the airstream around a fiber, they cross over streamlines, hit the fiber, and remain there if the attraction is strong enough. With flat-panel and other minimal-media-area filters having high air velocities (where the effect of inertia is most pronounced), the particle may not adhere to the fiber because drag and bounce forces are so high. In this case, a viscous coating (preferably odorless and nonmigrating) is applied to the fiber to enhance retention of the particles. This adhesive coating is critical to metal mesh impingement filter performance.

Interception. Particles follow the airstream close enough to a fiber that the particle contacts the fiber and remains there mainly because of van der Waals forces (i.e., weak intermolecular attractions between temporary dipoles). The adhesion process depends on air velocity through the media being low enough not to dislodge the particles, and is therefore the predominant capture mechanism in extended-media filters such as bag and deep-pleated rigid cartridge types.

Diffusion. The path of very small particles is not smooth but erratic and random within the airstream. This is caused by gas molecules in the air bombarding them (Brownian motion), producing an erratic path that brings the particles close enough to a media fiber to be captured by interception. As more particles are captured, a concentration gradient forms in the region of the fiber, further enhancing filtration by diffusion and interception. The effects of diffusion increase with decreasing particle size and media velocity.

Electrostatic Effects. Particle or media electrostatic charge can produce changes in dust collection affected by the electrical properties of the airstream. Some particles may carry a natural charge. Passive electrostatic (without a power source) filter fibers may be electrostatically charged during their manufacture or (in some materials) by mainly dry air blowing through the media. Charges on the particle and media fibers can produce a strong attracting force if opposite. Efficiency is generally considered to be highest when the media is new and clean.

6. EVALUATING AIR CLEANERS

In addition to criteria affecting the degree of air cleanliness, factors such as cost (initial investment, maintenance, and energy effectiveness), space requirements, and airflow resistance have led to the development of a wide variety of air cleaners. Comparisons of different air cleaners can be made from data obtained by standardized test methods.

The distinguishing operating characteristics are particle size removal efficiency, resistance to airflow, service life, and life-cycle cost. **Efficiency** measures the ability of the air cleaner to remove particles from an airstream. Minimum efficiency during the life of the filter is the most meaningful characteristic for most filters and applications. **Resistance to airflow** (or simply resistance) is the static pressure drop differential across the filter at a given face velocity. The term *static pressure differential* is interchangeable with pressure drop and resistance if the difference of height in the filtering system is negligible. **Life-cycle cost** is the evaluation of device performance in the application in terms of overall cost, along with filter service life, including element cost, energy consumption, maintenance, disposal, etc.

Air filter testing is complex, and no individual test adequately describes all filters. Ideally, performance testing of equipment should simulate operation under actual conditions and evaluate the characteristics important to the equipment user. Wide variations in the amount and type of particles in the air being cleaned make evaluation difficult. Another complication is the difficulty of closely relating measurable performance to the specific requirements of users. Recirculated air tends to have a larger proportion of lint than does outdoor air. However, performance tests should strive to simulate actual use as closely as possible.

Arrestance. A standardized ASHRAE synthetic dust consisting of various particle sizes and types is fed into the test airstream to the air cleaner and the mass fraction of the dust removed is determined. In the ASHRAE *Standard* 52.2 test, summarized in the segment on Air Cleaner Test Methods in this chapter, this measurement is called **synthetic dust** mass **arrestance** to distinguish it from other efficiency values.

The indicated mass arrestance of air filters, as determined in the arrestance test, depends greatly on the particle size distribution of the test dust, which, in turn, is affected by its state of agglomeration. Therefore, this filter test requires highly standardized test dust, dust dispersion apparatus, and other elements of test equipment and procedures. This test is particularly suited to distinguish between the many types of low-efficiency air filters in the minimum efficiency reporting value (MERV) 1 to 4 categories. These are generally roughing filters such as automatic rolls, metal washables, or screen mesh filters used for gross concentration removal of debris and very large particles. It does not adequately distinguish between higher-efficiency filters.

ASHRAE Atmospheric Dust-Spot Efficiency. This method evaluated discoloration (staining) of targets in upstream versus downstream sampling. The dust-spot efficiency method is no longer an ASHRAE standard of test; it was replaced with particle-size-specific testing under *Standard* 52.2.

Fractional Efficiency or Penetration. Defined-size particles are fed into the air cleaner and the percentage removed by the cleaner is determined, typically by a photometer, optical particle counter, or condensation nuclei counter. In fractional efficiency tests, the use of defined-particle-size aerosols results in an accurate measure of the particle size versus efficiency characteristic of filters over a wide atmospheric size spectrum. This method led to the ASHRAE *Standard* 52.2 test, in which a polydispersed challenge aerosol (e.g., potassium chloride) is metered into the test duct as a challenge to the air cleaner. Air samples taken upstream and downstream are drawn through an optical particle counter or similar measurement device to obtain removal efficiency versus particle size at a specific airflow rate in 12 designated particle size ranges (0.3 to 10 μm). High-efficiency particulate air (HEPA) testing, specifically the dioctyl phthalate (DOP) or polyalphaolefin (PAO) test for HEPA filters, is widely used for production testing in very small particle size ranges. For more information on the DOP test, see the DOP Penetration Test section.

Fractional efficiency is the measure of particles removed from the upstream concentration by a known device. The testing can be done in the field with atmospheric conditions, or in a laboratory with known particle challenges.

Penetration efficiency typically is the reference characteristic in HEPA filter testing, using DOP or PAO and determining the amount of specific particle penetration through a tested element.

Dust-Holding Capacity. Dust-holding capacity of air cleaners is the reported amount of synthetic dust retained in an air cleaner at the end of the test period. Atmospheric dust-holding capacity is a function of environmental conditions as well as variability of atmospheric dust (size, shape, and concentration), and is therefore impossible to duplicate in a laboratory test. Artificial dusts are not the same as atmospheric dusts, so dust-holding capacity as measured by these accelerated tests is different from that achieved in life-cycle cost evaluations and should not be used to compare filter life expectancies.

Differences in laboratory dust-holding capacity can result from variability of test aerosols, variabilities of the tested filter elements, measurement device tolerances, and atmospheric condition.

7. AIR CLEANER TEST METHODS

Air cleaner test methods have been developed by the heating and air-conditioning industry, the automotive industry, the atomic energy industry, and government and military agencies. Several tests have become standard in general ventilation applications in the United States. In 1968, the test techniques developed by the U.S. National Bureau of Standards (now the National Institute of Standards and Technology [NIST]) and the Air Filter Institute (AFI) were unified (with minor changes) into a single test procedure, ASHRAE *Standard* 52-1968. Dill (1938), Nutting and Logsdon (1953), and Whitby et al. (1956) give details of the original codes. After multiple revisions, ASHRAE *Standard* 52-1968 was discontinued in 2009 and replaced by ASHRAE Standard 52.2.

ASHRAE *Standard* 52.2-2012 contains **minimum efficiency reporting values (MERVs)** for air cleaner particle size efficiency. In 2008, the standard incorporated arrestance testing from the discontinued ASHRAE *Standard* 52.1. Table 3 provides an approximate cross-reference for air cleaners tested under ASHRAE *Standards* 52.1 and 52.2. Currently, there is no ASHRAE standard for testing electronic air cleaners.

