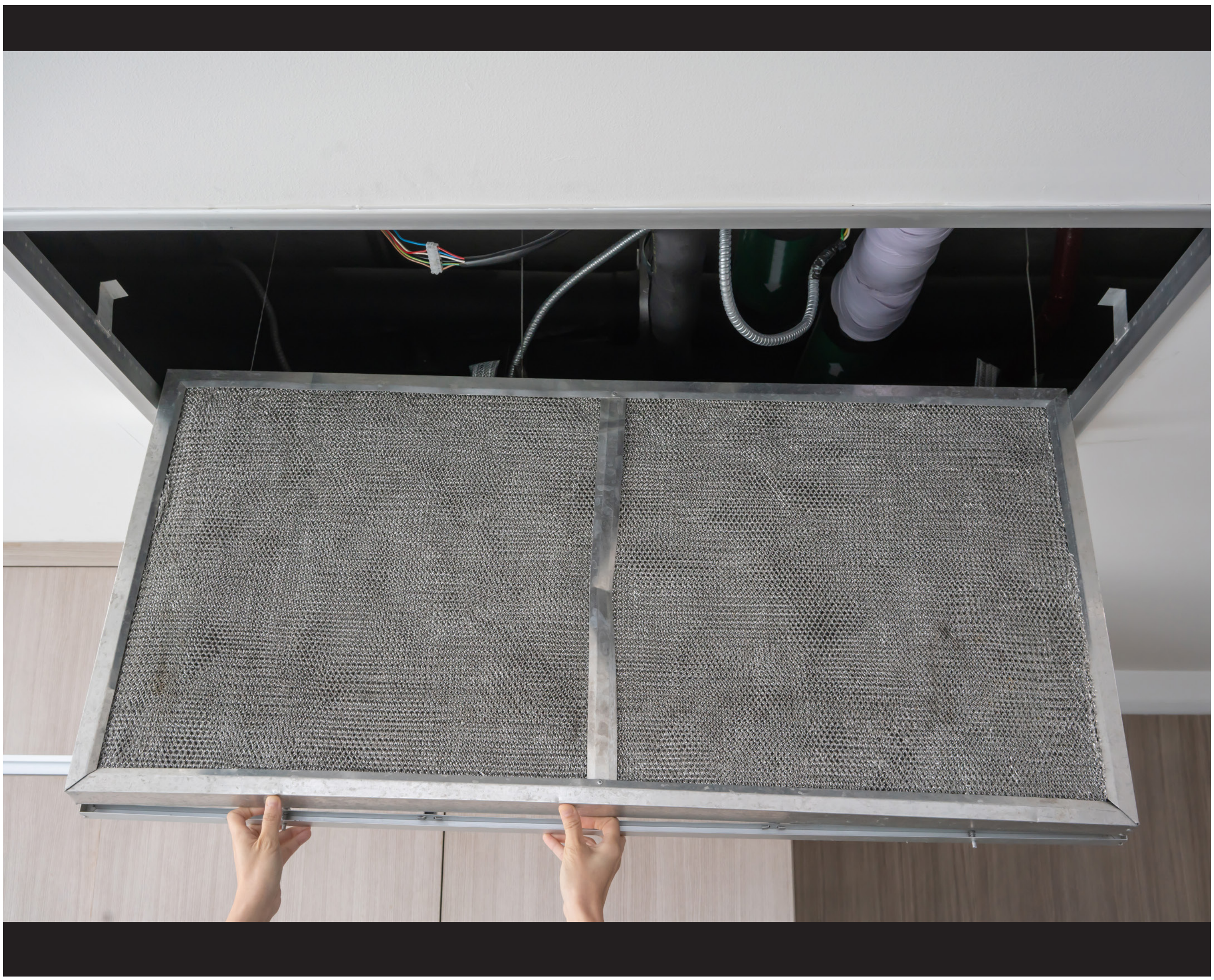
ELECTRIC POWER RESEARCH INSTITUTE

CHARACTERISTICS AND IMPLICATIONS OF INDOOR AIR QUALITY CONTROL IN COMMERCIAL BUILDINGS USING FILTRATION TECHNOLOGIES



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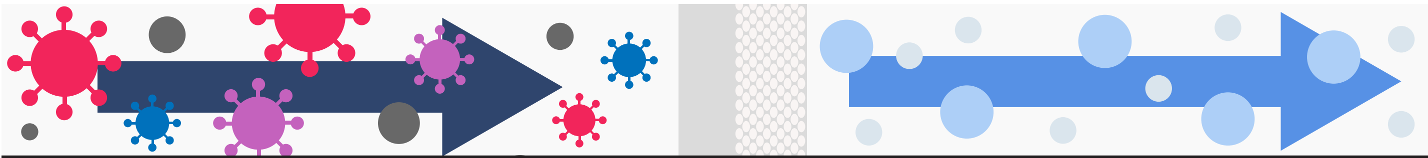

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RESEARCH QUESTION

How is air circulated in commercial buildings, and how is indoor air quality maintained? How do existing filtration and ventilation technologies and their control strategies affect the spread of pathogens in buildings?

KEY TAKEAWAYS

- Understanding filtration and the role it plays in buildings is ever more important as work and other social gathering places begin to re-open.
- MERV 13 and higher rated filters are effective in capturing airborne viruses, such as SARS-CoV-2.
- Higher MERV ratings will require additional fan power to maintain airflow over greater pressure drops. Actual values will depend on specific system specifications.
- Increased ventilation rates will require increased energy consumption for cooling/heating depending on the environment but may reduce viral infection rates.
- Increased air circulation within buildings may also be an alternative to ventilation if particle filtration rates are sufficient.
