chapter twelve

Air cleaning

Air cleaning is commonly used in industrial operations to reduce emissions of particulate dusts as well as gaseous and vapor-phase contaminants to the ambient atmosphere. It is also used as a contaminant control measure in indoor environments. Air cleaning is used both generically and to control specific contaminant problems. It is often used by individuals in an attempt to reduce exposure to allergens and other suspected indoor air contaminants. It is rarely used as a mitigation measure to resolve problem building complaints.

In most applications, air cleaning is a process in which airborne contaminants are removed from a moving airstream by some type of physical, chemical, or physical–chemical process. Less commonly, air cleaning is attempted by introducing charged ions into indoor spaces, or using oxidizing substances such as ozone (O_3) or passive systems such as plants.

Though air cleaning systems may be used generically to improve overall cleanliness in indoor spaces and protect mechanical equipment in (1) heating, cooling, and ventilation (HVAC) systems in mechanically ventilated buildings and (2) residential heating and cooling systems, air cleaners cannot, as many lay individuals believe, be universally applied for the control of all airborne contaminants. Most air cleaners have been designed to collect airborne particles, and thus cannot control gas/vapor-phase contaminants. However, air cleaners can be designed to control specific gas/vapor-phase substances or classes of substances, or a combination of particle and gas/vapor-phase contaminants.

I. Airborne particles and dusts

Most indoor spaces are sufficiently contaminated by airborne particles to warrant at least a minimum level of air cleaning. Particles may be generated indoors from a variety of activities and sources or enter indoor spaces from the ambient atmosphere through HVAC systems or natural ventilation processes. Particles may include fabric lint and paper dust, tobacco smoke, organic dusts (see Chapter 5), mineral particles, pollen and mold spores, industrially and photochemically derived particles, etc.

Airborne particles can be removed from indoor and outdoor air used for ventilation by application of relatively simple physical principles adapted from industrial gas cleaning. Air flows through air cleaning devices used for indoor environments are orders of magnitude less than those used for stack gases and large industrial local exhaust ventilation systems. Particle/dust loading rates are significantly lower as well. Airborne dust concentrations in indoor air rarely exceed 200 μg/m^3 and are usually <50 μg/m^3. Airborne particles are typically collected and removed from ventilation air by fibrous media filters; less commonly by electrostatic precipitation.

A. Filtration

A wide variety of filter types and filtration systems are used to remove airborne particles from supply air systems and indoor spaces. Filter panels are inserted into air-handling units (AHUs) upstream of blower fans in HVAC systems and domestic heating and cooling systems. These panels contain a medium which varies from a simple metal grid to the more commonly used fibrous mats which are oriented perpendicular to the direction of air flow. Filter materials may include glass, cellulose, or polymeric fibers, which vary from <1 to 100 μm in diameter. Filter mats vary in density and depth, with porosities in the range of 70 to 99%. Because of differences in fiber diameters and mat densities, filters vary in their ability to capture airborne particles.

1. Collection processes

Large particles (such as lint) may be collected on filters by sieve action. Most smaller particles are collected as a result of a number of particle deposition processes. These include interception, impaction, diffusion, and electrostatic attraction. Deposition of particles on filter fibers by interception, impaction, and diffusion processes can be seen in Figure 12.1.

Interception occurs when particles follow a streamline within one radius of a filter fiber (Figure 12.1a). As a particle collides with the perimeter of a fiber, it loses velocity and is captured. Interception is important in collecting particles with diameters >0.1 μm, and is a particularly important collection mechanism in the range of minimum collection efficiency. Collection efficiency increases with increasing filter density and is independent of particle velocity.

Impaction occurs when particles of sufficient size and mass cannot flow along fluid streamlines around filter fibers. Due to their inertial mass, large particles collide with filter fibers and are collected (Figure 12.1b). Collection efficiency increases with increasing particle size, particle velocity, and Stokes number (ratio of particle stopping distance to fiber diameter). Impaction is

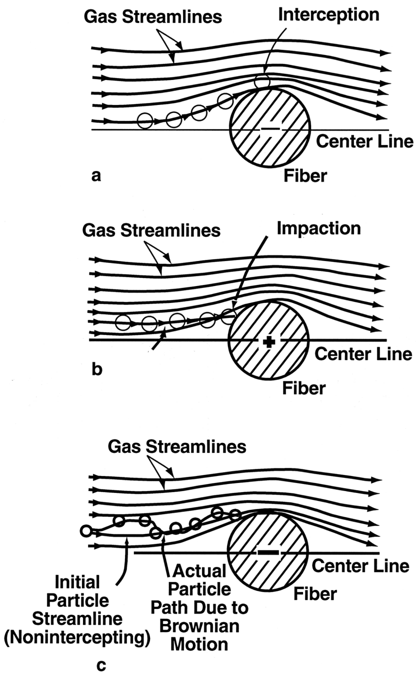


Figure 12.1 Particle deposition processes on filter fibers. (From Hinds, W.C., *Aerosol Technology — Properties, Behavior, and Measurement of Airborne Particles*, John Wiley & Sons, New York, 1982. With permission.)

an important particle collection mechanism for particles with aerodynamic diameters >1 µm.

Particles that are <1 µm in diameter behave like gases; i.e., they follow fluid streamlines and are subject to Brownian motion (random motion of molecules). As a consequence, they can diffuse to surfaces. Brownian motion/diffusion increases the probability that small particles (<1 µm) will move into an intercepting streamline and be deposited on a filter fiber (Figure 12.1c). Diffusion is the only collection mechanism for particles with diameters < 0.1 µm (Figure 12.2). Collection efficiency increases with decreasing particle size.

Particles can be collected on ordinary filter fibers by electrostatic processes in which particles which naturally carry a charge are attracted to fibers that carry an opposite charge. The relative role of electrostatic deposition (as compared to other deposition processes) in filtration has not been well-defined.

2. *Filter performance*

The efficiency or performance of a filter is determined by parameters involving particles, filters, and air flow. These include particle diameter, fiber diameter, filter packing density, filter depth, and air flow rate.

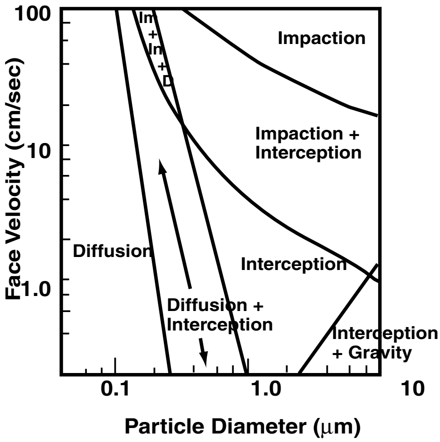


Figure 12.2 Relationship between particle size and deposition processes. (From Hinds, W.C., *Aerosol Technology — Properties, Behavior, and Measurement of Airborne Particles,* John Wiley & Sons, New York, 1982. With permission.)

As can be seen in Equation 12.1, the ability of a particle to penetrate a filter decreases exponentially with increasing filter thickness.

$$P = e^{-rt} \tag{12.1}$$

where P = penetration, %
e = natural log base
r = fractional capture per unit thickness
t = filter thickness, mm

The value of r depends on particle diameter, packing density, fiber density, and face velocity of the airstream.

Not surprisingly, easy-to-collect particles are collected on or near the surface of a filter. As particles move through it, particle size distribution changes (based on aerodynamic diameters). Each filter type is characterized by a particle size, usually between 0.05 and 0.5 μm, at which fractional collection efficiencies are minimal. This generalized relationship can be seen in Figure 12.3 for particles moving through a filter at 1 and 10 cm/sec. As face velocity increases, a minimum value for collection efficiency is reached. Collection due to diffusion at this point is at a minimum. These minimum collection efficiencies are used to specify the performance of high-efficiency filters. High-efficiency particulate absolute (HEPA) filters are reported to be 99.97% efficient at 0.3 μm. This means that they have a minimum 99.97% collection efficiency for the most difficult-to-collect particle size.

Collection efficiency is also a function of fiber diameter (Figure 12.4). The highest minimum collection efficiency and overall collection efficiency occur at the smallest fiber diameter tested (0.5 μm).

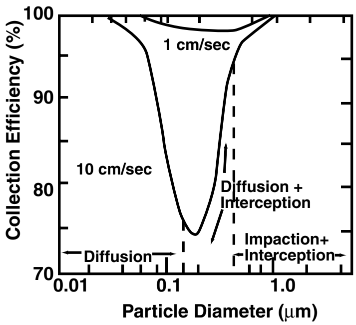


Figure 12.3 Relationship between particle size and collection efficiency. (From Hinds, W.C., *Aerosol Technology — Properties, Behavior, and Measurement of Airborne Particles*, John Wiley & Sons, New York, 1982. With permission.)

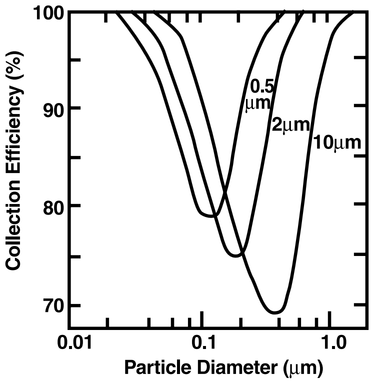


Figure 12.4 Relationship between filter fiber diameter and collection efficiency. (From Hinds, W.C., *Aerosol Technology — Properties, Behavior, and Measurement of Airborne Particles*, John Wiley & Sons, New York, 1982. With permission.)

As indicated in Equation 12.1, particle penetration decreases with increasing filter thickness. Collection efficiency increases as well. However, as filter thickness increases, resistance to air flow also increases, with a corresponding pressure drop and decreased air flow through the filter. Pressure drop is directly proportional to filter thickness and inversely related to fiber diameter. A significant pressure drop is undesirable because it reduces the air flow rate and volume of air treated.