Arrestance Test

ASHRAE *Standard* 52.2 defines synthetic test dust as a compounded test dust consisting of (by mass) 72% ISO *Standard* 12 103-A2 fine test dust, 23% powdered carbon, and 5% no. 7 cotton linters. A known amount of the prepared test dust is fed into the test unit at a known and controlled concentration. The amount of dust in the air leaving the test filter is determined by passing the entire airflow through a high-efficiency final filter (≥98%) downstream of the test filter and measuring the gain in filter mass. The synthetic mass **arrestance** is calculated using the masses of the dust captured on the final high-efficiency filter and the total dust fed.

Atmospheric aerosol particles range from a small fraction of a micrometre to tens of micrometres in diameter. The artificially generated dust cloud used in the ASHRAE arrestance method is considerably coarser than typical atmospheric dust. It tests the ability of a filter to remove the largest atmospheric aerosol particles and gives little indication of filter performance in removing the smallest particles. However, where the mass of dust in the air is the primary concern, this is a valid test because most of the mass is contained in the larger particles. Where extremely small particles (such as respirable sizes) are involved, arrestance rating does not differentiate between filters.

Dust-Holding Capacity (DHC) Test

Synthetic test dust (as described in the preceding section) is fed to the filter in accordance with ASHRAE *Standard* 52.2 procedures. The pressure drop across the filter (its resistance to airflow) rises as dust is fed. The test normally ends when resistance reaches the maximum operating resistance set by the manufacturer. However, not all filters of the same type retain collected dust equally well. The test, therefore, requires that arrestance be measured at least four times during dust loading and that the test be terminated when two consecutive arrestance values of less than 85%, or one value equal to or less than 75% of the maximum arrestance, have been measured. The ASHRAE **dust-holding capacity** is, then, the integrated amount of dust held by the filter up to the time the dust-loading test is terminated. (See ASHRAE *Standard* 52.2 for more detail.)

Particle Size Removal Efficiency (PSE) Test

ASHRAE *Standard* 52.2 prescribes a way to test air-cleaning devices for removal efficiency by particle size while addressing two air cleaner performance characteristics important to users: the ability of the device to remove particles from the airstream and its resistance to airflow. In this method, air cleaner testing is conducted at a specific airflow based on the upper limit of the air cleaner's application range. Airflows are based on specific face velocities between 0.60 and 3.80 m/s, which yields between 0.22 and 1.4 m^3/s for a nominal 610 by 610 mm filter. The test aerosol consists of laboratory-generated potassium chloride particles dispersed in the airstream. Optical particle counters measure and count the particles in 12 geometric logarithmic-scale, equally distributed particle size ranges both upstream and downstream for efficiency determinations. The test encompasses 0.3 to 10 μm polystyrene latex. The clean-filter efficiency test is followed by five dust loadings, using ASHRAE dust, to increase the pressure drop across the filter. Efficiency tests are performed after each dust loading.

A set of particle size removal efficiency performance curves is developed from the test and, together with the initial clean performance curve, is the basis of a composite curve representing performance in the range of sizes. Points on the composite curve are averaged and these averages are used to determine the MERV of the air cleaner. A complete test report includes (1) a summary of the test, (2) removal efficiency curves of the clean devices at each of the loading steps, and (3) a composite minimum removal efficiency curve.

In 2008, Appendix J on conditioning was added as an optional part of *Standard* 52.2. If used, this conditioning step replaces the current first (small) dust loading. This step simulates the efficiency drop seen in many charged filters in actual use: the high concentration of 40 to 50 nm aerosol exposes the filter to many particles of a size common in ambient and indoor air. This step does not completely remove the charge on the fibers. When Appendix J is used in a full *Standard* 52.2 test, the nomenclature used to report results is MERV-A (ASHRAE 2008).

DOP Penetration Test

For high-efficiency filters of the type used in cleanrooms and nuclear applications (HEPA filters), the normal test in the United States is the thermal DOP method, outlined in U.S. Military *Standard* MIL-STD-282 (Revision B; 2015) and U.S. Army document 136-300-175A (1965). DOP is dioctyl phthalate or bis-(2-ethylhexyl) phthalate, which is an oily liquid with a high boiling point. In this method, a smoke cloud of DOP droplets condenses from DOP vapor.

The count median diameter for DOP aerosols is about 0.18 μm, and the mass median diameter is about 0.27 μm with a cloud concentration of approximately 20 to 80 mg/m^3 under properly controlled conditions. The procedure is sensitive to the mass median diameter, and DOP test results are commonly referred to as efficiency at 0.30 μm particle size, believed to be the most penetrating particle size (MPPS) for the filtration materials currently used. This penetration diameter is velocity dependent.

The DOP smoke cloud is fed to the filter, which is held in a special test fixture. Any smoke that penetrates the body of the filter or leaks through gasket cracks passes into the region downstream from the filter, where it is thoroughly mixed. Air leaving the fixture thus contains the average concentration of penetrating smoke. This concentration, as well as the upstream concentration, is measured by a light-scattering photometer.

Filter penetration *P* (%) is given as

$$P = 100\left(\frac{\text{Downstream concentration}}{\text{Upstream concentration}}\right) \tag{1}$$

Penetration, not efficiency, is usually specified in the test procedure because HEPA filters have efficiencies so near 100% (e.g., 99.97% or 99.99% on 0.30 μm particles). Penetration and efficiency E are related by the equation $E = 100 - P$.

U.S. specifications frequently call for testing HEPA filters at both rated flow and 20% of rated flow. This procedure helps detect gasket leaks and pinholes that would otherwise escape notice. Such defects, however, are not located by the DOP penetration test.

Other popular test aerosols include polyalphaolefin (PAO Emery 3004), which is also a liquid aerosol similar in particle size distribution to DOP, and polystyrene latex spheres (PSL), a solid aerosol that can be made to a specified size.

The Institute of Environmental Sciences and Technology has published two recommended practices: IEST RP-CC 001.6, HEPA and ULPA Filters, and IEST RP-CC 007.3, Testing ULPA Filters.

Leakage (Scan) Tests

For HEPA filters, leakage tests are sometimes desirable to show that no small “pinhole” leaks exist or to locate any that may exist so they may be patched. Essentially, this is the same technique as used in the oil aerosol (DOP) penetration test, except that the downstream concentration is measured by scanning the face of the filter and its gasketed perimeter with a moving isokinetic sampling probe. The exact point of smoke penetration can then be located and repaired. This same test (described in IEST RP-CC 001.6) can be performed after the filter is installed. Smoke produced by a portable generator is not uniform in size, but its average diameter can be approximated as 0.6 μm. Particle diameter is less critical for leak location than for penetration measurement. The leak scan test is typically done for filters with 99.99% or higher efficiencies, in applications for which locating and repairing a discrete leak are more important.

ISO *Standard* 29462

In 2008, ASHRAE published *Guideline* 26 to provide a test method for evaluating filters in place in building HVAC systems. This guideline was adopted without technical change by the ISO and published as ISO *Standard* 29462-2013. Subsequently, ASHRAE withdrew *Guideline* 26.