- Increasing ventilation rates may dilute indoor pollutants but can increase the concentration of particulates from outdoor sources, and may require more frequent filter changes and overall system maintenance.

BACKGROUND

Indoor air quality (IAQ) is important for occupant health, and for this reason, fresh air is introduced into indoor spaces to dilute the concentration of harmful contaminants. Moisture content of the air also contributes to IAQ and must be controlled to avoid mold growth and maintain comfort levels. Maintaining good IAQ is now even more important to mitigate the spread of viruses such as COVID-19. IAQ is affected by many indoor and outdoor sources. Common pollutants from outdoors include plant pollens, pesticides, second-hand smoke, fires, and automobile exhausts. Indoor sources such as fireplaces, stoves, paint, and various cleaning products, can also negatively impact IAQ. Filtration removes undesired particulates when bringing outdoor air inside buildings. Ventilation ensures the concentration of pollutants is kept at minimal levels within buildings. They are often used in combination to provide good IAQ, as shown in a common air handler configuration in Figure 1.

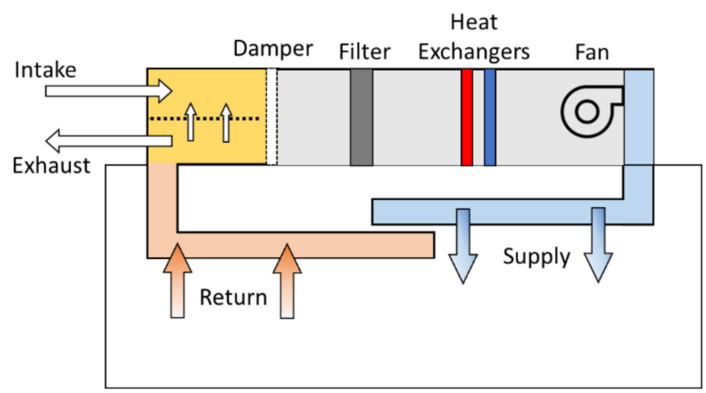


Figure 1. Typical commercial building ventilation with air handling unit, where a portion of return air can be mixed with fresh intake air and be recirculated through the building