3. *Filter applications and types*

Filters are used in a variety of air cleaning applications. Dust-stop filters used in HVAC systems and residential heating and cooling units are the major application. Higher-efficiency in-duct filters may be used to improve the physical cleanliness of indoor surfaces and reduce airborne allergen levels in residences. Free-standing modular air cleaners employing fibrous

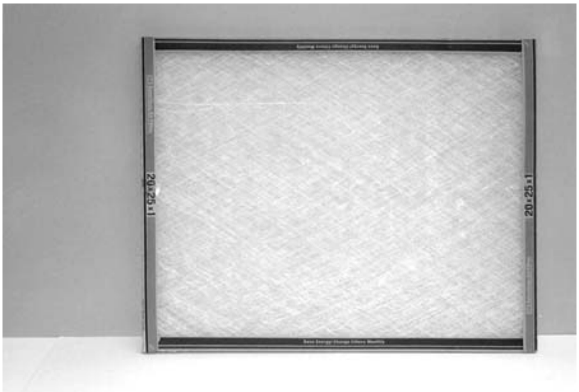


Figure 12.5 Dry panel-type filter.

filters are designed and widely used to clean air in small spaces such as rooms in residences. Filtration systems which require high performance characteristics (HEPA) are used in clean rooms in the manufacture of pharmaceuticals and semiconductors, in nuclear power plants and other nuclear facilities, and in hospital operating rooms. They are also used in portable home air cleaning devices.

Commercially available filters include wire mesh units used in older HVAC systems and cooking range hoods, and the more commonly used fibrous media filters. In the latter case, filters are described as dry, viscous-media, or charged-media filters (see electronic air filters). They may be single-use or renewable panels.

a. Dry-type panel filters. Dry-type panel filters (Figure 12.5) have high porosities and low dust spot efficiencies. As a consequence, their use is limited to dust-stop filters in HVAC systems and home heating and cooling units. They collect large particles such as lint by sieve action, impaction, and interception. They are typically used in systems with air velocities in the range of 200 to 700 ft/min (fpm) (60.9 to 213.3 m/min [mpm]). Newly exposed filters have low associated pressure drops (0.05 to 0.25″ H_2O, 12.4 to 62 pascals). Typically, they are allowed to reach pressure drops of 0.50 to 0.75″ H_2O (124 to 186 pascals) before being replaced. Collection efficiency increases significantly as filters become soiled. Replacement is required because of the associated increased resistance to air flow. Filter media used in dry-type panels include fiberglass, open cell foams, nonwoven textile cloths, and cellulose fibers.

b. Extended-surface dry-type filters. Extended-surface media filters have been developed to overcome the air resistance/pressure drop problems associated with use of thick, high-density, high-efficiency filtration media. Filter surface area is extended by pleating the filter medium; this significantly increases the surface area available for particle collection (relative to the flat

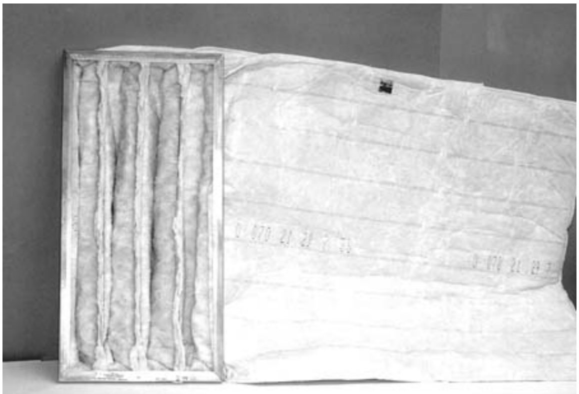


Figure 12.6 Bag-type filter.

face area of the filter). Pleat depth may be several inches to upwards of 12 to 18″ (30.4 to 45.7 cm) or more. As the medium surface area is increased, pressure drop decreases to acceptable levels (despite the increase in medium density and/or thickness).

Extended-media filters vary in thickness, density, fiber size, media composition, pleats per nominal face area, and depth. As such, their performance varies from medium to high efficiency. Cellulose, glass fiber, wool felt, or a variety of synthetic fibers are used in extended-media filters. Fibers are typically oriented randomly to form a mat.

Extended-media filters are available in several designs. They may be constructed in the form of bags which are similar in concept, and somewhat similar in design, to bags used in industrial applications. A bag-type extended-media filter used in HVAC systems is pictured in Figure 12.6.

In typical pleated filters, the medium is held in place by a panel frame or box (Figure 12.7). The V-shaped pleats may have a depth of 2 to 36″ (5.1

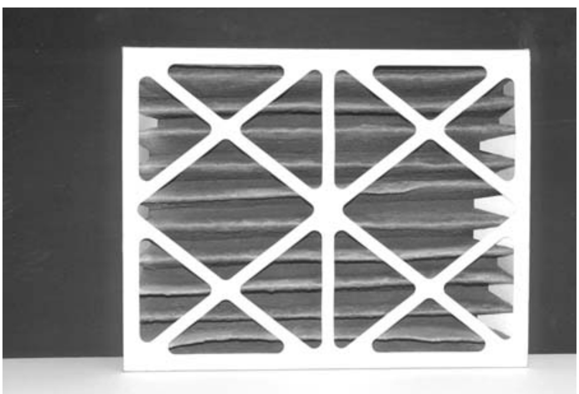


Figure 12.7 Medium efficiency pleated-panel filter.

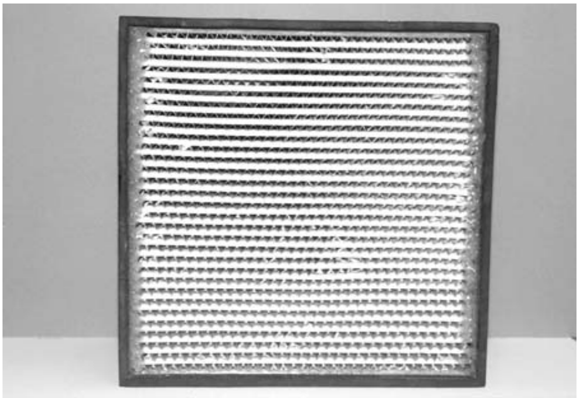


Figure 12.8 HEPA filter.

to 91.4 cm) or more, depending on the application. Increasing pleat number and filter depth are used to increase filtration efficiency, air volumes that can be cleaned, or both. The filter medium may be rigid enough to be self-supporting. In many high-efficiency filtration appliances, the filter medium is held in place by a combination of rigid corrugated metal spacers and a thick adhesive application between the filter medium and its surrounding panel, case, or box.

As indicated, extended-media filters provide higher performance than dry-panel filters. They are classified as medium, high, and very high efficiency. Medium-efficiency filters have dust spot efficiencies (described later) in the range of 40 to 60%. They consist of 5 to 10 µm diameter fibers that are in 1/4 to 1/2″ (6 to 12 mm)-thick mats. High-efficiency filters have dust spot efficiencies in the range of 80 to 90% or more, with fiber diameters in the range of 1 to 4 µm.

Very high particle cleaning efficiencies are achieved by HEPA filters (collection efficiencies of 99.97% or greater at a 0.3 µm DOP test [see DOP smoke penetration tests]). A HEPA filter is illustrated in Figure 12.8. Their small fiber diameters and high packing densities favor the collection of very small particles (circa 0.01 µm) by Brownian motion. Electrostatic forces cause small particle agglomeration and adherence to media fibers. In some applications, filter surfaces are coated to discharge static build-up so that they may be cleaned by a pneumatically operated pulse cleaning system and reused.

c. Viscous-media panel filters. Filter fibers are often coated with viscous, low-volatility oils to enhance particle collection and retention. Viscous-medium panel filters have high porosities and low resistance to air flow. They also have very low collection efficiencies for particles commonly found in indoor air, but are very efficient in collecting fabric dusts and very large particles (>10 µm). Typical operating velocities through such filters are in the range of 300 to 600 fpm (91.4 to 182.8 mpm).

d. Renewable-media filters. Renewable-media filters were developed to provide a filter surface that is slowly being moved to accommodate particle collection and HVAC system operating needs. They consist of a slowly moving curtain/filter unit which advances in response to pressure drop or a timer. As the medium becomes excessively soiled, it moves to a takeup roll on the bottom of the filter system. When the roll has been completely soiled, it must be removed and replaced. Need for replacement is usually signaled by an alarm. Such filters have high arrestance (described later) efficiencies (60 to 90%) and low dust spot efficiencies (20 to 30%). They are available as both dry and viscous types. In viscous-media renewable filter systems, the filter may pass through a reservoir of a viscous medium where it sheds its dust load and is recoated.

4. Air flow resistance

Because of their nature, all air cleaning systems using the principle of filtration must be designed and operated with due consideration to the effects of the filter on air flow. Filters with high packing densities have both increased collection efficiencies and resistance to air flow. As a filter becomes soiled, its resistance to air flow increases; as resistance increases, air flow decreases.

As indicated previously, extended-media filters are designed to provide high collection efficiencies at acceptable air resistances described as pressure drop (ΔP). Pressure drops associated with high-efficiency filters and filter soiling must be considered in the design and operation of cleaner units and HVAC systems. Of major importance is the selection and use of system blowers that will develop sufficient static pressure to overcome resistance to air flow and maintain desired volumetric air flows. As a consequence, blower fans must be adequately sized in terms of volumetric flow rate and horsepower rating.

For illustrative purposes, let us use two different fans for a small freestanding residential air cleaner (Table 12.1). Though both fans have the capacity to move 125 CFM of air at zero static pressure (no air resistance), they differ in horsepower. Fan #1 has a higher horsepower rating than fan #2. As resistance to air flow increases to 0.5″ H_2O, air flows associated with both fans decrease. At 0.5″ H_2O ΔP, fan #2 can pull virtually no air. Fan

Table 12.1 Air Flow Rates Under Different Static Pressures for Two Fans

Static pressure (″ H_2O)	Air flow rate (CFM) Fan #1	Air flow rate (CFM) Fan #2
0	125	125
0.1	120	115
0.2	115	105
0.3	110	98
0.4	105	85
0.5	100	—

horsepower required to draw air through a filter at a constant or near-constant rate increases with increased resistance to air flow. Fans with higher horsepower ratings are more expensive to purchase and operate. However, an adequately sized fan is essential for proper system performance.

If resistance becomes excessive, performance will decline significantly even when a properly sized fan is used. This occurs if filters are not replaced when they reach their design resistance values. Maximum acceptable resistance values for products are provided by manufacturers, who also provide resistance values for clean filters at their rated air flow.