ISO *Standard* 29462 presents a method for determining the in-place efficiency of individual particle filters or filter systems installed in building HVAC systems, as long as the filter or system is amenable to testing (e.g., enough space in the HVAC system to install sensors, well-sealed doors; a checklist is provided). Using a particle counter, particles in several size ranges between 0.3 and 5 μm that are circulating in the HVAC system are measured several times upstream and downstream of the filter to provide statistically robust data. Then, the removal efficiency is calculated by particle size. Pressure drop across the filter, temperature, and relative humidity are recorded. The test method is theoretically applicable to all filters in HVAC systems. However, it is unlikely to yield statistically significant results for filters with efficiencies lower than MERV 11 because of the size distribution of particles typically found in building HVAC systems.

Note that field data generally show larger uncertainties than measurements made in a laboratory. For filter/filter system tests, this is because of the variety of different HVAC environments and particle types likely to be encountered, and the difficulties in controlling environmental variables during the test. ISO *Standard* 29462 includes a procedure for reducing uncertainty by subjecting a reference filter to measurement both in the field and in a laboratory.

Other Performance Tests

The European Standardization Institute (Comité Européen de Normalisation, or CEN) developed EN *Standard* 779, Particulate Air Filters for General Ventilation—Requirements, Testing, Marking, in 1993. Its latest revision, Particulate Air Filters for General Ventilation—Determination of the Filtration Performance, was approved and published in 2012. Efficiency is reported as an average efficiency after loading with ASHRAE dust. In this latest revision, minimum efficiency requirements for discharged filters are 35% for F7, 55% for F8, and 70% for F9. This is 0.4 μm efficiency, measured on media samples after discharge in liquid isopropyl alcohol (IPA). The test aerosol as specified in the standard is DEHS. Eurovent working group 4B (Air Filters) developed Eurovent *Documents* 4/9 (1996), Method of Testing Air Filters Used in General Ventilation for Determination of Fractional Efficiency, and 4/10 (2005), In Situ Determination of Fractional Efficiency of General Ventilation Filters. CEN also developed EN *Standard* 1822-2009, which requires that HEPA and ULPA filters must be tested. Also, special test standards have been developed in the United States for respirator air filters (NIOSH 1995) and ULPA filters (IEST RP-CC 007.2).

In 2004, the International Organization for Standardization (ISO) reactivated technical committee TC 142, Cleaning Equipment for Air and Other Gases. The committee’s scope includes test methods for particle filters of various types and efficiencies, particle filter media, and room air cleaners. ASHRAE has cooperated closely with TC 142, and several ASHRAE documents have been used in the development of TC 142 standards.

The unanimously approved ISO 16890:2016 set of standards is a new global filtration standard for laboratory testing and rating. It has replaced EN *Standard* 779 (wherever specified) and is currently being discussed to replace ASHRAE *Standard* 52.2 in the United States. This standard uses a similar test procedure to ASHRAE *Standard* 52.2, but includes a unique rating system that relates measured filter performance to typical urban and rural air pollution conditions. The result is a removal efficiency specified in terms of PM and shown as ePM.

ISO *Standard* 16890 is split into four parts:

Part 1. Technical specifications, requirements and classification system based upon particulate matter efficiency (ePM)
Part 2. Measurement of fractional efficiency and air flow resistance
Part 3. Determination of the gravimetric efficiency and the air flow resistance versus the mass of test dust captured
Part 4. Conditioning method to determine the minimum fractional test efficiency

ISO *Standard* 29463, parts 2 to 5, have replaced EN *Standard* 1822, parts 2 to 5, for the method of test for very high efficiency filters. EN *Standard* 1822 Part 1 remains for the classification of filters.

Environmental Tests

Air cleaners may be subjected to fire, high humidity, a wide range of temperatures, mechanical shock, vibration, and other environmental stress. Several standardized tests exist for evaluating these environmental effects on air cleaners. U.S. Military Standard MIL-STD-282 includes shock tests (shipment rough handling) and filter media water-resistance tests. Several U.S. Atomic Energy

Commission agencies (now part of the U.S. Department of Energy) specify humidity and temperature-resistance tests (DOE 1997, 2003).

UL *Standard* 900. This destructive test procedure measures the amount of flame, smoke, or both generated by a filter when subjected to a burner in a test duct. Additionally, to pass, a filter must not generate sparks beyond the discharge length of the test duct.

This procedure does not consider filter performance regarding particle collection at any point of its test life, and pertains to a clean filter only. As filters accumulate particles, the burning, smoke, and spark characteristics change based on the contaminant in the media; thus, UL *Standard* 900 applies *only* to new filters. Once a filter has been put in service, the classification is no longer valid.

UL *Standard* 586. This test was specifically designed to evaluate the performance of a HEPA filter in extreme and rigorous conditions. While being particle challenged, the filter is subjected to extreme cold, heat, and humidity. In addition, there are shock tests simulating shipping and handling stresses to evaluate physical durability, and a flame test on the media. The standard also has some specific construction requirements for various portions of each element.

In 1991, UL *Standard* 586 was required by the Department of Defense for Nuclear material applications. It is an integral part of ASME *Standard* AG-1, Code on Nuclear Air and Gas Treatment.

The UL tests do not evaluate the effect of collected dust on filter flammability; depending on the dust, this effect may be severe. UL *Standard* 867 applies to electronic air cleaners.

AHRI Standards

The Air-Conditioning, Heating, and Refrigeration Institute published AHRI *Standards* 680 (residential) and 850 (commercial/industrial) for air filter equipment. *Standard* 680 applies to both media and electronic air cleaners, and specifies rating conditions for performance, capacity, and restriction. These standards establish (1) definitions and classification; (2) requirements for testing and rating; (3) specification of standard equipment; (4) performance and safety requirements; (5) proper marking; (6) conformance conditions; and (7) literature and advertising requirements. However, certification of air cleaners is not a part of these standards.

8. TYPES OF AIR CLEANERS

Common air cleaners are broadly grouped as follows:

In **fibrous media unit filters**, the accumulating dust load causes pressure drop to increase up to some maximum recommended or predetermined value before changing filters. During this period, efficiency normally increases. However, at high dust loads, dust may adhere poorly to filter fibers and efficiency drops because of offloading. Filters in this condition should be replaced or reconditioned, as should filters that have reached their final (maximum recommended) pressure drop. This category includes viscous impingement and dry air filters, available in low-efficiency to ultrahigh-efficiency construction.

Renewable media filters are fibrous media filters where fresh media is introduced into the airstream as needed to maintain essentially constant resistance and, consequently, constant average efficiency.

Electronic air cleaners require a power source and, if maintained properly by regular cleaning, have relatively constant pressure drop and efficiency. If they are not cleaned regularly, the accumulated dust can build up to the point that arcing can occur in the collection section. This may reduce collection efficiency as well as produce unwanted extraneous noise. Dust buildup in the ionizer section can also reduce efficiency.

Combination air cleaners combine the other types. For example, an electronic air cleaner may be used as an agglomerator with a fibrous media downstream to catch the agglomerated particles blown off the plates. Low-efficiency pads, throwaway panels and automatically renewable media roll filters, or low- to medium-efficiency pleated prefilters may be used upstream of a high-efficiency filter to extend the life of the better and more costly final filter. Charged media filters are also available that increase particle deposition on media fibers by an induced electrostatic field. With these filters, pressure loss increases as it does on a non-charged fibrous media filter. The benefits of combining different air cleaning processes vary.