AIR HANDLING IN COMMERCIAL BUILDINGS

Ventilation, or the introduction of fresh air to enclosed spaces, plays a critical role in buildings to maintain indoor air quality. It also affects energy consumption and moisture control. In general, air is moved into buildings for ventilation through pathways such as vents and windows by some driving force. It can be separated into natural ventilation and mechanical ventilation depending on the driving force. Commercial buildings may employ a combination of these systems. Commercial buildings are subject to standards on minimum ventilation rates (ANSI/ASHRAE/IESNA Standard 62.1, "Ventilation for Acceptable Indoor Air Quality") to provide acceptable IAQ that minimizes adverse health effects. ASHRAE Standard 62.1 requires minimum ventilation rates in breathing zones ranging from 0.06 to 0.48 cfm/ft^2. CA Title 24 is stricter, generally requiring minimum ventilation rates ranging from 0.15 to 1.5 cfm/ft^2. Building envelope and ventilation systems are also subject to energy efficiency requirements (ANSI/ASHRAE/IESNA Standard 90.1, "Energy Standard for Buildings Except Low-Rise Residential Buildings"). These standards are important because as the building envelope becomes tighter, the required mechanical ventilation increases due to less infiltration.

In natural ventilation, air is moved through pressure differences created by natural forces such as temperature and pressure as demonstrated in Figure 2. Stack ventilation relies on warm indoor air naturally rising and exiting buildings, which creates a vacuum that pulls in cooler air from outside. Cross ventilation relies on wind that drives fresh air into the building and forces indoor air to exit on the opposite side of the building. These systems require minimal power consumption, but need large openings provided by actuated windows with varying degrees of controls. Air may also infiltrate or exfiltrate through the building envelope depending on pressurization.

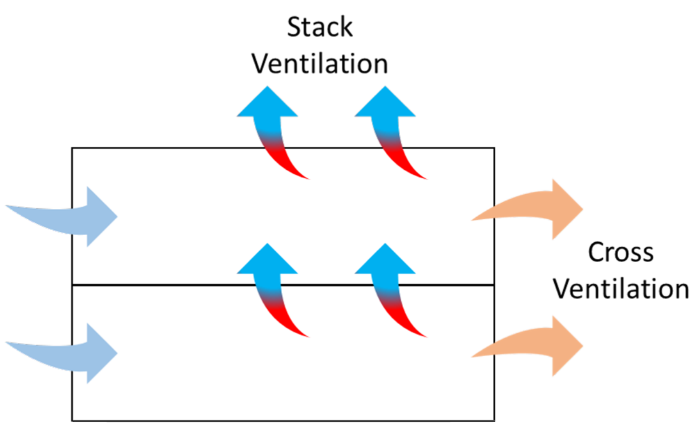


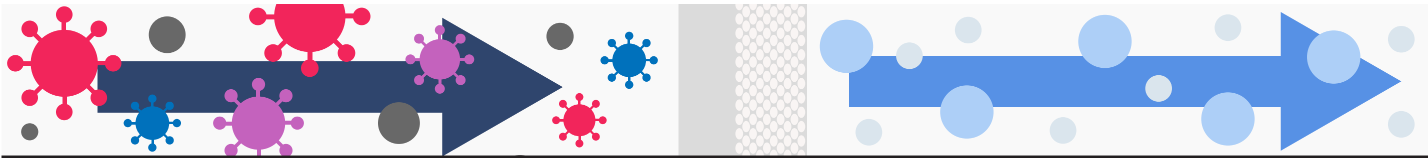
Figure 2. Natural stack and cross ventilation in which air is drawn within the building by wind of pressure and temperature differences.

Natural ventilation is largely dependent on uncontrollable climate conditions and difficult to control building characteristics. As a consequence, there are several drawbacks:

1. Some areas can experience very high airflow which may be uncomfortable for occupants while other areas may be stagnant.
2. In the absence of natural driving conditions (i.e. wind and temperature difference), the systems may provide little to no ventilation.
3. Occupant comfort may be jeopardized in locations with extreme temperatures and humidity.
4. If outdoor conditions are unsafe, such as during wildfires, natural ventilation can introduce harmful particulates indoors.
5. Most systems do not have adequate filters due to the large openings, exposing the building interior to undesired elements such as dust and insects.