In many HVAC system applications, a differential pressure gauge monitors pressure differences (ΔP) upstream and downstream of the filter. The pressure drop increases as the filter becomes soiled. In some systems, an alarm sounds when the pressure drop exceeds a predetermined value. The alarm signals maintenance personnel that filters need to be changed to maintain desired system air flows. In other cases, maintenance personnel periodically check pressure gauges to determine filter change requirements.

Sensors or pressure drop indicators are not present in most residential and many HVAC applications. Because of the variability of dust loading on filters, particularly in HVAC systems, it is difficult to know exactly when filters need to be replaced. In such cases, filter replacement is a matter of judgment by service personnel and homeowners. Filters are often replaced on a routine schedule irrespective of their condition. Since excessively soiled filters cause decreased air flows and increased operating costs in HVAC and home heating and cooling systems, it is important that operators implement an appropriate service plan.

B. Electrostatic air cleaners

Electrostatic air cleaners remove airborne particles by electrostatic forces. Three basic designs are used: ionizing plates, and the charged-media ionizing and nonionizing types.

1. Ionizing-plate cleaners

Ionizing-plate electrostatic air cleaners are widely used to collect airborne particles in HVAC systems and residential applications. Their operation is based on the principle that airborne particles can be given a positive or negative charge and then collected on metal plates with the opposite charge. In industrial applications, particles are negatively charged; in indoor applications, they are positively charged.

Both single- and two-stage electronic cleaners are available for use in indoor applications. A two-stage cleaner is illustrated in Figure 12.9. In the first stage, a high electric potential (12,000 volts) is applied to thin, vertical, tungsten wires. Electrons are accelerated toward the positively charged ionizing wires. The accelerated electrons strike air molecules, stripping them of

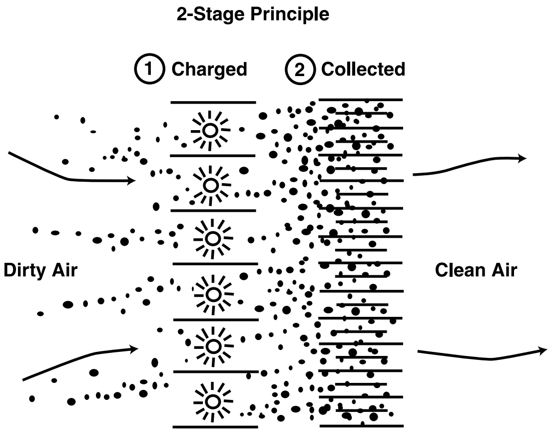


Figure 12.9 Two-stage electronic air cleaner particle collection.

electrons and creating positive ions and additional electrons. The process produces a corona discharge near ionizing wires.

Positive ions become attached to airborne particles by deposition processes. As a consequence, these particles become positively charged. The magnitude of the charge on individual particles depends on the number of charges deposited. Particles with high surface areas gain more charge and therefore have a higher probability of being collected.

Charged particles flow with the airstream into a collector section (second stage) consisting of a series of vertically placed, parallel, thin, metal plates. Alternate plates may be positively and negatively charged by a high DC voltage (6000 V). Positively charged particles are attracted to a negatively charged plate. The magnitude of the electrostatic force acting on a particle depends on its charge, the distance between plates, and the voltage applied.

Particles deposited on collection plates lose their original charge and take on the charge of the collecting surface, where they remain attached to the plate and other collected particles by molecular adhesion and cohesion. As particle buildup occurs, electrostatic forces diminish in magnitude. Collection efficiency decreases as a consequence. Collection plates must be cleaned of their accumulated dust load periodically to restore their initial collection efficiency. Hot water is typically used to clean collection plates; in some systems washing is done automatically.

Electronic air cleaner collection efficiencies depend on particle migration velocity, collection surface area, travel path length (distance through a collection field), and air flow rate. Migration velocity is directly proportional to a particle's charge and the strength of the electric field. In electronic air cleaners used for indoor applications, the travel path length is relatively short, typically 6 to 12″ (15.2 to 30.5 cm). In industrial applications, travel path length may be 20 to 25′ (6.1 to 7.6 m) or longer, with collection efficien-

Table 12.2 Relationship Between Flow Rate and Electronic Air Cleaner Dust Spot Efficiency

Flow rate (CFM)	Dust spot efficiency (%)
400	93
550	90
750	85

cies of approximately 99%. In indoor applications, collection efficiencies are rarely >95%, and are usually less.

As seen in Table 12.2, collection efficiencies are significantly affected by volumetric air flow rates. As air velocity increases, particles have less time to be drawn to and deposited on collection plates. As a consequence, collection efficiency is reduced. Because of the sensitivity of electronic air cleaners to changes in velocity, it is common to use prefilters, perforated plates, etc., to induce some resistance and provide uniform velocity air flow through the collection system.

In single-stage electronic air cleaners, ionizing wires are placed between collection plates. Because of reduced travel path lengths, single-stage cleaners are less efficient than two-stage units. They have the advantage of requiring less space in AHUs.

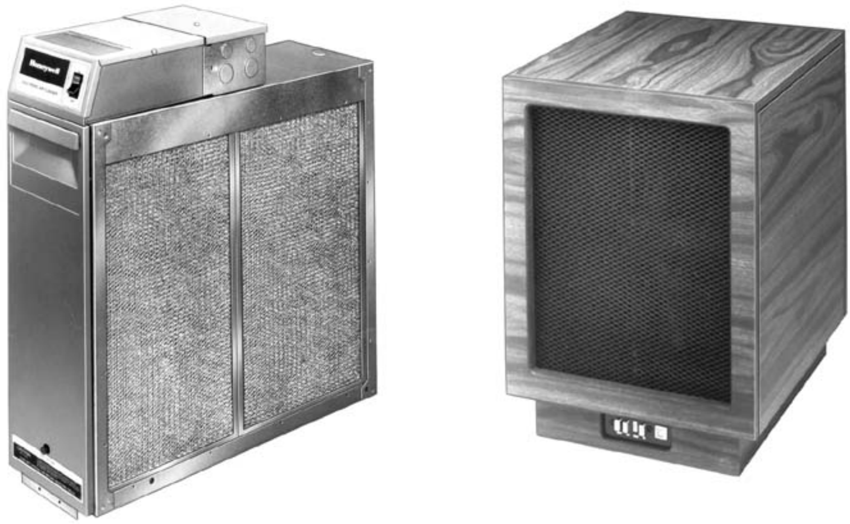
Electronic air cleaners are available as modular, free-standing units; modular units that can be suspended from a ceiling or mounted on a wall; in-duct units installed in residential heating and cooling systems; or units of various sizes placed in AHUs of mechanically ventilated buildings. A residential in-duct and a portable free-standing electronic air cleaner are pictured in Figure 12.10.

Resistance to air flow in electronic air cleaners is very low; as a consequence, volumetric air flows are constant. Because of low air flow resistance, energy requirements for fan systems are also low. Maintenance is usually limited to cleaning collector plates. It is both desirable and common to use dust stop filters as prefilters to maintain high collection efficiencies for small particles and reduce the need for cleaning.

Electronic air cleaners have one major disadvantage. Because of the high voltages used, they produce ozone (O_3). Ozone production varies among products and product vendors. It is common to smell the sweet odor of O_3 in residences where electronic cleaners are in continuous operation (portable and in-duct units). The presence of O_3 in buildings is of concern because of its known health effects, its ability to oxidize fabric dyes and crack rubber and soft plastics, and its ability to initiate indoor chemical reactions.

2. *Charged-media ionizing cleaners*

In this type of air cleaner, dust in an airstream is charged by passing it through a corona discharge ionizer and then collected on a charged-media filter.



a b

Figure 12.10 Residential in-duct and free-standing electronic air cleaners. (Courtesy of Honeywell, Inc., Minneapolis.)

3. *Charged-media nonionizing cleaners*

These cleaners include characteristics of electrostatic and dry-filter particle collection. They consist of a dielectric filter mat made of glass fiber, cellulose, or other fibrous materials supported on or in a gridwork of alternately charged (12,000 V) or grounded members. Consequently, a strong electrostatic field develops in the filter medium. Particles approaching the filter medium are polarized and drawn to it, where deposition takes place. Because of increased resistance to air flow associated with soiling, such filters need to be replaced periodically.

C. *Performance measurement*

Air cleaners vary in their collection efficiency (as well as overall particle removal) for particles of different aerodynamic diameters, resistance to air flow, service life, and particle-holding capacity. As a consequence, there is a need for uniform evaluation and rating of filter performance. Test procedures prescribed under ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standards 52.1-76 provide performance characteristics of most commercially available filters and filtration systems. Two different ASHRAE test methodologies were used to evaluate filter and filtration system performance. In the Spring of 2000, ASHRAE published a new standard, 52.2-1999, which is likely to serve as the primary filter test methodology in the future. These methodologies, plus an additional methodology for HEPA filters, are described below.

Table 12.3 Performance of Dry Media Filters

Media type	Arrestance (%)	Dust spot efficiency (%)
Fine open foams/textile nonwovens	70–80	15–30
Mats of glass fiber/multi–ply cellulose/wool felt	85–90	25–40
Mats of 5–10 µm fibers, 6–12 mm thick	90–95	40–60
Mats of 3–10 µm fibers, 6–12 mm thick	>95	60–80
Mats of 1–4 µm fibers, mixtures of fiber types	>95	80–90

Source: From ASHRAE, Air cleaners, in *Equipment Handbook*, ASHRAE, Atlanta, 1983, chap. 10.

1. Arrestance

Arrestance is a measure of the ability of a filter to collect relatively large particles. It is a measure of the performance of panel filters that are used to protect mechanical equipment or serve as prefilters where low-efficiency cleaning is acceptable.

Arrestance values are determined by aerosolizing a standard dust mixture upstream of the filtration system. The ASHRAE dust mixture includes, by weight, 72% standard air-cleaner fines, 23% molacco black, and 5% No. 7 cotton linters ground in a mill. This dust mixture is designed to take into account the large variability in composition and size of particles that enter HVAC system AHUs. Arrestance values are based on the weight of standard dust collected on or in the filter compared to the weight of the standard dust mixture aerosolized upstream of the filter. Arrestance values for a number of filter media/filters are found in Table 12.3. Note that, in general, arrestance values are relatively high, and increase with increasing filter density and smaller fiber size. Because arrestance focuses on weight, it is a measure of large particle (>10 µm) cleaning effectiveness.