9. FILTER TYPES AND PERFORMANCE

Panel Filters

Viscous impingement panel filters are made up of coarse, highly porous fibers. Filter media are generally coated with an odorless, nonmigrating adhesive or other viscous substance, such as oil, which causes particles that impinge on the fibers to stick to them. Design air velocity through the media usually ranges from 1 to 4 m/s. These filters are characterized by low pressure drop, low cost, and good efficiency on lint and larger particles (10 µm and larger), but low efficiency on normal atmospheric aerosol. They are commonly made 13 to 100 mm thick. Unit panels are available in standard and special sizes up to about 610 by 610 mm. This type of filter is commonly used in residential furnaces and air conditioning and is often used as a prefilter for higher-efficiency filters.

Filter media materials include metallic wools, expanded metals and foils, crimped screens, random matted wire, coarse (15 to 60 µm diameter) glass fibers, coated animal hair, vegetable or synthetic fibers, and synthetic open-cell foams.

Although viscous impingement filters usually operate between 1.5 and 3 m/s, they may be operated at higher velocities. The limiting factor, other than increased flow resistance, is the danger of blowing off agglomerates of collected dust and the viscous coating on the filter.

The loading rate of a filter depends on the type and concentration of dirt in the air being handled and the operating cycle of the system. Manometers, static pressure differential gages, or pressure transducers are often installed to measure pressure drop across the filter bank. This measurement can identify when the filter requires service. The final allowable pressure differential may vary from one installation to another, but, in general, viscous impingement filters are serviced when their operating resistance reaches 125 Pa. Life-cycle cost (LCC), including energy necessary to overcome the filter resistance, should be calculated to evaluate the overall cost of the filtering system. The decline in filter efficiency caused by dust coating the adhesive, rather than by the increased resistance because of dust load, may be the limiting factor in operating life.

The manner of servicing unit filters depends on their construction and use. Disposable viscous impingement panel filters are constructed of inexpensive materials and are discarded after one period of use. The cell sides of this design are usually a combination of cardboard and metal stiffeners. Permanent unit filters are generally constructed of metal to withstand repeated handling. Various cleaning methods have been recommended for permanent filters; the most widely used involves washing the filter with steam or water (frequently with detergent) and then recoating it with its recommended adhesive by dipping or spraying. Unit viscous filters are also sometimes arranged for in-place washing and recoating.

The adhesive used on a viscous impingement filter requires careful engineering. Filter efficiency and dust-holding capacity depend on the specific type and quantity of adhesive used; this information is an essential part of test data and filter specifications. Desirable adhesive characteristics, in addition to efficiency and dust-holding capacity, are (1) a low percentage of volatiles to prevent excessive evaporation; (2) viscosity that varies only slightly within the service temperature range; (3) the ability to inhibit growth of bacteria and mold spores; (4) high capillarity or ability to wet and retain dust particles; (5) high flash point and fire point; and (6) freedom from odorants or irritants.

Typical performance of viscous impingement unit filters operating within typical resistance limits is shown as MERV 1 through 6 in Table 3.

Dry extended-surface filters use media of random fiber mats or blankets of varying thicknesses, fiber sizes, and densities. Bonded glass fiber, cellulose fibers, wool felt, polymers, synthetics, and other materials have been used commercially. Media in these filters are frequently supported by a wire frame in the form of pockets, or V-shaped or radial pleats. In other designs, the media may be self supporting because of inherent rigidity or because airflow inflates it into extended form (e.g., bag filters). Pleating media provides a high ratio of media area to face area, thus allowing reasonable pressure drop and low media velocities.

In some designs, the filter media is replaceable and is held in position in permanent wire baskets. In most designs, the entire cell is discarded after it has accumulated its maximum dust load.

Efficiency is usually higher than that of panel filters, and the variety of media available makes it possible to furnish almost any degree of cleaning efficiency desired. The dust-holding capacities of modern dry filter media and filter configurations are generally higher than those of panel filters.

Using coarse prefilters upstream of extended-surface filters is sometimes justified economically by the longer life of the main filters. Economic considerations include the prefilter material cost, changeout labor, and increased fan power. Generally, prefilters should be considered only if they can substantially reduce the part of the dust that may plug the protected filter. A prefilter usually has an arrestance of at least 70% (MERV 3), but is commonly rated up to 92% (MERV 6). Temporary prefilters protecting higher-efficiency filters are worthwhile during construction to capture heavy loads of coarse dust. Filters of MERV 16 and greater should always be protected by prefilters. A single filter gage may be installed when a panel prefilter is placed adjacent to a final filter. Because the prefilter is frequently changed on a schedule, the final filter pressure drop can be read without the prefilter in place every time the prefilter is changed. For maximum accuracy and economy of prefilter use, two gages can be used. Some air filter housings are available with pressure taps between the pre- and final filter tracks to accommodate this arrangement.

Typical performance of some types of filters in this group, when operated within typical rated resistance limits and over the life of the filters, is shown as MERV 7 through 16 in Table 3.

Initial resistance of an extended-surface filter varies with the choice of media and filter geometry. Commercial designs typically have an initial resistance from 25 to 250 Pa. It is customary to replace the media when the final resistance of 125 Pa is reached for low-resistance units and 500 Pa for the highest-resistance units. Dry media providing higher orders of cleaning efficiency have a higher average resistance to airflow. The operating resistance of the fully dust-loaded filter must be considered in design, because that is the maximum resistance against which the fan operates. Variable-air-volume and constant-air-volume system controls prevent abnormally high airflows or possible fan motor overloading from occurring when filters are clean.

Flat panel filters with media velocity equal to duct velocity are made only with the lowest-efficiency dry-type media (open-cell foams and textile denier nonwoven media). Initial resistance of this group, at rated airflow, is generally between 10 and 60 Pa. They are usually operated to a final resistance of 120 to 175 Pa.

In intermediate-efficiency extended-surface filters, the filter media area is much greater than the face area of the filter; hence, velocity through the filter media is substantially lower than the velocity approaching the filter face. Media velocities range from 0.03 to 0.5 m/s, although approach velocities run to 4 m/s. Depth in direction of airflow varies from 50 to 900 mm.

Intermediate-efficiency filter media include (1) fine glass or synthetic fibers, from nanofiber to 10 μm in diameter, in mats up to 13 mm thick; (2) wet laid paper or thin nonwoven mats of fine glass fibers, cellulose, or cotton wadding; and (3) nonwoven mats of comparatively large-diameter fibers (more than 30 μm) in greater thicknesses (up to 50 mm).