Natural ventilation alone is seldom able to provide acceptable indoor conditions in commercial buildings. CA Title 24 requires buildings that are naturally ventilated to have mechanical systems as backup, unless the openings to the outside are permanent or controls are in place to keep them open when the space is occupied. ASHRAE Standard 62.1 has a minimum outdoor opening to conditioned space ratio, below which the building is required to have a mechanical ventilation system. In mechanical ventilation, air is moved using fans, usually as part of the heating, ventilation, and air conditioning (HVAC) systems, which conditions the delivered air to desired temperatures and humidity. An example of mechanical ventilation in a commercial building with an air handling unit is shown in Figure 1. HVAC systems require proper engineering design and installation to ensure the indoor blower fans are sized appropriately and the proper amount of air is delivered to each area of the building.

HVAC systems encompass a variety of different technologies. Cooling can be provided by vapor compression or evaporative cooling while heating can be provided by vapor compression or direct fuel combustion. Forced air systems use air as the heat transfer medium and deliver conditioned air with fan coil units (FCUs) or air handler units (AHUs). AHUs and FCUs can be connected to central chillers, boilers or heat pumps that service the entire building or can be self-contained in rooftop units (RTUs) to service defined areas. There are also hydronic systems that use a combination of radiation and



convection to deliver thermal comfort in radiators, these are usually used for heating purposes and require a separate ventilation system.

In both AHUs and FCUs, air is delivered to the indoor space through supply plenum or ducts and is extracted from the indoor space through return plenums or ducts. AHUs can bring in fresh outdoor air and serve multiple zones while FCUs typically serve a single zone. Both may contain dampers and filters placed upstream of the heat exchangers to remove dust and other particulates from the air supplied to the building. Filters and dampers can cause significant pressure drops and must be accounted for when sizing the fans. Depending on the design, AHUs can reduce thermal and latent load by recirculating a fraction of return air, as shown in the configuration in Figure 1.

AHUs commonly serve multiple areas within a building and can be of the variable or constant air volume type (VAV or CAV). CAV systems are simpler to design and supply a constant volume of air per unit time and adjust capacity by varying the supply air temperature. They tend to be less efficient since the air flow is fixed and temperatures in individual zones may be controlled by reheat systems. This may also cause discomfort for occupants since the thermal load in the connected areas can be different. VAV systems can support different setpoints for each of the connected areas. VAV boxes are connected to the ductwork and contain dampers that modulate the amount of air delivered to each area. Variable speed fans account for changes to total air flow requirements that result from the operation of individual zone VAV boxes.

Additionally, outside air supply to buildings can be provided by demand control ventilation (DCV) systems, which adjust the ventilation rate based on occupancy determined by using CO_2 sensors. DCV systems must be able to provide ventilation at the minimum rate required by the occupancy but can reduce the ventilation rate when the space is not occupied. For certain types of space (e.g. reception areas), DCV systems are allowed to not ventilate at all when the space is not occupied. Under CA Title 24, these systems can be used when the space has a design occupancy less than 40 ft^2/person, and has either an air economizer, modulating outside air control, or design outdoor airflow rate greater than 3000 cfm. Title 24 requires the indoor CO_2 concentration be no more than 600 ppm above the ambient level (~400 ppm).

System maintenance is important as ducts may become leaky or blocked and filters need to be replaced periodically. Some systems contain pressure sensors within the ductwork as part of fault detection, as blockage or old filters will cause increased pressure drop. ASHRAE Standard 62.1 also requires ventilation and indoor air quality related control systems be inspected semi-annually.

DISINFECTION/ FILTRATION TECHNOLOGIES

MECHANICAL FILTRATION

Mechanical filtration techniques can be used to physically trap particles from airstreams by using porous structures of fibers or other membrane materials.[1] There are a wide range of contaminants that exist and can be captured by various filtration technologies. Sizes of some example contaminants are in Table 1.[2] While the actual size of viruses is small, transmission of viruses is possible when viruses are contained in airborne bioaerosols.