2. Dust spot efficiency

The dust spot efficiency test is a better indicator of filter performance over a broad range of particle sizes. It is employed to measure the performance of medium to high efficiency extended-media filters and electronic air cleaners. It measures discoloration differences (as determined by optical density) observed on glass fiber filter tape samples collected both upstream and downstream of filter/filtration units. Dust spot efficiency of the filtration unit is expressed as percent reduction of the optical density of downstream compared to upstream samples.

Dust spot efficiencies for a range of filter media/filters are also summarized in Table 12.3. Note the significant differences between arrestance and dust spot efficiency values. High dust spot efficiencies are associated with filter media with small fiber diameters and high packing densities. Though dust spot efficiency is a relatively good measure of overall dust collection efficiency, it is subject to some error due to differences in optical properties of collected particles. Darker particles absorb more light and therefore result in higher optical density readings than similar concentrations of lighter colored particles.

The dust spot test was designed to measure an objectionable characteristic (ability to soil interior building surfaces) caused by relatively small diameter (<10 μm) particles. It was developed in response to limitations of the arrestance testing method. Because arrestance and dust spot testing measure different performance characteristics, values derived from these tests cannot be used interchangeably. However, filters with medium to high dust spot efficiencies also have high arrestance values.

3 Minimum efficiency reporting values

ASHRAE, under its recently published standard 52.2-1999, established a test protocol to test filter performance based on measuring fractional collection efficiencies. These efficiencies are determined by conducting particle counts both upstream and downstream of filters challenged by exposure to laboratory-generated potassium chloride aerosols in 12 different size ranges (smallest 0.3–0.4 μm; largest 7–10 μm).

In addition to measuring the performance of clean filters, particle size fractional efficiency curves are developed at incremental dust loadings. These curves are used to develop composite curves that identify minimum efficiency in each particle size range. Minimum efficiency composite values are averaged in three size ranges (0.3–1.0 [E1], 1.0–3.0 [E2], and 3.0–10.0 [E3] μm) to determine minimum efficiency reporting values (MERVs). Filters with MERV values of 1 to 4 are very low efficiency; they would be used as furnace filters. Pleated filters would have MERV values of 5 to 8; box/bag filters, 9 to 12; box/bag filters, 13 to 16; and HEPA filters, 17 to 20.

4. DOP smoke penetration tests

Measurements of particle collection efficiencies >98% are made using the DOP (dioctyl phthalate) smoke penetration method. It is typically used to test the performance of HEPA filters.

In this method, an aerosol of DOP is produced with a uniform particle diameter of 0.3 μm, the size range of minimal collection efficiency for most HEPA filters. DOP particles that pass (penetrate) through the filter or leak around filter-sealing gaskets are determined downstream by means of a photometer that measures light scattering. Their concentration is compared to that measured upstream of the filter. Filter penetration is calculated by using the following equation:

$$P = 100\frac{C_2}{C_1} \tag{12.2}$$

where P = % penetration
C_1 = upstream concentration
C_2 = downstream concentration

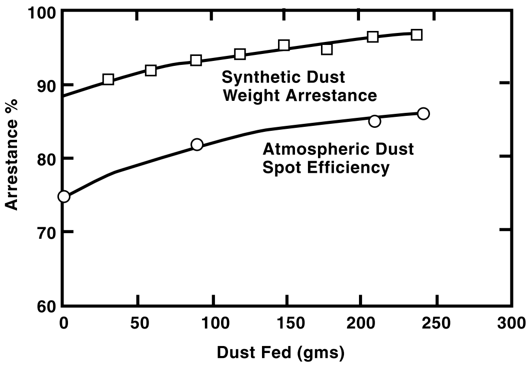


Figure 12.11 Relationship between filter loading and collection efficiency. (From *ASHRAE Equipment Handbook*, ASHRAE, Atlanta, 1983, chapter 10. With permission.)

Because HEPA filters have efficiencies near 100%, penetration rather than efficiency is typically reported. Penetration can be converted to % efficiency by using the following equation:

$$E = 100 - P \tag{12.3}$$

where E = efficiency (%)

5. *Filter soiling and efficiency*

As a filter becomes soiled, the mat of collected particles serves as a collection medium so that collection efficiency increases with increased service life. This increase in both arrestance values and dust spot efficiency as a function of dust exposure can be seen in Figure 12.11. As a consequence, "dirty" filters have an associated increase in cleaning efficiency. Notice, however, the significant effect on air flow resistance with increasing filter dust loads in Figure 12.12.

D. Use considerations

Air cleaners designed to control airborne particles are used in a variety of applications. In mechanically ventilated buildings, low-efficiency dust stop filters and renewable-media filters are used to protect mechanical equipment. Increasingly, a higher level of particle cleaning and performance is being designed and specified for mechanically ventilated buildings to achieve and maintain cleaner indoor spaces. Medium efficiency extended-surface filters, or bag filters, are commonly specified by mechanical engineers and installed by building owners/operators.

In most residential environments, air cleaning is limited to dust stop filters used in heating and cooling systems to protect mechanical equipment. In the 1980s, a significant air cleaner market targeted to average consumers

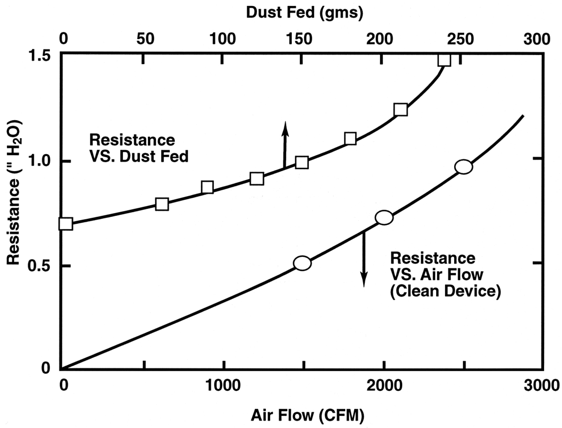


Figure 12.12 Relationships between filter loading and resistance and resistance and volumetric air flow. (From *ASHRAE Equipment Handbook*, ASHRAE, Atlanta, 1983, chapter 10. With permission.)

developed. This market included a variety of products which can be categorized on the basis of cost, potential air cleaning capacity, and efficiency.

1. *Residential and consumer air cleaners*

a. Fan and filter desktop cleaners. At the low end of the market are devices that range in cost from $20 to $100. They are small desktop devices that use dry, loosely packed, low-density filters located upstream of a high velocity, low air resistance axial fan. Some units utilize electrostatically charged electret filters (thin plastic materials imprinted with high voltage charges). In most cases, such devices have insufficient capacity to clean air in even a single closed room. Performance tests conducted in a 1200 ft^3 (33.6 m^3) room have indicated that tobacco smoke removal effectiveness of such devices under static chamber conditions (i.e., no air flow in or out of the space) is little better than using no device at all.

b. Negative ion generators. The simplest and least expensive devices generate ions that diffuse out into building air and attach to particles which plate out on building surfaces. More advanced models are designed to eliminate the "dirty wall effect" associated with simple ion generators. In such devices, an attempt is made to draw charged particles into the air cleaner (by using a suction fan), where they can be deposited on an electrostatically charged panel filter. In other ionizers, a stream of negatively charged ions is generated in pulses, and charged particles theoretically are drawn passively to the ionizer, which contains a positively charged cover.

Negative ion generators have long been used as health-promoting devices, particularly by a small population of medical practitioners who treat allergy patients. There is limited evidence that negative ions may affect an individual's sense of well-being and alleviate allergy symptoms. Because such health claims cannot be definitively established, manufacturers cannot promote negative ion generators for such purposes. After being forced from the market in the early 1960s by the Food and Drug Administration (FDA), these devices were reincarnated as air cleaners. They have been shown to be relatively effective in removing smoke from a 1200 ft^3 test room under static conditions.

c. Portable extended-media and electronic cleaners. Air cleaners of this type are portable devices which are larger, and more expensive and effective than desktop units. They utilize extended-media high-efficiency filters, HEPA filters, or two-stage electronic systems. A portable electronic air cleaner can be seen in Figure 12.10b. Air flow rates are dependent on the filter type, blower capacity, and fan horsepower. These devices utilize good quality high-efficiency filters/filtration systems and should be relatively effective in cleaning particles from air in a single room with an air volume up to 3200 ft^3 (*circa* 90 m^3).

As they are widely recommended by allergists, the use of such portable high-efficiency air cleaners is common. They have been demonstrated to be relatively effective in reducing smoke particle concentrations in a single room under static conditions. An approximate 70% reduction in particle levels was observed when an air cleaner with a HEPA filter was placed in the bedrooms of 32 allergy patients for a 4-week period. These studies indicated that portable high-efficiency devices can be used to reduce particle levels in a single room when operated continuously. However, portable electronic air cleaners operated continuously in closed rooms may produce considerable odor (from O_3 and other products) and even irritation effects.

d. In-duct cleaners. In-duct air cleaning devices are widely used in North American residences. In-duct devices employ either extended-media filters or electronic systems (Figure 12.10a). In-duct systems are installed in cold air returns immediately upstream of furnace blower fans. They are designed to clean the air of an entire residence and, except in very large residences, have the capacity to provide whole-house air cleaning. These systems, however, only remove particles when the furnace or cooling system blower fan is activated. In most cases, operation is intermittent since it responds to heating and cooling needs. In-duct systems need to be run continuously to achieve the air cleaning performance they are designed for. Most in-duct filtration media and electronic air cleaners have dust spot efficiencies of 90% or better.

The installation of an in-duct cleaning system can significantly reduce airborne particle levels by the initial action of moving contaminated air through the filter/filtration system and by its continuous recirculation. For maximum cleaning effectiveness, it is desirable to use a high-efficiency filter/filtration system and a high recirculation rate. The effect of two different recirculation rates on cleaning efficiency can be seen in Figure 12.13.