Electret filters, which require no power, are composed of electrostatically charged fibers. The charges on the fibers augment collection of smaller particles by interception and diffusion (Brownian motion) with Coulomb forces caused by the charges. Examples of this type of filter include resin wool, electret, and an electrostatically sprayed polymer. The charge on resin wool fibers is produced by friction during the carding process. During production of the electret, a corona discharge injects positive charges on one side of a thin polypropylene film and negative charges on the other side. These thin sheets are then shredded into fibers of rectangular cross section. The third process spins a liquid polymer into fibers in the presence of a strong electric field, which produces the charge separation. Efficiency of charged-fiber filters is determined by both the normal collection mechanisms of a media filter (related to fiber diameter) and the strong local electrostatic effects (related to the amount of electrostatic charge). The effects induce efficient preliminary loading of the filter to enhance the caking process. However, ultrafine-particle dust collected on the media can affect the efficiency of electret filters.

Very high-efficiency dry filters, **HEPA (high-efficiency particulate air) filters**, and **ULPA (ultralow-penetration air) filters** are made in an extended-surface configuration of deep space folds of submicrometre glass fiber paper. These filters operate at duct velocities from 1.3 to 2.6 m/s, with resistance rising from 120 to more than 500 Pa over their service life. These filters are the standard for cleanroom, nuclear, and toxic particulate applications, and are increasingly used in numerous medical and pharmaceutical applications.

Membrane filters are used mainly for air sampling and specialized small-scale applications where their particular characteristics compensate for their fragility, high resistance, and high cost. They are available in many pore diameters and resistances and in flat-sheet and pleated forms.

Renewable-media filters may be one of two types: (1) moving-curtain viscous impingement filters or (2) moving-curtain dry-media roll filter. Commonly described as **automatic roll filters**, these are typically lower on the efficiency scale.

In one viscous type, random-fiber (nonwoven) media is furnished in roll form. Fresh media is fed manually or automatically across the face of the filter, while the dirty media is rewound onto a roll at the bottom. When the roll is exhausted, the tail of the media is wound onto the take-up roll, and the entire roll is thrown away. A new roll is then installed, and the cycle repeats.

Moving-curtain filters may have the media automatically advanced by motor drives on command from a pressure switch, timer, or media light-transmission control. A pressure switch control measures the pressure drop across the media and switches on and off at chosen upper and lower set points. This saves media, but only if the static pressure probes are located properly and unaffected by modulating outdoor and return air dampers. Most pressure drop controls do not work well in practice. Timers and media light-transmission controls help avoid these problems; their duty cycles can usually be adjusted to provide satisfactory operation with acceptable media consumption.

Filters of this replaceable roll design generally have a signal indicating when the roll is nearly exhausted. At the same time, the drive motor is deenergized so that the filter cannot run out of media. Normal service requirements involve inserting a clean roll of media

Table 2 Performance of Renewable Media Filters (Steady-State Values)

Description	Type of Media	ASHRAE Arrestance, %	ASHRAE Dust-Holding Capacity, g/m^2
20 to 40 μm glass and synthetic fibers, 50 to 65 mm thick	Viscous impingement	70 to 82	600 to 2000
Permanent metal media cells or overlapping elements	Viscous impingement	70 to 80	N/A (permanent media)
Coarse textile denier nonwoven mat, 12 to 25 mm thick	Dry	60 to 80	150 to 750
Fine textile denier nonwoven mat, 12 to 25 mm thick	Dry	80 to 90	100 to 550

at the top of the filter and disposing of the loaded dirty roll. Automatic filters of this design are not, however, limited to the vertical position; horizontal arrangements are available for makeup air and air-conditioning units. Adhesives must have qualities similar to those for panel viscous impingement filters, and they must withstand media compression and endure long storage.

The second type of automatic viscous impingement filter consists of linked metal mesh media panels installed on a traveling curtain that intermittently passes through an adhesive reservoir. In the reservoir, the panels give up their dust load and, at the same time, take on a new coating of adhesive. The panels thus form a continuous curtain that moves up one face and down the other face. The media curtain, continually cleaned and renewed with fresh adhesive, lasts the life of the filter mechanism. The precipitated captured dirt must be removed periodically from the adhesive reservoir. New installations of this type of filter are rare in North America, but are often found in Europe and Asia.

The resistance of both types of viscous impingement automatically renewable filters remains approximately constant as long as proper operation is maintained. A resistance of 100 to 125 Pa at a face velocity of 2.5 m/s is typical of this class.

Special automatic dry filters are also available, designed for removing lint in textile mills, laundries, and dry-cleaning establishments and for collecting lint and ink mist in printing press rooms. The medium used is extremely thin and serves only as a base for the build-up of lint, which then acts as a filter medium. The dirt-laden media is discarded when the supply roll is used up.

Another form of filter designed specifically for dry lint removal consists of a moving curtain of wire screen, which is vacuum cleaned automatically at a position out of the airstream. Recovery of the collected lint is sometimes possible with these devices.

ASHRAE arrestance and dust-holding capacities for typical viscous impingement and dry renewable-media filters are listed in Table 2.

Electronic Air Cleaners

Electronic air cleaners use an electrostatic charge to enhance filtration of particulate contaminants such as dust, smoke, and pollen. The electrostatic charge can create higher efficiencies than mechanical means alone. Electronic air cleaners are available in many designs, but fall into two major categories: (1) electronic, plate-type precipitators and (2) electrically enhanced air filtration.

Plate Precipitators. Precipitators use electrostatic precipitation to remove and collect particulate contaminants on plates. The air cleaner has an ionization section and a collecting plate section.

In the ionization section, small-diameter wires with a positive direct current potential between 6 and 25 kV are suspended equidistant between grounded plates. The high voltage on the wires creates an ionizing field for charging particles. The positive ions created in the field flow across the airstream and strike and adhere to the particles, imparting a charge to them. The charged particles then pass into the collecting plate section.

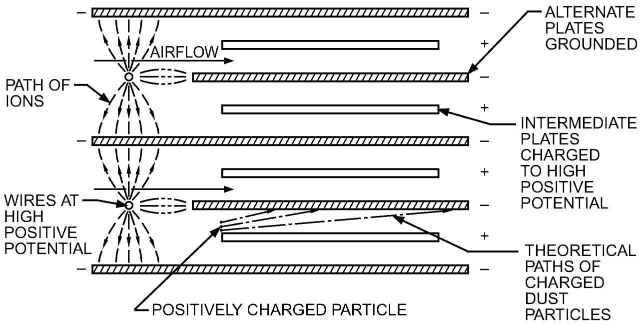

Fig. 2 Cross Section of Plate-Type Precipitator Air Cleaner

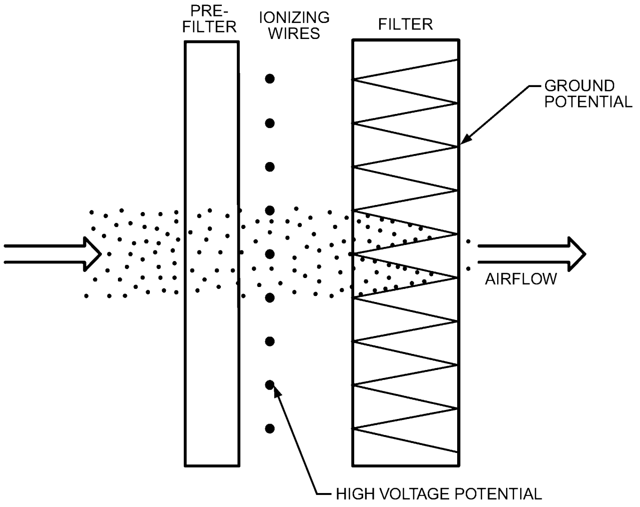

Fig. 3 Electrically Enhanced Air Cleaner

The collecting plate section consists of a series of parallel plates equally spaced with a positive direct current voltage of 4 to 10 kV applied to alternate plates. Plates that are not charged are at ground potential. As the particles pass into this section, they are attracted to the plates by the electric field on the charges they carry; thus, they are removed from the airstream and collected by the plates. Particle retention is a combination of electrical and intermolecular adhesion forces and may be augmented by special oils or adhesives on the plates. Figure 2 shows a typical electronic air cleaner cell.