Table 1. Example Contaminant Size Ranges

Contaminant	Approximate Size Range (microns)
Human Hair, Spores, Pollen	10 - 100
Bacteria	0.1 - 10
Smoke, Smog	0.01 – 0.1
Bioaerosols[3]	0.02 - 100
Viruses	0.01 – 0.1
Molecules/Compounds	0.0001 – 0.001

These systems typically require the replacement of filters over time. The Minimum Efficiency Reporting Values (MERVs) are a standard developed by ASHRAE used to report the filter's ability to capture particles between 0.3 and 10 microns. Typical MERV filters range from 1–16 and show effectiveness in trapping specific particles described in Table 2.[4]

1 https://www.ashrae.org/technical-resources/filtration-disinfection

2 https://www.eypae.com/publication/2020/air-filter-merv-ratings-what-do-they-mean

3 https://aerosol.ees.ufl.edu/Bioaerosol/Section02.html#:~:text=Individual%20bioaerosol%20particles%20can%20range,clusters%2C%20thereby%20forming%20larger%20particles.

4 https://www.epa.gov/indoor-air-quality-iaq/what-merv-rating-1

Table 2. MERV Rating and Average Particle Size Efficiency

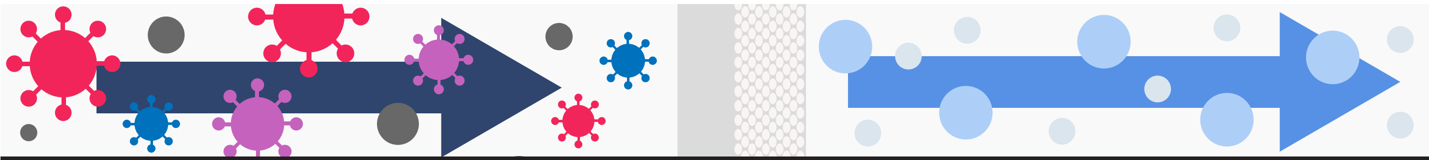
Standard 52.2 Minimum Efficiency Reporting Value (MERV-A)	Composite Average Particle Size Efficiency, % in Size Range, µm			
	Range 1 (0.30 to 1.0 µm)	Range 2 (1.0 to 3.0 µm)	Range 3 (3.0 to 10.0 µm)	Average Arrestance, %
1-A	N/A	N/A	E_3-A < 20	$A_{avg} < 65$
2-A	N/A	N/A	E_3-A < 20	$65 \le A_{avg}$
3-A	N/A	N/A	E_3-A < 20	$70 \le A_{avg}$
4-A	N/A	N/A	E_3-A < 20	$75 \le A_{avg}$
5-A	N/A	N/A	$20 \le E_3$-A	N/A
6-A	N/A	N/A	$35 \le E_3$-A	N/A
7-A	N/A	N/A	$50 \le E_3$-A	N/A
8-A	N/A	$20 \le E_2$-A	$70 \le E_3$-A	N/A
9-A	N/A	$35 \le E_2$-A	$75 \le E_3$-A	N/A
10-A	N/A	$50 \le E_2$-A	$80 \le E_3$-A	N/A
11-A	$20 \le E_1$-A	$65 \le E_2$-A	$85 \le E_3$-A	N/A
12-A	$35 \le E_1$-A	$80 \le E_2$-A	$90 \le E_3$-A	N/A
13-A	$50 \le E_1$-A	$85 \le E_2$-A	$90 \le E_3$-A	N/A
14-A	$75 \le E_1$-A	$90 \le E_2$-A	$95 \le E_3$-A	N/A
15-A	$85 \le E_1$-A	$90 \le E_2$-A	$95 \le E_3$-A	N/A
16-A	$95 \le E_1$-A	$95 \le E_2$-A	$95 \le E_3$-A	N/A