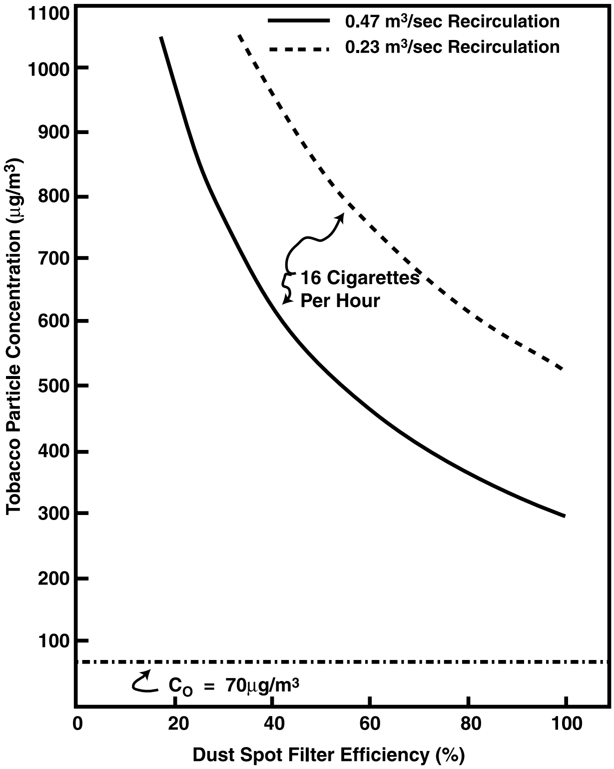


Figure 12.13 Effect of dust spot filter efficiency and recirculation rate on tobacco particle concentration. (From McNall, P.E., *Arch. Environ. Health*, 30, 552, 1975. With permission.)

Performance of an in-duct electronic air cleaner in a residence during a period of smoking can be seen in Figure 12.14. Smoke particle concentration decreased by about 70% in 2 hours to reach a steady-state concentration as occupant smoking continued. It decreased by an order of magnitude after smoking ceased. Other studies with in-duct electronic air cleaners in residences have demonstrated an order of magnitude or more reduction of airborne particles in unoccupied spaces. However, particle concentrations decreased by only 40 to 60% when studied over extended periods of time with unrestricted occupant activity. Occupant activities significantly reduced the apparent performance of filtration units by affecting particle generation and resuspension rates.

2. *Air cleaning to control particulate-phase biological contaminants*

Air cleaners are used in hospitals to limit infections among surgical and immunocompromised patients. Bacterial contamination of air in operating rooms is a major concern because of the significant potential for postoperative infections. The major cause of such infections is *Staphylococcus aureus* shed by

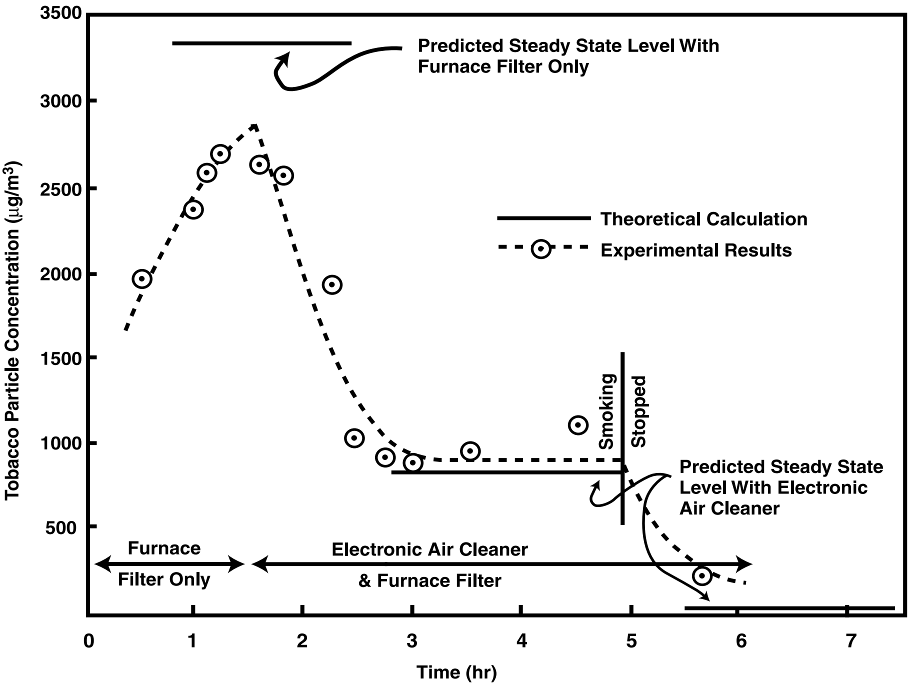


Figure 12.14 Effect of the operation of an in-duct electronic air cleaner on measured tobacco particle concentration in a residence. (From McNall, P.E., *Arch. Environ. Health*, 30, 552, 1975. With permission.)

surgical staff. Typically, surgical rooms use a combination of HEPA filters and laminar air flow. In one study of a surgery room operated at an air exchange rate of 20 ACH, culturable/viable bacterial levels were observed to decrease by approximately 89% when the system was operated under empty-room conditions and approximately 88% while surgery was in progress.

Air cleaners have been evaluated relative to their potential for reducing airborne mold levels in residences. In a study of culturable/viable airborne mold levels in residences, investigators observed significant reductions in total culturable/viable mold counts in residences using in-duct electronic air cleaners. Average reductions in 21 residences were approximately 77% (with a range of 66 to 87%) when the system was operated continuously and 50% (with a range of 0 to 83%) when the air cleaner was operated intermittently. The author has observed reductions in total airborne mold levels (viable and nonviable mold spores and particles) of 90% in a single-family residence using an extended-media filter.

In another study, cat allergen levels were reduced by 38% on the main level and 4% in the basement of a house with an in-duct HEPA filter when the blower system was operated continuously. Air cleaning appeared to be relatively ineffective when a significant active allergen-producing source (two cats) was present.

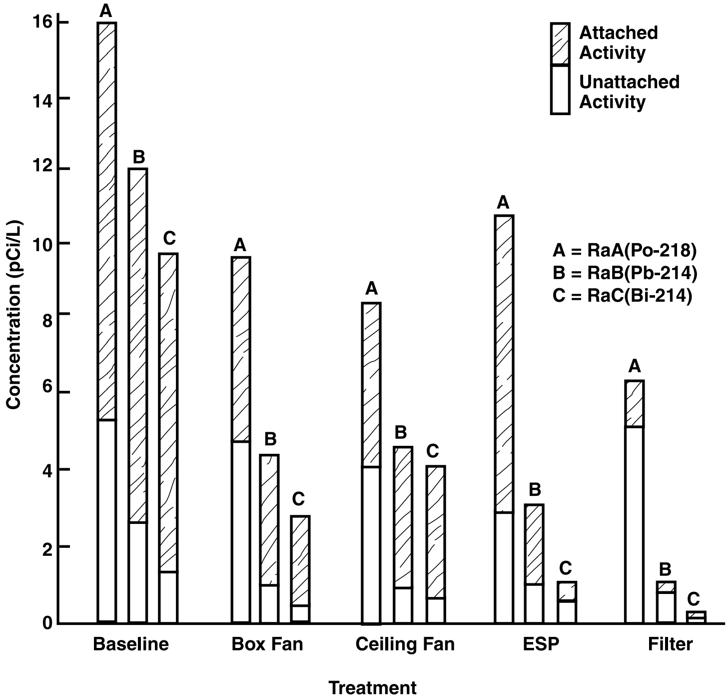


Figure 12.15 Effects of air treatments on radon decay product concentrations. (From Hinds, W.C. et al., *JAPCA*, 33, 134, 1983. With permission.)

The main reason for using an air cleaner in residential environments is to reduce the severity and prevalence of symptoms associated with allergy or asthma. Several studies have shown limited but less-than-definitive diminution of symptoms of allergy and asthma in patients in controlled studies using portable and in-duct high-efficiency air cleaners.

3. Radon control

Because of their particulate nature, radon decay product (RDP) exposures can, in theory, be significantly reduced by using an air cleaner. Radon decay products attached to particles were observed to have been reduced by 70% and 89%, respectively, in a 78 m^3 chamber in studies which evaluated the performance of portable electronic and HEPA air cleaners. However, use of HEPA filters resulted in a threefold increase in unattached (to particles) RDP activity. The effects of air cleaning on RDP concentrations can be seen in Figure 12.15.

Though air cleaners are apparently relatively effective in reducing airborne RDP levels, increases in the unattached fraction relative to the attached fraction by HEPA filtration is of unknown, but worrisome, public health consequence since unattached RDPs can penetrate more deeply into the lungs. Consequently, USEPA does not recommend the use of air cleaning to reduce exposure to RDPs in residences.

4. Air cleaner use problems

Air cleaners are often purchased by consumers in response to physician recommendations or as a result of a personal desire to alleviate symptoms of allergy, asthma, or other building-related health concerns. Consumers and physicians are unaware of the limitations of air cleaners and their use in general, and limitations of specific air cleaner types and models. With the possible exception of negative ion generators, desktop devices are apparently ineffective. Portable and in-duct extended-media filters, on the other hand, can be used effectively if selected for the appropriate reason and operated properly.

Individuals often purchase air cleaners for generic use in alleviating allergy symptoms, ostensibly by reducing airborne allergen levels. Unfortunately, only a few airborne allergens are amenable to significant control by air cleaning. These include mold spores and hyphal fragments, and pet allergens when pets are no longer present to actively produce allergen. Dust mite fecal pellets and fragments are very large (>10 μm) and do not remain airborne for more than 10 minutes or so. Exposure occurs on disturbance. The same is likely true for cockroach allergens as well. For such allergens, air cleaning is unlikely to have any measurable benefit.

Though in-duct cleaning devices have the potential to significantly reduce airborne levels of mold and other small particles, air cleaning can only occur when the blower fan is operating. In residences using in-duct systems, the blower fan is usually not wired to allow blower fan operation independent of heating/cooling system activation. In residences where independent operation of blower and heating/cooling systems is possible, residents are rarely aware that good system performance requires continuous or near-continuous operation.