In lieu of positive direct current, a negative potential also functions on the same principle, but generates more ozone. With voltages of 4 to 25 kV (dc), safety measures are required. A typical arrangement makes the air cleaner inoperative when the doors are removed for cleaning the cells or servicing the power pack. Electronic air cleaners typically operate from a 120 or 240 V (ac) single-phase electrical service. The high voltage supplied to the air cleaner cells is normally created with solid-state power supplies. The electric power consumption ranges from 40 to 85 W per m^3/s of air cleaner capacity.

Electrically Enhanced Air Filtration. Electrically enhanced air cleaners incorporate an electrostatic field to charge contaminants before capture in a high-efficiency pleated filter. Advantages include high efficiency and reduced maintenance frequency. Figure 3 shows that the air cleaners consist of an ionizing section and a filtration section. The ionizing section has a prefilter to prevent large debris from entering the air filter and to focus the electrostatic field. The air is charged in a high-voltage ionizing section. In the ionization section, the ionizer is connected to a high-voltage power supply and the particulate is charged. The charged particles are collected in the media filter at earth ground potential.

Maintenance. Plate-type air cleaner cells must be cleaned periodically with detergent and hot water. Some designs incorporate automatic wash systems that clean the cells in place; in others, the cells are removed for cleaning. The frequency of cleaning (washing) the cell depends on the contaminant and the concentration. Industrial applications may require cleaning every 8 h, but a residential unit may only require cleaning every one to three months. The timing of the cleaning schedule is important to keep the unit performing at peak efficiency. For some contaminants, special attention must be given to cleaning the ionizing wires.

The air cleaner must be maintained based on the recommendations of the manufacturer. Electrically enhanced air cleaners have a longer service life between maintenance than plate-type precipitators. Maintenance consists of replacing the filter and cleaning the ionizing section and prefilter.

Performance. Currently AHRI *Standard* 680 is the industry-accepted test method for electronic air cleaners. This test involves loading the filter with a dust that does not contain a conductive component and allows comparison to media filtration.

Application. As with most air filtration devices, duct approaches to and from the air cleaner housing should be arranged so that airflow is distributed uniformly over the face area. Panel prefilters should also be used to help distribute airflow and to trap large particles that might short out or cause excessive arcing in the high-voltage section of the air cleaner cell. Electronic air cleaner design parameters of air velocity, ionizer field strength, cell plate spacing, depth, and plate voltage must match the application requirements (e.g., contaminant type, particle size, volume of air, required efficiency). Many units are designed for installation into central heating and cooling systems for total air filtration. Other self-contained units are furnished complete with air movers for source control of contaminants in specific applications that need an independent air cleaner.

Optional features are often available for electronic air cleaners. Afterfilters such as roll filters collect particulates that agglomerate and blow off the cell plates. These are used mainly where heavy contaminant loading occurs and extension of the cleaning cycle is desired. Cell collector plates may be coated with special oils, adhesives, or detergents to improve both particle retention and particle removal during cleaning. High-efficiency dry extended-media area filters are also used as afterfilters in special designs. The electronic air cleaner used in this system improves the service life of the dry filter and collects small particles such as smoke.

A **negative ionizer** uses the principle of particle charging, but does not use a collecting section. Particles enter the ionizer of the unit, receive an electrical charge, and then migrate to a grounded surface closest to the travel path.

Space Charge. Particulates that pass through an ionizer and are charged, but not removed, carry the electrical charge into the space. If continued on a large scale, a space charge builds up, which tends to drive these charged particles to walls and interior surfaces. Thus, a low-efficiency electronic air cleaner used in areas of high ambient dirt concentrations (or a malfunctioning unit), can blacken walls faster than if no cleaning device were used (SMACNA 2010).

Ozone. All high-voltage devices can produce ozone, which is toxic and damaging not only to human lungs, but to paper, rubber, and other materials. When properly designed and maintained, an electronic air cleaner produces an ozone concentration that only reaches a fraction of the limit acceptable for continuous human exposure and is less than that prevalent in many American cities (EPA 1996). Continuous arcing and brush discharge in an electronic air cleaner may yield an ozone level that is annoying or mildly toxic; this is indicated by a strong ozone odor. Although the nose is sensitive to ozone, only actual measurement of the concentration can determine whether a hazardous condition exists.

Outdoor air can also be a source of indoor ozone. Weschler et al. (1989) found that ozone levels indoors closely tracked outdoor levels, despite ozone's reactions with HVAC interior surfaces. Indoor concentrations were typically 20 to 80% of outdoor concentrations depending on the ventilation rate. The U.S. Environmental Protection Agency (EPA) limits the maximum allowable exposure to ozone in outdoor air to 0.070 ppm averaged over 8 h (EPA 2015). ASHRAE *Standard* 62.1 requires ozone removal systems in buildings where the intake air concentration exceeds the EPA limit.

10. SELECTION AND MAINTENANCE

To evaluate filters and air cleaners properly for a particular application, consider the following factors:

- Types of contaminants present indoors and outdoors
- Sizes and concentrations of contaminants
- Air cleanliness levels required in the space
- Air filter efficiency needed to achieve cleanliness
- Space available to install and access equipment
- Life-cycle costing, including
  - Operating resistance to airflow (static pressure differential)
  - Disposal or cleaning requirements of spent filters
  - Initial cost of selected system
  - Cost of replacement filters or cleaning
  - Cost of warehousing filter stock and change-out labor

Savings (from reduced housekeeping expenses, protection of valuable property and equipment, dust-free environments for manufacturing processes, improved working conditions, and even health benefits) should be credited against the cost of installing and operating an adequate system. The capacity and physical size of the required unit may emphasize the need for low maintenance cost. Operating cost, predicted life, and efficiency are as important as initial cost because air cleaning is a continuing process.

Panel filters do not have efficiencies as high as can be expected from extended-surface filters, but their initial cost and upkeep are generally low. Compared to moving-curtain filters, panel filters of comparable efficiencies require more attention to maintain the resistance within reasonable limits. However, single-stage, face- or side-access, low- to medium-efficiency filters of MERV 6 to 10 from a 50 mm pleat to a 300 mm deep cube, bag, or deep pleated cartridge, require less space with lower initial cost, and have better efficiency. The bag and cartridges generally have a similar service life to that of a roll filter.

If efficiency of MERV 11 or higher is required, extended-surface filters or electronic air cleaners should be considered. The use of very fine glass fiber mats or other materials in extended-surface filters has made these available at the highest efficiency.