The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) causing the coronavirus disease (COVID-19) can spread from one person to another through droplets of saliva or discharge from the nose. When COVID-19 patients cough or sneeze, the particles (i.e., bioaerosols) can travel through the air for longer distance. Chia et al. identified SARS-CoV-2 particle sizes by sampling contaminated surfaces in the airborne infection isolation rooms.[5] The samples identified SARS-CoV-2 PCR-positive particles are in the size ranges of 1-4 µm and >4 µm. ASHRAE states that MERV 13 and higher rated filters are effective in capturing airborne viruses; however, at least MERV 14 filters are preferred.[6] As shown in Table 2, the MERV-13 filter is 85% efficient in the range of 1 – 3 µm and 90% efficient in >3 µm range at capturing particles and the MERV-14 filter is 90% efficient in the range of 1 – 3 µm and 95% efficient in >3 µm range at capturing particles. In the August 2020 ASHRAE Journal, "Study of Viral Filtration Performance of Residential HVAC Filters" (Zhang et. al, 2020),[7] a variety of MERV rated filters were tested for viral filtration efficiency using droplet aerosols with mass median aerodynamic diameters of 1 – 3 microns, similar to bioaerosols human viruses may be encapsulated in and the relevant results are shown below. All of the filters tested were of the same size (20" x 25" x 1") and were tested with the same air velocity of 295 feet per minute (fpm). Although the sample size was small (n=6), the results show increasing viral filtration efficiency and higher pressure drops as MERV increases. Therefore, the higher MERV-rated filters can cause increased pressure drop and energy consumption to

5 Po Ying Chia, et al. Detection of Air and Surface Contamination by SARS-CoV-2 in hospital rooms of infected patients. Nature Communications. 2020.

6 https://www.ashrae.org/technical-resources/filtration-disinfection

7 https://images.magnetmail.net/images/clients/ASHRAE//attach/AJ_Newsletter/Zhang_Digital_First.pdf



pull air through the filter. Thus, there is a need to verify if a building's HVAC system is sufficiently capable of accommodating the higher MERV-rated filters.

Table 3. Filter Rating, Filtration Efficiency, and Pressure Drop

Filter	Mean Viral Filtration Efficiency	Mean Pressure Drop (Pa)
MERV 5	32%	43
MERV 12	78%	38
MERV 13	89%	45
MERV 14	97%	60

In practice however, the pressure drop of the system may vary with filter size, type, and manufacturer. Larger ducts may require larger filters which allow for higher airflow with lower pressure drops. Moreover, the design of the filter may have an impact as well. Filter thickness, material type, and geometry may all impact the pressure drops and lifespan of the filters. Springer[8] reports on laboratory testing of a variety of different MERV filters, and notes that under the same conditions pressure drops associated with each varied substantially, even for filters with the same MERV rating.

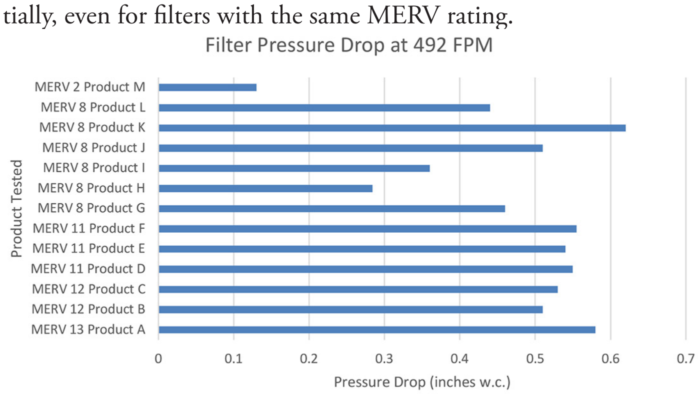


Figure 3. Filter Pressure Drop at Constant Fan Speed by Product (data from homenergy.org)

The impacts of different filters can vary depending on the HVAC system. Fans powered by permanent split capacitor (PSC) motors tend to respond to flow restrictions by supplying less airflow while maintaining a relatively constant power draw. This can lead to reduced heating/cooling capacity which causes longer runtimes and increased energy usage. This also reduces the amount of air circulation throughout the building. Systems powered by electronically commutated motors (ECM) can maintain a relatively constant airflow with small changes in static pressure drop at the cost of increased power usage. An example test scenario can be seen below. In this scenario the ECM motor is able to keep the airflow constant as the pressure increases, but the power consumption increases as well. The data shows that the MERV 8 filter with the lowest pressure drop requires around 480 W, but when using the MERV 13 filter this value increases to approximately 540 W (12.5% increase) with the ECM motor.[9] Since the fan is one of the major components of HVAC energy consumption, it is expected that a similar increase in energy usage may be incurred when upgrading to higher MERV filters.