Consumers often purchase a portable air cleaner with the assumption that it can clean the air of a whole house if it is operated in a central location. Such portable devices have relatively low design and actual air flows (compared to in-duct systems). Performance decreases with increasing air volume when flow capacity is insufficient. Portable air cleaners achieve their best performance in single closed rooms (e.g., bedrooms). Good performance depends on air cleaner placement; in most cases, placement near the center of the room or near an allergy patient's nighttime breathing zone is recommended.

5. Ozone production

Electronic air cleaners and negative ion generators employ high voltages which cause ionization. Consequently, they have the capability to produce significant quantities of O_3. Because of its toxicity at low concentrations, its potential effects on rubber products, soft plastics, and fabric dyes, and its role in initiating indoor chemical reactions that produce irritants; O_3 production by such devices is of concern. Products sold as medical devices are regulated by the Food and Drug Administration (FDA). The FDA limits O_3 emission from these products so that an indoor level may not exceed 0.05

ppmv. With intermittent operation, in-duct electronic air cleaners are unlikely to cause any significant elevation of O_3. However, elevated levels may be expected when electronic air cleaning devices are operated continuously, particularly in a closed room.

6. Clean rooms

The need for nearly particle-free environments has led to the development and utilization of clean rooms. They are widely used in the semiconductor industry, pharmaceutical manufacture, aerospace and military applications, and for some medical purposes. Their early history reflects the parallel needs for very high efficiency filters in the nuclear and aerospace industries.

In first-generation clean rooms of the 1950s, very high levels of airborne particle control were achieved by the installation of HEPA filters in AHUs of clean room units. Such filters, even at that time, had DOP efficiency ratings of 99.97% at 0.3 μm. Clean rooms utilizing laminar flow principles were developed in 1962. In laminar flow, air moves uniformly in what is, in essence, parallel streamlines across a space. Laminar flow is used to minimize cross-streamline turbulence. Particles present or generated in the space tend to stay in a streamline until they are removed. Laminar flow patterns are induced by the uniform introduction of low-velocity air through a wall or ceiling area. Laminar flow patterns in a simple clean room design can be seen in Figure 12.16. In an ideal situation, the entire ceiling would serve as a perforated supply air plenum and the floor as a perforated exhaust plenum.

In conventional rooms, particles deposited on room surfaces can be resuspended by foot traffic and other movements that produce turbulent eddies. Under laminar flow conditions, air moves in predictable paths, and turbulent eddy formation is minimized. Laminar flow patterns are disturbed by the presence of people and objects. When a streamline is broken by an object, it may reform some distance downstream. If broken streamlines are not reformed, other streamlines transport airborne particles across the room.

The purpose of laminar flow is to remove (purge) particles generated in a clean room by workers and their activities and to prevent the resuspension of particles from horizontal surfaces, particularly the floor. Laminar flow systems facilitate the use of high purging air flows without the particle-disturbing turbulence typically associated with such air flows. However, as volumetric air flows increase to a critical level, they begin to resuspend more particles than they purge. An optimal flow rate widely used in clean rooms is 20 air changes per hour (ACH).

Clean rooms are limited in size and volume to optimize environmental control. As laminar air flow travel distances increase, particles are purged less effectively.

High recirculation rates are used to move air through HEPA filters. Sufficient makeup air is also provided to adequately dilute human bioeffluents. Recirculation rates on the order of 75% are typically employed.

HEPA filters are located in AHUs on the discharge side of blower fans (rather than the suction side) to prevent inward leakage of particles through

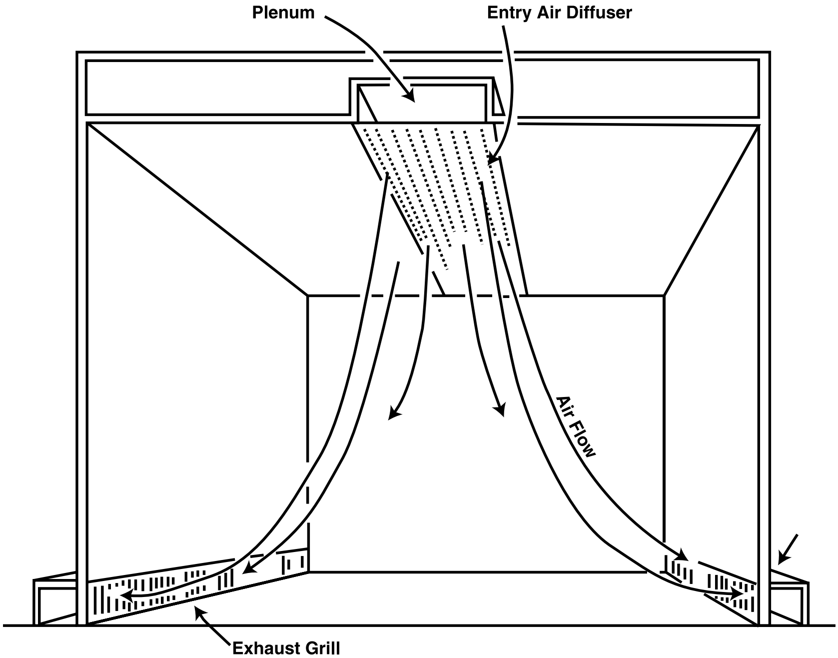


Figure 12.16 Laminar air flow in a clean room.

inadequately sealed ductwork or filter gaskets. Leakage is outward when the filter is on the discharge side. Placing HEPA filters in the last position before the ductwork ensures that unfiltered air will not enter the room. It is critically important to install HEPA filters so that leakage does not occur around them. Achieving an absolutely airtight seal is, however, very difficult.

Pressurization is used to assure that air entering the room is filtered. It is facilitated by air locks which are used by employees for room entry and egress.

Many modern clean rooms have very high cleanliness requirements. As a consequence, HEPA filters with DOP efficiencies on the order of 99.995% or higher are commonly used.

In addition to HEPA filters, laminar flows, and high recirculation rates, clean room users employ a variety of practices to limit particle generation, resuspension, and deposition. These include the use of clothing that covers particle-generating parts of the body and produces few particles itself. It also includes the use of low particle-generating equipment and materials.

II. Gas and vapor-phase contaminants

Application of air cleaning for removal or control of gas/vapor-phase contaminants is, in most cases, a much more difficult undertaking than it is for airborne particles. This is due in part to the fact that the many substances found in indoor air have different chemical properties and, as a consequence, cannot be effectively removed by generic removal processes. The most commonly used technique for removing gas/vapor-phase substances from indoor air and ventilation airstreams is adsorption. Other control approaches that have been attempted include absorption, catalytic oxidation/reduction, botanical air cleaning, and ozonation.

A. Adsorption

Adsorption is a process by which gas, vapor, or liquid-phase substances are physically removed from fluids (including air) by adherence to, and retention on, solid sorbents. This adherence is due to Van der Waal's forces acting on the surface of solids to hold molecules to their surface. The sorbing material is the adsorbent (or sorbent); the adsorbed molecules, the adsorbate (or sorbate). Sorbate condenses (capillary condensation) in the submicroscopic pores of the sorbent.

Though adsorption is a chemical/physical phenomenon, chemical reactions generally do not take place. However, when molecules are adsorbed on a surface, heat is released (heat of adsorption) which is approximately equal to the amount of heat produced when a gas/vapor condenses. As a consequence, sorbate is present on the sorbent as a liquid. Desorption processes require sufficient energy to convert the sorbate to a gas or vapor.

A variety of materials have good sorbent properties. They include activated carbons, activated alumina, silica gel, zeolites, porous clay minerals, and molecular sieves. These materials are widely used in industrial and commercial applications where certain sorbent properties are required. They are used in air cleaning, water softening, and as "kitty litter." Sorbents have high surface-to-volume ratios. Their structure consists of large numbers of submicroscopic pores and channels. Most sorption occurs in pores that have cross-sectional diameters of 10 to 30 angstrom units (Å).

Sorbents may be polar or nonpolar. Metal oxide-, silicaceous-, and active earth-type sorbents are polar. Since polar compounds attract each other, and water is strongly polar, sorbents such as silica gel sorb and retain water preferentially. As such, they cannot effectively remove gases (other than water vapor) in the humid atmospheres common to most air cleaning applications. Activated carbons are nonpolar and have limited affinity for water vapor. They preferentially sorb and retain organic vapors.

B. Activated carbons

Activated carbons are commonly used for solvent recovery and air cleaning in industrial applications, and air cleaning in indoor applications. They are produced in a two-step process in which carbonaceous materials such as wood (primarily hardwoods), coal, coconut and other shells, fruit pits, etc., are heated in a neutral atmosphere and then oxidized at high temperature. Substances that cannot be easily carbonized are volatilized, and numerous submicroscopic pores are produced. Activated carbons originating from different materials vary in their structural properties (e.g., pore size, hardness, density) and, as a consequence, differ in their ability to sorb and retain vapor- (and liquid-phase) substances.

1. Hardness and size

Activated carbons vary in hardness depending on materials and processes used in their production. Hardness is an important use parameter of activated carbons since they must withstand the impact, compression, and sheer forces associated with their use. When air moves through a bed of activated carbon at high flow rates, it causes individual granules of activated carbon to vibrate. Such vibration may cause fragmentation, decrease in granule size, and loss of carbon mass from the bed. This may produce voids in thin-bed adsorption panels and result in reduced sorption efficiency (since air preferentially flows through voids).

Activated carbons are produced in size ranges described by U.S. Sieve Series standard mesh sizes. An 8-14 mesh size, for example, describes activated carbon particles with dimensions of 2.36 × 1.4 mm. Mesh numbers increase with decreasing granule size. A mesh size of 6-14 is typically specified for general purpose air cleaning.

Granule size is a major determinant of air cleaning effectiveness. Effectiveness increases with decreasing granule size. As the sorption bed becomes more tightly packed (as a consequence of smaller granular size), the distance that a sorbate molecule must travel to come into contact with a sorbent surface decreases. As a consequence, the transfer rate of vapor to carbon increases. Though cleaning performance is enhanced when activated carbons with small granule sizes are employed, such use has the same pressure drop problems associated with high-efficiency particle filters.