Initial cost of an extended-surface filter is lower than for an electronic unit, but higher than for a panel type. Operating and maintenance costs of some extended-surface filters may be higher than for panel types and electronic air cleaners, but efficiencies are always higher than for panel types; the cost/benefit ratio must be considered. Pressure drop of media-type filters is greater than that of electronic types, and slowly increases during their useful life. Advantages include the fact that no mechanical or electrical services are required. Choice should be based on both initial and operating costs (life-cycle costs), as well as on the degree of cleaning efficiency and maintenance requirements.

Although electronic air cleaners have higher initial and maintenance costs, they have high initial efficiencies in cleaning atmospheric air, largely because of their ability to remove fine particulate contaminants. System resistance remains unchanged as particles are collected, and efficiency is reduced until the resulting residue is removed from the collection plates to prepare the equipment for further duty. The manufacturer must supply information

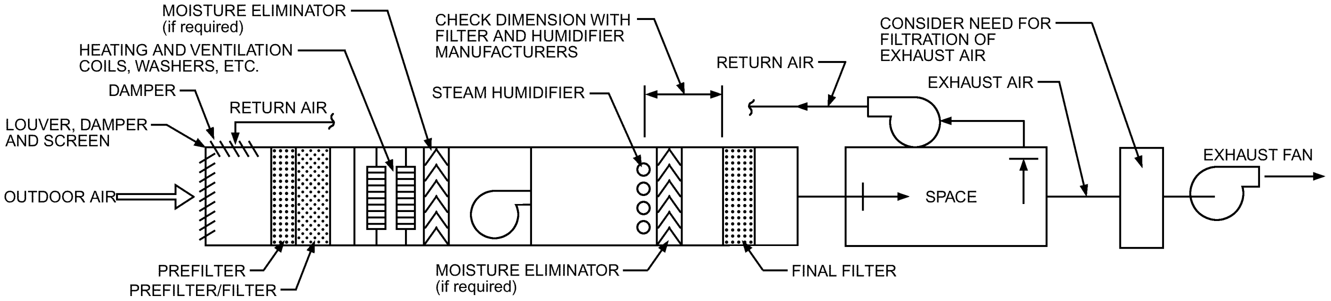

Fig. 4 Typical Filter Locations for HVAC System

Table 3 Cross-Reference and Application Guidelines

Standard 52.2 MERV	Arrestance Value	Example Range of Contaminants Controlled	Example Applications	Sample Air Cleaner Type(s)
E-1 Range				
MERV 16 MERV 15 MERV 14 MERV 13	N/A N/A N/A N/A	0.3 to 1.0 μm size range: bacteria, smoke (ETS), paint pigments, face powder, some virus, droplet nuclei, insecticide dusts, soldering fumes	Day surgery, general surgery, hospital general ventilation, turbo equipment, compressors, welding/soldering air cleaners, prefilters to HEPAs, LEED for existing (EB) and new (NC) commercial buildings, smoking lounges	Box-style wet-laid or lofted fiberglass, box-style synthetic media, minipleated synthetic or fiberglass paper, depths from 50 to 300 mm. Pocket filters of fiberglass or synthetic media 300 to 900 mm.
E-2 Range				
MERV 12 MERV 11 MERV 10 MERV 9	N/A N/A N/A N/A	1.0 to 3.0 μm size range: milled flour, lead dust, combustion soot, *Legionella*, coal dust, some bacteria, process grinding dust	Food processing facilities, air separation plants, commercial buildings, better residential, industrial air cleaning, prefiltration to higher-efficiency filters, schools, gymnasiums	Box-style wet-laid or lofted fiberglass, box-style synthetic media, minipleated synthetic or fiberglass paper, depths from 50 to 300 mm. Pocket filters either rigid or flexible in synthetic or fiberglass, depths from 300 to 900 mm.
E-3 Range				
MERV 8 MERV 7 MERV 6 MERV 5	N/A N/A N/A N/A	3.0 to 10 μm size range: pollens, earth-origin dust, mold spores, cement dust, powdered milk, snuff, hair spray mist	General HVAC filtration, industrial equipment filtration, commercial property, schools, prefilter to high-efficiency filters, paint booth intakes, electrical/phone equipment protection	Wide range of pleated media, ring panels, cubes, pockets in synthetic or fiberglass, disposable panels, depths from 25 to 600 mm.
MERV 4 MERV 3 MERV 2 MERV 1	>70% >70% >65% <65%	Arrestance method	Protection from blowing large particle dirt and debris, industrial environment ventilation air	Inertial separators

Note: MERV for non-HEPA/ULPA filters also includes test airflow rate, but it is not shown here because it is of no significance for the purposes of this table.
N/A = not applicable.

on maintenance or cleaning. Also, note that electronic air cleaners may not collect particles greater than 10 μm in diameter.

Figure 4 shows where filtration can be placed in an HVAC system. Each area indicates the point of potential need for particulate removal.

The typical contaminants listed in Table 3 appear in the general reporting group that removes the smallest known size of that specific contaminant. The order in which they are listed has no significance, and the list is not complete. The typical applications and typical air cleaners listed are intended to show where and what type of air cleaner could be and/or has been traditionally used. Traditional usage may not represent the optimum choice, so using the table as a selection guide is not appropriate when a specific performance requirement is needed. An air cleaner application specialist should then be consulted and manufacturers' performance curves should be reviewed.

Note that MERV 17 to 20, which were shown in early versions of ASHRAE *Standard* 52.2, were retracted because ASHRAE testing procedures do not cover these filter levels. Refer to the IEST (2007, 2009) or ISO (2013) classification system for these products.

Common sense and some knowledge of how air cleaners work help the user achieve satisfactory results. Air cleaner performance varies from the time it is first installed until the end of its service life. Generally, the longer a media-type filter is in service, the higher the efficiency. The accumulation of contaminants begins to close the porous openings, and, therefore, the filter is able to intercept smaller particles. However, there are exceptions that vary with different styles of media-type filters. Electronic air cleaners and charged-fiber media filters start at high efficiency when new (or after proper service, in the case of electronic air cleaners), but their efficiency decreases as contaminants accumulate. Some air cleaners, particularly low-efficiency devices, may begin to shed some collected contaminants after being in service. Testing with standardized synthetic loading dust attempts to predict this, but such testing rarely, if ever, duplicates the air cleaner's performance on atmospheric dust.

Residential Air Cleaners

Panel air filters with a MERV of 1 to 4 used for residential applications may be of spun glass and only filter out the largest of particles. These filters may prevent damage to downstream equipment, but they do little to improve air quality in the residence. Offermann et al. (1992) described a series of tests used to rate residential air cleaners. The tests were run in a test house with environmental tobacco smoke (ETS) as the test particulate (mass mean diameter = 0.5 μm). The typical residential air filter is not effective on these very small respirable-sized particles. To remove particles effectively in the 0.5 μm range, use 50 mm pleated filters or extended-surface filters with a 100 to 150 mm pleat depth. Extended-surface pleated filters often have a higher dust-holding capacity and lower static pressure than equivalent-efficiency 50 mm filters.