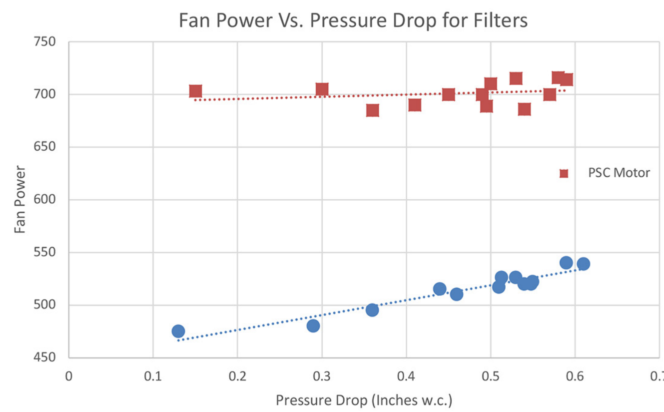


Figure 4. Fan power vs. pressure drop for various filters (data from homenergy.org)

PSC motors have less variable fan power with different filters, but compromise on airflow. The figure below shows how airflow can drop approximately 10% when using a MERV 2 filter compared to a MERV 13 filter.[10]

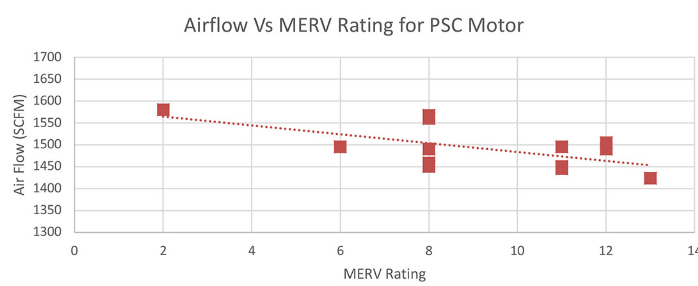
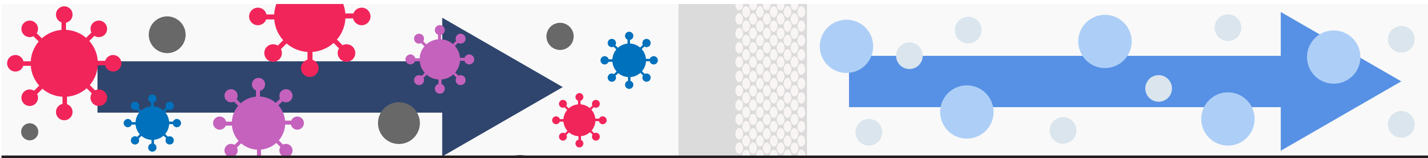


Figure 5. Airflow vs. MERV rating for PSC motor (data from homenergy.org)

8 https://www.homeenergy.org/show/article/nav/issues/page/4/id/667

9 https://www.homeenergy.org/show/article/nav/issues/page/4/id/667

10 https://www.homeenergy.org/show/article/nav/issues/page/4/id/667



High Efficiency Particulate Air (HEPA) Filters are another class of mechanical filtration with higher particle trapping efficiency than MERV 16; they can theoretically capture 99.97% of particles with a size of 0.3 microns. HEPA filters must be sealed properly in their filter racks for proper functionality and due to the increased pressure drop, may not be able to be retrofitted into HVAC systems. HEPA filters may be located in HVAC systems, but can also be found in portable HEPA machines (that can be moved between rooms), pre-assembled systems or ad hoc assemblies. Due to the higher costs and larger blower needed to sustain the pressure drop, HEPA filtration systems in commercial spaces are mainly used for medical purposes, high-tech cleanroom applications and other industries where quality control and cleanliness is of high importance.[11]