2. Adsorbability

The degree of physical attraction between a sorbate and a molecule is described as adsorbability. It is a direct function of a sorbate's critical temperature and boiling point. Gases such as oxygen (O_2), nitrogen (N_2), hydrogen (H_2), carbon monoxide (CO), and methane (CH_4) have critical temperatures below –50°C and boiling points below –150°C. As a consequence, they cannot be sorbed at ambient temperatures.

Low boiling point gases/vapors such as ammonia (NH_3), hydrogen chloride (HCl), hydrogen sulfide (H_2S), ethylene (C_2H_2), and formaldehyde (HCHO) have critical temperatures between 0 and 150°C and boiling points between –100 and 0°C. As a consequence, they are moderately adsorbable. However, because of poor retention, activated carbons without special impregnants are not suitable for removal of such gases from air.

Organic vapors that have boiling points >0°C have an increased tendency to be sorbed and retained on activated carbons. These include the higher aldehydes, ketones, alcohols, organic acids, ethers, esters, alkylbenzenes, halocarbons, and nitrogen and sulfur compounds.

In general, the adsorbability of gases and vapors increases with increased molecular size and weight. Small, highly volatile molecules (very volatile organic compounds, VVOCs) have lower adsorbability on activated carbons than larger, lower-volatility compounds (VOCs). In an organic compound series such as paraffins, olefins, and aromatic compounds, adsorbability increases with increased carbon numbers.

3. *Adsorption capacity*

Activated carbons differ in their ability to sorb and retain sorbate molecules determined on a sorbent weight basis. Adsorption capacity, described as the weight of the sorbate collected per weight of sorbent, depends on (1) sorbent surface area; (2) active sorbent pore volume; (3) gas/vapor sorbate properties; and (4) environmental factors such as temperature, relative humidity, and pressure.

Surface areas for commonly used activated carbons range from 500 to 1400 m^2/g. An inverse exponential relationship exists between pore size and surface area; surface area available for sorption decreases dramatically as pore size increases.

Adsorption capacity of activated carbons is rated relative to their ability to sorb carbon tetrachloride (CCl_4) vapors. A standard weight of activated carbon is exposed to a saturated dry stream of CCl_4 at 68°F (20°C) until the sorbent no longer increases in weight. The ratio of the weight of sorbed CCl_4 to the weight of activated carbon is the maximum possible sorption of CCl_4. This adsorptive capacity, expressed as CTC% (or g CTC/g carbon), ranges from a low of 20 to a high of 90% for different activated carbons.

Though adsorption capacity is determined by using CCl_4 as a standard, other chemical substances will differ in their adsorption capacity on a given activated carbon. As an example, reported adsorption capacities for carcinogenic vapors such as 1,2-dibromomethane, CCl_4, and 1,1-dimethyl hydrazine are 1.020 g/g, 0.741 g/g, and 0.359 g/g, respectively.

As indicated, adsorption capacity can be affected by environmental conditions such as temperature, pressure, and relative humidity. Under elevated temperatures and low pressures, significant loss in adsorption capacity occurs. Fortunately, such temperature and pressure extremes do not occur in nonindustrial air cleaning applications.

Under ordinary ambient (outdoor) conditions, relative humidity is the most likely factor to affect adsorption capacity. Nonpolar activated carbons can nevertheless sorb water vapor from the atmosphere. At high relative humidities (>50%) significant reductions in adsorption capacities have been reported for activated carbons.

4. *Retentivity*

Retentivity is a property of both the sorbate and sorbent, described as the maximum concentration of vapor retained by a sorbent when the vapor content of an airstream is reduced to zero. It is measured by passing clean,

Figure 12.17 Thin-bed activated carbon panel.

dry air at constant temperature and pressure over a bed of sorbent previously saturated with a specific vapor. Retentivity is expressed as the ratio of the weight of the retained vapor to the weight of the sorbent. The retentivity ratio is always less than the adsorption capacity. This indicates that sorbents have a higher capacity to sorb vapors than to retain them. Though activated carbons have a relatively high adsorption capacity for water vapor, retentivity is low. Because of this low water vapor retentivity, sorbed gases and vapors flowing through an activated carbon bed will cause sorbed water to leave the sorbent and progressively reduce its sorptive capacity for water vapor. Activated carbons are poor sorbents for low-molecular-weight substances such as HCHO and ethylene (C_2H_2) because they are poorly retained.

5. Carbon beds and filters

Gas/vapor air cleaning in industrial and indoor applications is often accomplished by passing contaminated air through a bed of activated carbon. Carbon beds used in solvent recovery and industrial air cleaning have depths of circa 1 to 2 meters (3 to 6′). In indoor applications, such bed depths are impractical. As a consequence, thin-bed panels with bed depths of 25 to 30 mm (1 to 1.25″) are used (Figure 12.17). Because of severe pressure drop problems with such thin-bed filters, they are usually inserted in a module with multiple V configurations, much like that in an extended-surface pleated filter.

Increasingly, activated carbons are being introduced into pleated extended-surface fiber filters. Dry-processed carbon, composite-based adsorption filters utilize very fine activated particles evenly dispersed throughout the filter mat. Like other extended-surface media filters, they have the advantage of low pressure drops and can be used in many applications without expensive filter modules and thin-bed panel filters.

6. Gas/vapor removal in carbon beds

Gas/vapor-phase contaminants are removed in a distinct pattern of adsorption waves (Figure 12.18). As air moves through an activated carbon sorbent

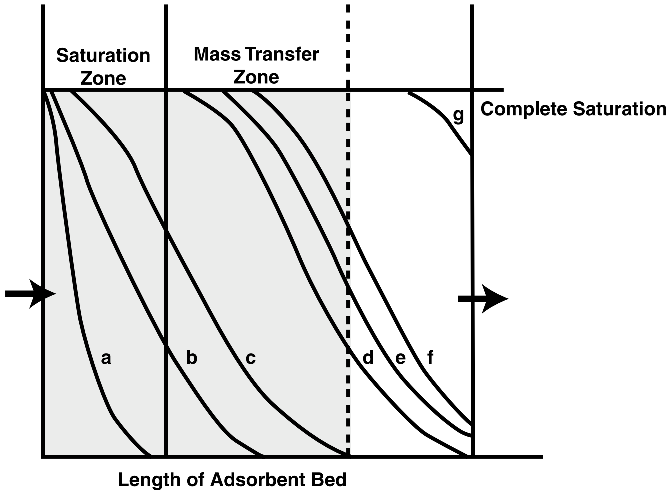


Figure 12.18 Adsorption patterns in an activated carbon bed. (From Turk, A.C., Adsorption, in *Air Pollution*, 3rd ed., Vol. IV, Stern, A.C., Ed., Academic Press, New York, 329, 1977. With permission.)

bed, concentrations of contaminants in the airstream fall rapidly to zero at some finite distance downstream. As sorption continues, carbon granules near the face gradually become completely saturated. In the saturation zone, a dynamic equilibrium becomes established between saturated sorbent and in-coming contaminants. Downstream of this saturation or equilibrium zone, carbon granules are actively sorbing influent gases/vapors. This is described as the mass transfer zone. It is an area of the bed between zero concentration and complete saturation. It moves progressively from one face of the bed to the other with time. It can be described over time by curves a–g. When the bed reaches the condition described by curve e, breakthrough occurs, and the bed has reached the end of its useful life. Carbon in the bed must now be replaced or reactivated.

7. Reactivation and replacement

In industrial and commercial applications, saturated sorbents are reactivated once they become saturated. They are reactivated (desorbed) by passing low-temperature steam or hot air through the bed. In most indoor applications, thin-bed filters are replaced with new filters when they become saturated. They are often discarded but may be returned to the manufacturer for reactivation.

8. Residence time

Because of the limited bed depth associated with thin-bed filters used in indoor applications, residence time of air moving through such filters is a critical factor in their performance. It would take approximately 0.08 seconds to traverse a 25 mm (1″) thin-bed filter under standard air velocity conditions. In closely packed thin-bed activated carbon filters, the half-life of a contaminant (time required to reduce the concentration by 50%) flowing though it is 0.01 seconds. In theory, four half-lives would be required to achieve 90% contaminant removal and require a minimum bed depth of 10 to 13 mm (0.4 to 0.5″).

9. Service life

When contaminant breakthrough (breakpoint) occurs, the sorbent is becoming saturated and needs to be replaced. It is difficult to know with certainty when the breakpoint is reached. The service life of a thin-bed filter can be calculated using the following equation:

$$T = \frac{6.43(10^6)SW}{EQMC} \tag{12.4}$$

where T = service life, hr
S = fractional saturation of sorbent (retentivity)
W = sorbent weight, lb (kg)
E = fractional sorption efficiency
Q = air flow rate, CFM (L/sec)
M = average molecular weight of sorbate
C = average vapor concentration, ppmv

Applying this equation to the removal of toluene (the most common and abundant indoor contaminant) by a small room air cleaner, let us make the following assumptions:

E = 0.95

C = 0.20 ppmv

Q = 100 CFM (47.5 L/sec)

S = 0.30

W = 6 lb (2.27 kg)

then

$$\begin{aligned} T &= \frac{6.43 \times 10^6 \times 0.30 \times 6}{0.95 \times 100 \times 92 \times 0.20} \\ &= 6621 \text{ hr} \\ &= 276 \text{ days} \end{aligned}$$

If one knew the average concentration of individual contaminants and their sorption and retention potentials, service life could be calculated from Equation 12.4. For toluene alone at an average concentration of 0.20 ppmv, the service life is predicted to be approximately 9 months. An equivalent TVOC (total VOC) concentration would be approximately 0.77 mg/m^3, a moderate level of VOCs in indoor spaces. Under such use conditions, the sorbent would require replacement after approximately 9 months of continuous operation. At concentrations of 1.5 mg/m^3 TVOC (a high TVOC concentration), sorbent life would be about 4.5 months. If in the initial case the TVOC level were 0.77 mg/m^3 and flow rate were increased to 200 CFM (to clean a larger air volume), service life would be approximately 4.5 months.

The service life of thin-bed carbon filters is difficult to determine under real-world conditions. A variety of approaches have been suggested to determine when carbon filters applied for odor control should be replaced. These include (1) detection of odor when the filter is saturated, (2) removal of sample carbon granules to determine their degree of saturation in the laboratory, and (3) challenge with odoriferous compounds such as isoamyl acetate (banana oil) or wintergreen.