In addition to particle removal efficiency, system runtime has a large impact on the effectiveness of air cleaners used in central residential forced-air heating and cooling systems. These systems typically operate only in response to demands for heating or cooling. ASHRAE research project 1691 (Azimi et al. 2016) used building energy modeling combined with an indoor air mass balance model to predict the impacts of various MERV filters on reducing indoor concentrations of $PM_{2.5}$ and ultrafine particles (UFPs) of outdoor origin. The researchers estimate that low system runtimes mean that even the highest levels of filtration efficiency cannot achieve more than ~50% particle removal in the space, and that effectiveness depends strongly on home vintage, climate zone, and ventilation strategy. Touchie and Siegel (2018) analyzed central residential system runtime data from over 7000 homes in North America and found that the median system runtime was only 18%, with considerable variation between homes. Moreover, at low to average runtimes, filter efficiency matters much less for effectiveness because the system does not run enough for a sufficient air volume to pass through the filter and have a substantial impact on particle concentrations. Increasing runtimes (e.g., by operating systems in fan-only mode continuously or for great cycle lengths) can improve filtration effectiveness but comes with an additional energy cost.

VAV Systems

ASHRAE *Standard* 52.1 tests on numerous different media-type air cleaners under both constant and variable airflow showed no significant performance differences under different flow conditions, and the air cleaners were not damaged by VAV flow. Low-efficiency air cleaners did show substantial reentrainment for both constant and VAV flow (Rivers and Murphy 2000).

Antimicrobial Treatment of Filter Media

Several varieties and all efficiencies of filters have been treated with antimicrobial additives. The key performance goal is to reduce the growth of microbial organisms in filter components (e.g., the media itself, separators in high-efficiency minipleats, framing components). The intent is not to make the air clean and free of viable microbes, but rather to prevent filter components from becoming the microbial reservoir.

An ASHRAE-funded research project tested low-efficiency filters for microbial reduction at both initial and loaded efficiencies (Foarde et al. 2000). Under normal use, fibrous air cleaners were found to be unlikely to become a source of microbial contamination to the space, and antimicrobial treatment usually did not increase the filtration efficiency for bioaerosols. In the United States, EPA guidelines must be met for the antimicrobial product to be used in air filters.

11. AIR CLEANER INSTALLATION

Many air cleaners are available in units of convenient size for manual installation, cleaning, and replacement. A typical unit filter may be a 510 to 610 mm square or rectangle, from 25 to 1000 mm in depth, and of either the dry or viscous impingement type. In large systems, the frames in which these units are installed are bolted or riveted together to form a filter bank. Automatic filters are constructed in sections offering several choices of width up to 20 m and generally range in height from 1 to 5 m, in 100 to 150 mm increments. Several sections may be bolted together to form a filter bank.

Several manufacturers provide side-loading access filter sections for various types of filters. Filters are changed from outside the duct, making service areas in the duct unnecessary, thus saving cost and space.

Of course, in-service efficiency of an air filter is sharply reduced if air leaks through the bypass dampers or poorly designed filter-holding frames. The higher the filter efficiency, the more careful attention must be paid to the rigidity and sealing effectiveness of the frame. In addition, high-efficiency filters must be handled and installed with care. The National Air Filtration Association (NAFA 2006) suggests some precautions needed for HEPA filters.

Air cleaners may be installed in the outdoor-air intake ducts of buildings and residences and in the recirculation and bypass air ducts; however, the prefilters (in a two- or three-stage system) should be placed upstream of heating or cooling coils and other air-conditioning equipment in the system to protect that equipment from dust. Dust captured in an outdoor-air intake duct is likely to be mostly greasy particles, whereas lint may predominate in dust from within the building.

Where high-efficiency filters protect critical areas such as cleanrooms, it is important that filters be installed as close to the room as possible to prevent pickup of particles between the filters and the outlet. The ultimate installation is the unidirectional flow room, in which the entire ceiling or one entire wall becomes the final filter bank.

Published performance data for all air filters are based on straight-through unrestricted airflow. Filters should be installed so that the face area is at right angles to the airflow whenever possible. Eddy currents and dead air spaces should be avoided; air should be distributed uniformly over the entire filter surface using baffles, diffusers, or air blenders, if necessary. Filters are sometimes damaged if higher-than-normal air velocities impinge directly on the face of the filter.

Failure of air filter installations to give satisfactory results can, in most cases, be traced to faulty installation, improper maintenance, or both. The most important requirements of a satisfactory and efficiently operating air filter installation are as follows:

- The filter must be of ample capacity for the amount of air and dust load it is expected to handle. An overload of 10 to 15% is regarded as the maximum allowable. When air volume is subject to future increase, a larger filter bank should be installed initially.
- The filter must be suited to the operating conditions, such as degree of air cleanliness required, amount of dust in the entering air, type of duty, allowable pressure drop, operating temperature, and maintenance facilities.

The following recommendations apply to filters installed with central fan systems:

- Duct connections to and from the filter should change size or shape gradually to ensure even air distribution over the entire filter area.
- Locate the filter far enough from the fan to prevent or reduce reentrainment of particles, especially during start/stop cycles.
- Provide sufficient space in front of (upstream) or behind (downstream of) the filter, or both, depending on its type, to make it accessible for inspection and service. A distance of 500 to 1000 mm is required, depending on the filter chosen.
- Provide conveniently sized access doors to the filter service areas.
- All doors on the clean-air side should be gasketed to prevent infiltration of unclean air. All connections and seams of the sheet-metal ducts on the clean-air side should be airtight. The filter bank must be caulked to prevent bypass of unfiltered air, especially when high-efficiency filters are used.
- Install lights in the plenum in front of and behind the air filter bank.
- Filters installed close to an outdoor air inlet should be protected from the weather by suitable louvers or an inlet hood.

- In areas with extreme rainfall or where water can drip over or bounce (travel) up in front of the inlet, use drainable track moisture separator sections upstream of the first filter bank. Place a large-mesh wire bird screen in front of the louvers or in the hood.
- Filters, other than electronic air cleaners, should have permanent indicators (airflow resistance gage) to give notice when the filter reaches its final pressure drop or is exhausted, as with automatic roll media filters.
- Electronic air cleaners should have an indicator or alarm to indicate when high voltage is off or shorted out.

12. SAFETY CONSIDERATIONS

Safety ordinances should be investigated when the installation of an air cleaner is contemplated (UL, AFI, NIST). Combustible filtering media may not be allowed by some local regulations. Combustion of dust and lint on filtering media is possible, although the media itself may not burn. This may cause a substantial increase in filter combustibility. Smoke detectors and fire sprinkler systems should be considered for filter bank locations. In some cases, depending on the contaminant, hazardous material procedures must be followed during removal and disposal of the used filter. Bag-in/bag-out (BI/BO) filter housings should be seriously considered in those cases.

Many air filters are efficient collectors of bioaerosols. When provided moisture and nutrients, the microorganisms can multiply and may become a health hazard for maintenance personnel and building occupants. Moisture in filters can be minimized by preventing (1) entrance of rain, snow, and fog; (2) carryover of water droplets from coils, drain pans, and humidifiers; and (3) prolonged exposure to elevated humidity. Changing or cleaning filters regularly is important for controlling microbial growth. Good health-safety practices for personnel handling dirty filters include using face masks and safety glasses, thorough washing upon completion of the work, and placing used filters in plastic bags or other containers for safe disposal.

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