ELECTRONIC AIR FILTRATION

Electronic air filtration generally occurs in combination with mechanical filtration methods. Usually electronic filtration systems start with a mechanical pre-filter to capture larger particles. Then electrically charged systems are used to charge particles or generate ions that are then collected by charged plates, enhanced mechanical air filters, or other surfaces. The efficiency of electronic filtration systems depends on their operating flow rate and how they are cleaned and maintained. Performance of electronic filters can be similar to mechanical filters of equivalent particle removal performance but may benefit from reduced maintenance costs in replacing expensive filters and reduced noise. However, some electronic air cleaners can produce ozone that can negatively impact health and are classified as Ozone-Generating Devices.[12]

GAS-PHASE AIR CLEANERS

Gas-phase air cleaners are effective in removing volatile organic compounds, odors, and ozone from air. Most of these cleaners rely on sorbent materials such as carbon for adsorbing compounds from the air. This can be due to physisorption which is the bonding of contaminant molecules through intermolecular attraction or chemisorption which is a bond formed between the sorbent and chemical bond. The capabilities for adsorption depend on the sorbent material and contaminant. Lower molecular weight molecules tend to be less easily adsorbed at low concentrations. Some sorbent-based air cleaning equipment can also be regenerated through heating, allowing captured compounds to be released to the outdoor environment. Gas-phase air cleaning products can be packaged with filtration capacities that can also remove particles including bioaerosols from the air.

OTHER TECHNOLOGIES

Table 3. Additional air filtration technologies

Technology	Description
Light Based Technologies	Light-based disinfection technologies are used generally to inactivate viral, bacterial, and fungal organisms, preventing the spread of disease. In particular, the UV-C (particularly 265nm wavelength) light provides the highest germicidal effects. There are a variety of UV-C LEDs that are emerging for use in a wide range of applications. This includes in-duct air disinfection, upper-air disinfection, in-duct surface disinfection, and portable room decontamination. Direct exposure to UV-C energy may impact human health, so PPE may be needed to prevent damage to eyes/skin from overexposure. For more details, please see the recent EPRI Quick Insight on Light Based Technologies for Air and Surface Disinfection (3002019267).
Ozone	Ozone (O_3) is a gas that can deactivate viruses, bacteria, and fungi from surfaces and air. As mentioned above, ozone can be harmful to human health and therefore should never be used in occupied spaces. Ozone generators can be sold as air cleaners. However, at concentrations that do not exceed public health standards, ozone has little potential to remove indoor air contaminants.[13]
Vaporized Hydrogen Peroxide (VHP)	Hydrogen peroxide (H_2O_2) may also be vaporized to fill spaces and disinfect all surfaces in a room. Since vaporized hydrogen peroxide (VHP) is toxic, spaces must be sealed and unoccupied during treatment. The space must also be scrubbed after the prescribed exposure times before reoccupying the space. The application of this technology is mainly in hospitals.
Photocatalytic Oxidation (PCO)	Photocatalytic oxidation is another chemical purification technology that can destroy particles as small as 1nm. It works by combining UV light with a titanium oxide (TiO_2) catalyst to develop radicals that can break down contaminants.[14] There are limited studies on health impacts. However, it is possible that by-products are formed by incomplete oxidization. Benefits of photocatalytic oxidation include a low pressure drop, long life cycle, and ability to treat a wide variety of compounds. However, the lamp energy and possibility of ozone generation can be downsides.[15]

11 https://ushomefilter.com/hepa-filters/

12 https://www.ashrae.org/file%20library/about/position%20documents/filtration-and-air-cleaning-pd.pdf

13 https://www.epa.gov/indoor-air-quality-iaq/ozone-generators-are-sold-air-cleaners

14 https://www.hamiltonthorne.com/index.php/products/air-purification-systems/photocatalytic-oxidation-pco

15 https://www.ashrae.org/file%20library/about/position%20documents/filtration-and-air-cleaning-pd.pdf

ON-GOING EPRI WORK

EPRI's Customer Technologies and Advanced Buildings programs will continue to research air filtration technologies and stay abreast of advancements that may be of value to our utility members and their customers. If you are interested in pursuing any specific research projects related to air filtration, please reach out to the technical contacts listed below.

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