10. Catalytic properties

Activated carbons are often used to remove objectionable gases from emission sources, indoor air, and other media, based on their catalytic abilities. Activated carbons have been used in southern California to remove O_3 from ambient air serving greenhouses and, in some cases, building HVAC systems. In addition to catalytically destroying O_3, activated carbons can destroy other oxidants such as ozonides, peroxides, and hydroperoxides. Activated carbon filters are used to reduce O_3 emissions from O_3-generating equipment such as electrostatic photocopiers and other high-voltage devices.

In the presence of O_2, activated carbons can catalytically oxidize H_2S to elemental sulfur. H_2S is a common malodorant associated with sewage treatment, oil/gas extraction and refining, and a variety of decomposition processes. It is a common contaminant in groundwater supplies used for domestic and industrial purposes, and can be removed from water by activated carbon filters.

In addition to their natural catalysis of compounds such as O_3 and H_2S, activated carbons can be impregnated with catalysts for specific applications.

C. Chemisorption

The large surface area associated with sorbents provides an optimum environment for a variety of chemical reactions. To facilitate such reactions, sorbents are coated or impregnated with selected chemicals that will react with target substances which come into contact with the chemical impregnants. The process is called chemisorption. It is the process by which contaminant levels are determined from gas sampling tube measurements (see Chapter 9).

Chemisorption media are produced by impregnating activated carbon, activated aluminum, silica gel, etc., with catalysts that include bromine, metal oxides, elemental sulfur, iodine, potassium iodide, and sodium sulfide. Bromine-impregnated activated carbons are used to chemically sorb ethylene, which reacts catalytically to produce ethylene bromide, a sorbable gas. Carbons impregnated with metallic oxides are used to oxidize H_2S under low O_2 conditions. Elemental sulfur- and iodine-impregnated activated carbons can be used to sorb mercury by producing stable mercuric sulfide and mercuric iodide, respectively. Such impregnated carbons can be used to reduce exposure to mercury associated with accidental spills of mercury and elemental mercury-releasing compounds. Sodium sulfide and other impregnants have been used to remove HCHO and have been used in residential applications.

Activated alumina impregnated with potassium permanganate ($KMnO_4$) has been widely used in industrial and commercial air cleaning systems and has seen limited residential use. Though activated alumina does not have the sorptive capacity of activated carbons, it can be used effectively for the control of low-molecular-weight gases, such as HCHO and C_2H_2, and odors in buildings. Organic vapors are sorbed on the surface of the activated alumina where they are oxidized by $KMnO_4$ in a thin film of water. If oxidation is complete, CO_2 and H_2O vapor will be produced as by-products. If incomplete, it has the potential to produce a variety of oxidized compounds such as aldehydes and ketones, and in the case of halogens, substances such as hydrogen chloride (HCl). $KMnO_4$-impregnated activated alumina is used commercially to remove C_2H_2 from fruit storage facilities. On use, the pink-colored $KMnO_4$ is reduced to the brown-colored $KMnO_2$, manganese oxide.

D. Performance studies

Performance evaluations of air cleaning systems in nonindustrial, nonresidential buildings, and residential environments have been limited. Several studies have been conducted to evaluate the performance of thin-bed activated alumina filters on HCHO in residences. In a study using a portable cleaner with an air flow of 130 CFM (61 L/s), HCHO levels were reduced by 25 to 30% in a mobile home and 35 to 45% in a urea–formaldehyde-foam-insulated (UFFI) house. In another study using a cleaner with an 1800 CFM (849 L/s) flow rate, HCHO levels were reduced on the order of 75%. A study of thin-bed activated carbon filters showed that they were effective (on the order of 80%) in removing VOCs in the low ppbv range found in buildings, with a projected service life of 60 to 466 days. The effectiveness of dry-processed carbon composite-based filters has been evaluated under laboratory conditions. Such filters have been reported to have 10 times the adsorption capacity of large mesh activated carbon, but they apparently have much shorter service lives.

E. Absorption

Absorption is widely used to remove gas-phase contaminants from industrial waste streams. In such processes, contaminants are brought into contact with water or chemically reactive liquid, slurry, or solid media. The process is called scrubbing. Depending on the application, cleaning efficiencies for target contaminants are on the order of 70 to 99%. The process has been evaluated for use in controlling HCHO under laboratory conditions.

F. Room temperature catalysts

Low-temperature catalysts were developed by a U.S. company for use in residential air cleaners. The room temperature catalyst, which included a mixture of copper and palladium chlorides, was mixed with an equal quantity of activated carbon in a thin-bed filter. Performance studies conducted in a 1152 ft^3 (32.3 m^3) room under static conditions indicated that this system was capable of significantly reducing levels of O_3, H_2S, sulfur dioxide (SO_2), CO, and ammonia (NH_3), and relatively ineffective in reducing concentrations of nitric oxide (NO), nitrogen dioxide (NO_2), and benzene. Its performance under real-world conditions has not been reported.

G. Botanical air cleaning

Proposed by a NASA scientist, botanical air cleaning is a relatively novel approach to removing vapor-phase contaminants from indoor air. Based on this concept, air would be cleaned by the active uptake and metabolism of contaminants by plant leaves. In initial static chamber studies, significant reductions in HCHO and other VOCs were reported. Other studies indicated this uptake was mostly associated with potting soil. Though uptake of various VOCs and other gases by plant materials can be shown in chamber investigations, no studies have been conducted to demonstrate the efficacy of plant use in indoor environments under real-world conditions. Because absorption is passive and contaminant generation is dynamic, the use of plants to control indoor air contaminants effectively is not probable. Nevertheless, it has caught the fancy of many Americans who have attempted to use plants for air cleaning purposes.

H. Ozonation

Ozone is a powerful oxidizing substance produced by high-voltage systems incidentally or for special purposes (e.g., water treatment). Ozone generators are commonly used by contractors as an odor control measure in post-fire rehabilitation of buildings. In the past two decades, a number of companies have sold O_3 generators as air cleaning devices to homeowners, schools, and a variety of building owners. The assumption has been made by manufacturers that O_3 generated in a space will react with aldehydes and other VOCs to produce harmless CO_2 and H_2O vapor, and that the levels of O_3 used are not harmful to the health of human occupants. Studies conducted on these devices indicate that, when operated as recommended, O_3 concentrations generated are not adequate to significantly reduce VOC concentrations; they are, however, above ambient air quality and occupational exposure limits (particularly for individuals in the near vicinity of operating devices). As a consequence of potential consumer exposure hazards, a number of states have sued manufacturers of O_3 generators, alleging they pose a substantial risk to public health. Ozone generators continue to be widely sold in North America.

The deliberate introduction of O_3 into indoor spaces poses several additional concerns. As a powerful oxidant, O_3 bleaches fabric dyes and cracks rubber and plastic products. As indicated in Chapter 4, it initiates indoor chemical reactions that produce a variety of new irritants.

III. Air cleaners as contaminant sources

Though air cleaners are designed to clean air, they have been reported to be sources of indoor contaminants such as VOCs and microbial organisms and products. There have been reports of significant emissions of toluene and xylene from oil-treated particle filters, and a variety of odorous aldehydes (hexanal, heptanal, octanal, nonenal) and small organic acids from filters infested with microorganisms. Filters can also be a source of fibrous particles shed through HVAC systems and, as indicated previously, electronic air cleaners can be a significant source of O_3.

Filters in HVAC systems can capture and retain fungal spores and mycelial fragments which subsequently grow on collected dusts. Such growth can penetrate filter media, contaminating other filters, air, and surfaces downstream. These fungi can produce allergens that can be detected in building air independent of mold spore/particle concentrations.

Biocides are commonly used in filters. Though there is some potential for them to become airborne, biocide levels in indoor air associated with filter use have not been evaluated and reported.

Oxidizing media such as $KMnO_4$ have the potential to produce a variety of small aldehydes and ketones in addition to CO_2 and H_2O vapor. They also have the potential to produce HCl from the oxidation of chlorinated solvents such as methyl chloroform, commonly found in indoor environments. Studies on such potential contaminants have not been conducted. As indicated previously, ozonation is the deliberate introduction of O_3 for what is described as air cleaning purposes. It poses both direct and indirect indoor air quality/indoor environment concerns.

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Questions

1. What is the primary use of air cleaning in indoor spaces? Why?
2. How do fibrous media filters collect dust particles?
3. What is the relationship between particle size and the ability of media filters to collect particles efficiently?
4. What factors affect the performance of fiber media filters?
5. Describe the properties and performance of HEPA filters.
6. Describe the relationship between filter collection efficiency and pressure drop.
7. Why are extended media filters used in many building applications?
8. Describe uses for viscous and renewable media filters.
9. Describe the relationship between filter soiling, air flow resistance, and cleaning efficiency.
10. Describe the principle of operation and cleaning effectiveness of electronic air cleaners.
11. What are the advantages and disadvantages of using extended media and electronic air cleaners as in-duct devices in residential air cleaning?
12. How is the performance of dust air cleaning devices determined?
13. What is the difference between arrestance and dust spot efficiency?
14. How effective are free-standing air cleaning devices commonly available in the market and purchased by consumers?
15. How do ion generators work? How effective are they?

16. If you were to use an air cleaner at home to reduce your exposure to allergens, what factors should you consider before you purchase it?
17. What are the advantages and disadvantages of using in-duct dust air cleaners?
18. Describe air cleaning principles used in clean rooms.
19. What chemical/physical processes can be used to remove gas/vapor contaminants in indoor air?
20. Describe sorbent use in air cleaning.
21. What properties of activated carbons affect their performance in air cleaning applications?
22. Describe the movement of contaminant vapors through an activated sorbent bed.
23. How can one determine when an activated carbon sorbent bed filter needs to be replaced?
24. Describe how the catalytical properties of activated carbons can be used for specific air cleaning applications.
25. What is chemisorption? Describe a specific application.
26. What factors limit the performance of free-standing air cleaners using sorption/chemisorption principles in residential air cleaning?
27. Describe botanical air cleaning and its limitations.
28. Why is ozonation an undesirable air cleaning practice?
29. How may air cleaners be a source of indoor contaminants?